Imperial College London

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Innovating for renewable energy in developing countries:

Evidence from the photovoltaic industry in China

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Abstract

This study proposes an empirical investigation of whether and how the Chinese firms that make solar photovoltaic (PV) components are developing only the minimum knowledge necessary to adopt and assimilate externally developed technology or whether they can make substantial technological improvements and/or generate new production processes or products.

Previous studies of PV development in China have left industrial development and firm-level capability building almost unexplored. Moreover, the literature about firm-level technological change in developing countries has largely focused on analysing the development of a minimum knowledge base necessary to 'use' imported engineering-based technology, along with a static view of what induces firms to learn and to innovate.

By combining and contrasting two approaches – one with a technological capability and intra-firm learning focus and the other with a wider systemic perspective, the study explores the Chinese PV firms' effort towards innovation leadership and the static and systemic factors that influence their innovativenss.

The study is based on a survey conducted in China from May to July 2005 with a selected number of PV manufacturers, as well as on personal interviews with other PV stakeholders.

The analysis shows that PV firms in China had progressed well beyond basic operational capabilities and were quickly moving away from being mere users of imported PV components. Although knowledge has been accumulated in the PV technology family that is closest to maturity (i.e. c-Si) and despite considerable differences between the firms, the Chinese firms can be competitive beyond cheap labour and have learnt to be more efficient and to reduce production costs through technological capability improvements and the acquisition of other non technological and proprietary assets. This is because of (a) a learning process that has emphasised in-house R&D for quality improvements and for the development of new production processes and products; and (b) because of a domestic innovation system that has

grown and has helped firms to enhance their capabilities. International surges in solar PV demand, together with promotional schemes to support PV installed capacity in several mature economies (most notably Germany), have provided the Chinese firms with opportunities and motivation to add technological and qualitative value.

Originality statement and list of publications

I hereby declare that this thesis is my own work and that it has not been previously submitted, either in the same form or different form, to this or any other University for a degree.

Signed:

Nicoleta Marigo

Date: 3/06/2009

The thesis draws on work that has previously been published elsewhere:

MARIGO, N. (2004) Economic growth and the 'luxury' of a clean environment: is a short cut possible in China? IN WEBER, M. (Ed.) *Welfare, Environment and Changing US-Chinese Relations: 21st Century Challenges in China,* Cheltenham, Edward Elgar, 23-44.

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List of Abbreviations

a-Si	Amorphous Silicon
AC	Alternating Current
BIPV	Building-Integrated Photovoltaics
BoS	Balance of Systems
c-Si	Crystalline Silicon
CAS	Chinese Academy of Science
CCRE	Capacity Building for the Rapid Commercialization of Renewable Energy in China
CdTe	Cadmium Telluride
CE	Conformité Européene
CEO	Chief Executive Officer
CEPRI	Chinese Electrical Power Research Institute
CIS	Community Innovation Survey
CIS/CIGS	Copper-Indium-Selenide / Copper-Indium-Gallium-Selenide
CO_2	Carbon dioxide
CREIA	Chinese Renewable Energy Industry Association
DC	Direct Current
EPIA	European Photovoltaic Industry Association
EPO	European Patent Office
EU	European Union
EU-25	European Union with 25 Member States
EVA	Ethyl Vinyl Acetate
GaAs	Gallium Arsenide
GDP	Gross Domestic Product
GEF	Global Environment Facility
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit
GW	Gigawatts
ICCEPT	Imperial College Centre for Environmental Policy and Technology
IEA	International Energy Agency
IEA-PVPS	International Energy Agency Photovoltaic Power Systems Programme

IEC	International Electrotechnical Commission
IP	Intellectual Property
IPR	Intellectual Property Right
IS	Innovation System
IT	Information Technology
JV	Joint Venture
mc-Si	Multicrystalline Silicon
MIGA-WB	Multilateral Investment Guarantee Agency – World Bank
MMP	Maximum Power Point trackers
MOA	Ministry of Agriculture
MOST	(China) Ministry of Science and Technology
MWp	Megawatt peak
NSFC	(China) National Natural Science Foundation
NDRC	(China) National Development Reform Commission
NGO	Non-Governmental Organisation
NIS	National Innovation System
NRI	National Research Institutes
OBM	Own Brand Manufacture
ODM	Own Design and Manufacture
OECD	Organization for Economic Cooperation and Development
OEM	Original Equipment Manufacture
PV	Photovoltaic(s)
R&D	Research and Development
RE	Renewable Energy
REDP	Renewable Energy Development Program
RET	Renewable Energy Technologies
RMB	Renminbi (the currency of the People's Republic of China).
S&E	Science and Engineering (degrees)
S&T	Science and Technology
sc-Si	Single Crystal Silicon
SDPC	State Development and Planning Commission
SECO	State energy conservation office (Texas)
SETC	State Economic and Trade Commission
SGS	Solar Grade Silicon

Si	Silicon
SIPO	State Intellectual Property Office of the People's Republic of China
SOEs	State-Owned Enterprises
TC	Technological Capability
TIS	Technological Innovation System
TÜV	Technischer Überwachungs-Verein (Technical Monitoring Association)
UN	United Nations
UNDP	United Nations Development Programme
VC	Venture Capital
Wp	Watts peak
WB	World Bank
WIPO	World International Patent Office
WOFE	Wholly Owned Foreign Enterprise
WWF	World Wild Found

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1 INTRODUCTION

Picture 1 A sign on the Great Wall, Beijing - China

Picture 2 Detail of a street in Shanghai - China



Source: Pictures taken by the author during fieldwork in China, May-July 2005

This thesis is an empirical investigation of the innovation effort underway in a rapidly industrialising country, China, to develop domestic technological capacity for the manufacturing of renewable energy technologies (RET). The study seeks to understand whether the Chinese firms involved in one fast-growing RE technology, solar photovoltaic (PV), are developing only the knowledge necessary to adopt and assimilate externally developed technology and innovation or whether they are able to make substantial technological improvements or even to generate completely new production processes or products. Moreover, the study aims to explore the factors that have determined the current level of knowledge, how they have changed over time and what could drive firms to improve further.

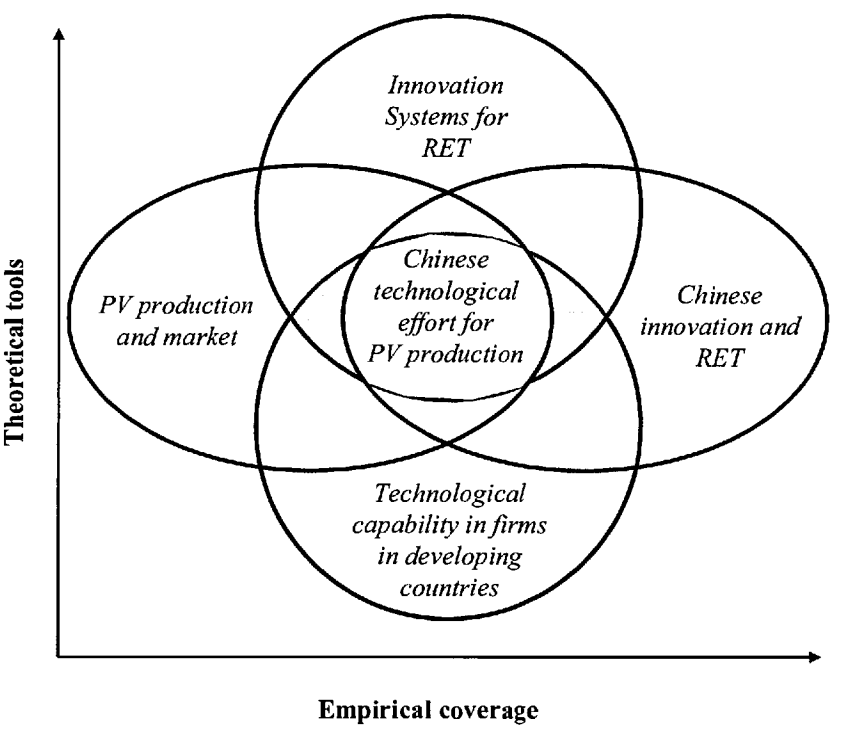
The thesis' main focus is hence on the *nature and determinants of the technological effort underway in the PV sector in China.* In other words, it explores what PV firms in China can do, how and why they can do it, and seeks insights into their potential for further innovative activity.

Since its 'opening' in 1978, China has shown that it can be the cheapest and biggest manufacturing subcontractor in the world. The crucial questions which rest at the heart of growth are, however: can China innovate and, more importantly, can it innovate in environmentally-sound energy technologies, given the pressing need to restrain its carbon dioxide emissions and to secure affordable energy supplies to fuel its growing economy and population?

Two literatures have contributed to this study's insights into the nature and the determinants of technological change in solar PV: the literature about technological capability accumulation and learning in firms in developing countries (Bell, 1984, Lall, 1992, Bell and Pavitt, 1993, Dutrénit, 2000, Romijn, 2002) and the innovation system literature (see among others Lundvall, 1992, Nelson, 1992, Freeman and Soete, 1997), in particular the branch of the latter that has been recently applied to better understand the emergence and the diffusion of RET (Foxon et al., 2005, Jacobsson and Bergek, 2004).

The Venn diagram in Figure 1 depicts the theoretical approaches, represented by the shaded circles, and the empirical areas of application covered by the study. The intersection of the different areas constitutes the core of this research.

Figure 1 The theoretical tools and empirical coverage of the thesis



Source: Author's elaboration

This chapter is organised as follows: section 1.1 presents the background of the study by briefly introducing the four areas that compose the empirical and the theoretical setting of the thesis (as illustrated by the four circles in the Venn diagram). Section 1.2 introduces the core research problem and its main motivations. Section 1.3 details the research objectives and questions while Section 1.4 provides some working definitions. Section 1.5 provides an overview of the methodological approach, together

with the key analytical and empirical challenges faced by the thesis. Section 1.6 discusses the thesis' novelty and original contribution. Section 1.7 presents the structure of the thesis.

1.1 Background

Modern societies are increasingly dependent upon the use of large quantities of energy, most of it in the form of fossil fuels, for virtually all aspects of life. However the extensive use of fossil fuels (i.e. oil, natural gas and coal), which constituted two-thirds (66.1%) of the world's total electricity generated in 2004 (IEA, 2006), is under scrutiny for its negative impact on the local and global environment and for the dependence of many countries upon scarce energy resources concentrated in restricted regions of the world (Intergovernmental Panel on Climate Change, 2001).

Renewable energy technologies (RET), especially 'new' RET, which include small hydro, modern biomass[1], wind, solar PV and geothermal, can address these concerns both because of their limited (although non-uniform) impacts on the environment and because they are inexhaustible sources of energy that can be accessed locally. A number of further reasons make them a particularly attractive option also for many developing countries (Clini and Moody-Stuart, 2002, Martinot et al., 2002). These include the possibility of reaching remote locations and rural areas currently not reached by the national grid (i.e. opportunities for off-grid applications) and the possibility of creating jobs, capital, and sources of revenue to local communities (i.e. opportunities for local development).

Despite their attractiveness, RET, in particular some like PV, have not yet reached full technological and commercial maturity and cannot compete with conventional fossil fuels on costs, except in some niche markets. They therefore need policy support to stimulate technical progress and speed up the technological learning necessary to drive down costs.

Although several policy instruments have been used to encourage a larger market diffusion of RET (Menanteau et al., 2003, Reiche and Bechberger, 2004), emerging evidence (Jacobsson and Bergek, 2004, Foxon et al., 2005) suggests that

[1] The expression 'modern biomass' refers to biomass produced in a sustainable way, which: "[...] excludes traditional uses of biomass as fuel wood and includes electricity generation and heat production, as well as transportation fuels, from agricultural and forest residues and solid waste" (Goldemberg and Teixeira Coelho, 2004, p. 711).

policy interventions in this area cannot be exclusively viewed in market terms but need to be understood in a wider 'innovation perspective' that also encompass technological and industrial development.

Innovation as a systemic process

There has been increasing recognition in the literature that technological change, and more specifically innovation in energy technology, is best understood as a process which results from the interactions with the system in which the technology is embedded (Sagar and Holdren, 2002, Jacobsson and Bergek, 2004, Foxon et al., 2005). The central idea behind the 'innovation system' approach is that technological development and diffusion are both an individual and a collective act, where firms, institutions and other actors, like for instance research organisations, all work towards innovation. Therefore, the determinants of technological change are not only to be found within the individual firm but also within the broader innovation system in which they operate.

The literature shows that if we want to understand more about RET development and diffusion and most of all to guide the policy process aimed at speeding up technological learning, we need to have a better understanding of the innovation system that surrounds RET.

PV production and market

Cost reductions via technical progress and market diffusion, together with a better understanding of the innovation process involved, are particularly important for a specific RET like solar PV.

A recent study highlights the contribution solar PV might make to both future global electricity supply and the mitigation of climate change (Greenpeace and EPIA, 2006). This study points out that in twenty years' time enough solar power could be produced to satisfy the electricity needs of 20% of the entire EU-25. In environmental terms this would mean reducing carbon dioxide (CO_2) emissions by 353 million tonnes, equivalent to the current combined emissions of Australia and New Zealand

Although solar PV has witnessed significant growth rates in the last decade and as a consequence the cost of the product has been declining, it must fall further for this expansion to continue. To meet this challenge, innovation in all PV technology families (Green, 2001) and new advances in applications (Barnham et al., 2006) will be crucial.

China's need for innovation and RET

Developing countries might benefit more than other countries from a wider use of PV and RET more broadly, because these are the countries where the strongest growth in the use of energy is expected in the years to come (Energy Information Administration, 2008). This particularly applies to rapidly industrialising countries, like India or China, where robust economic growth is driving the increase in energy demand and in CO_2 emissions (Wang and Watson, 2008).

China's rapid economic development has been driven so far by exports fuelled by an abundant and cheap labour force (OECD, 2007). In order to remain competitive in an increasing global economy, however, China must climb up the value-chain and put technical change and innovation at the heart of growth. This ability is foremost important in low carbon energy technologies, not only because China's current energy demand is dominated by fossil fuels and an increased attention to RE production and demand could lead to a more sustainable energy future, but also because RET represent a rapidly expanding international market (Martinot, 2008) and there are profits to gain in growing value-added faster than leading-edge competitor firms in other countries.

Manufacturing in developing countries

The promotion of technological innovation in developing countries is becoming a fashionable academic subject. Increasing interest in the literature stems partly from the fact that the set of liberalisation and deregulation policies that have dominated the development agendas of many industrialising countries in recent years have shown limits in promoting sustainable growth in the developing world (Aubert, 2005). This is particularly true for the waves of restructuring that have washed over electric utilities in both industrialised countries and, at an increasing pace, also in many developing countries (Besant-Jones, 2006). These trends are shrinking the involvement of the state in the energy sector while broadening the role of private entrepreneurs (Wamukonya, 2003). If this was done to increase sectoral efficiency and to maximise revenues from the sales of government assets, there are concerns that private companies might emphasise short term returns, putting innovation at a disadvantage. This is particularly critical for the development of RETs, which need innovation to drive down costs and policy support to take them to a level playing field with electricity from mature fossil fuel technologies.

These developments call for a greater attention to how technology is created, enhanced and diffused in developing countries (Aubert, 2005). Since technology is developed largely in firms, understanding technological change means looking within manufacturing firms (Forbes and Wield, 2002).

1.2 The problem definition and the motivation

The manufacture of RET and more specifically of PV components (i.e. modules, cells, etc.) has a role to play in developing countries because it can help local industrial development and provide at the same time, potentially secure and more sustainable sources of energy. Although manufacturing of PV system components has been so far concentrated in mature economies (mainly in Germany and Japan), rapidly industrialising countries like India or China are quickly emerging as PV component producers.

Until the late 1990s, the Chinese PV industry had an extremely limited production capacity. It used out-of-date technology on a small scale (Zhu, 2004) and was described as weak when compared to foreign competitors, constrained by bottlenecks in equipment, resources and knowledge, and unable to deliver good quality products at competitive prices (Dai and Shi, 1999).

Only five years later, in the first half of 2005, China's PV module manufacturing capacity ranked fifth in the world (Chen, 2004) and one of its module manufacturers was about to become one of the top five PV producers in the world.

How has this been possible? Is China only assembling foreign PV cells (that have high knowledge content) into modules, thanks to its abundant cheap labour, or it is moving up the value chain and developing the skills necessary to change the technology?

The factors that lie behind the emergence of the Chinese PV industry have never been explored before and are the main concern of this thesis. Existing studies about PV in China have either focussed on the demand side (seeking to explore market development options, see for instance: Wallace et al., 1998, Byrne et al., 2001) or on the development of those skills useful to install, operate and maintain imported PV system (IEA-PVPS, 2003, Ling et al., 2002). The few studies that have addressed industrial development or firm-level capability building in PV in China (Dai and Shi,

1999, Zhu, 2004, Zhao, 2004) have done so in a descriptive way that can only be used by this study as background information.

We believe a better understanding of what China is doing to build up its own PV manufacturing industry and what is driving it towards innovation might have a bearing not only for the development of the PV industry in China and possibly in other developing countries but also, more broadly, for our understanding of innovation dynamics in these countries.

Previous studies that have addressed firm-level innovation in developing countries have been concerned about the development of a minimum base of knowledge necessary to acquire, assimilate and eventually improve, to suit specific local conditions, technology developed elsewhere. Innovation, in this specific development context, thus means 'using' and reproducing existent technologies. Although we do not deny that this effort is of fundamental importance for firms to acquire and enhance capabilities, especially in certain engineering-based technologies, it does not pay attention to firms as autonomous generators of technologies, which is what we seek to understand in the context of the PV firms in China. This is in an environment in which, it has been argued, the ability to compete effectively at home and in international markets will largely determine the survival of a production venture: "[...] being borrowers (or say imitators) of technology rather than innovators leaves the developing countries at a distinct disadvantage since they are unable to derive monopoly profit in any of their production activities" (Huq, 2003, p. 1).

Moreover, the fact that firms are part of a larger innovation system which is becoming more and more complex, calls for a broadening of the analytical focus: firm-level factors of technological accumulation and improvement are simply no longer enough to understand more complex dynamics.

This study hence aims at understanding the nature and the determinants of the innovation effort underway in China to develop domestic technological capacity for the manufacture of PV components.

In so doing, the study not only explores an area, the technological innovativeness of the PV industry in China, that has not attracted scholars' attention so far, but also aims at a wider contribution about innovation for low carbon energy technologies in rapidly industrialising countries.

1.3 Objectives and research questions

The analysis of this thesis focuses on the *firms involved in PV production in China and on the innovation system that surrounds them.* This choice rests on the following considerations:

- Firms are at the centre of this study's analysis because, as explained previously, technology is developed largely in firms and looking inside the black box of technological change means looking within firms that are the 'engine' of economic development.
- Technological development is regarded in this study as a systemic phenomenon in which the component parts of the economic system evolve alongside each other and influence each other with continuing feedback. Firms are part of this system.

The aims of the study are to:

- Explore the innovative effort of the Chinese PV manufacturers by developing an analytical framework specific to solar PV and that combines insights from both the technological capability (TC) and the innovation system (IS) literatures.
- Apply the analytical framework to a selected number of Chinese PV manufacturers, in order to identify the requirements and constraints to innovation, as well as the characteristics of the enabling environment and, therefore, the opportunities for intervention.
- Discuss the relevance of the findings for other developing countries and the implications for their strategies and policies to enter PV manufacturing and more broadly, other RET.

To reach these objectives this study is guided by two *research questions*:

1. How advanced is what PV firms in China can do?
2. What factors affect the knowledge accumulation process, how have they changed over time and how might they drive the firms' innovation effort further?

1.4 Working definitions

We believe some initial working definitions could be useful at this point. These definitions, which draw upon both the TC and the IS literatures, will be further explored throughout the thesis and revisited in Chapter 7.

Innovation

The term 'innovation' covers a broad range of activities, including organisational, financial, marketing and technological innovation. This study focuses on the latter, which can be defined as: "[...] a process by which firms master and implement the design and production of goods [...] that are new to them, irrespective of whether or not they are new to their competitors - domestic or foreign" (Ernst et al., 1998, pp. 12-13).

With such a definition, the emphasis is not exclusively on innovation as a single event, a 'big bang', but rather on the: "[...] process of implementing innovative activities that permit firms to learn and master the underlying principles and characteristics of the knowledge which might be externally or internally produced but which are new to the firm' (Kiggundu, 2006, p. 19).

This definition embraces also, but not exclusively, the notion of non-frontier, adaptive and incremental innovation activities often undertaken in developing country contexts.

Two 'types' of technological innovation are taken into account by this thesis: 'product innovation', the knowledge about how to create or improve products, and 'process innovation', the knowledge about how to produce them.

Innovation system

An 'innovation system' is defined in this study as: "[...] the elements and relationships which interact in the production, diffusion and use of new, and economically-useful, knowledge" (Lundvall, 1992).

Technological capabilities

In line with the approach adopted by the TC literature (see Chapter 2), this study conceptualises technical change in firms in terms of the acquisition of 'technological capabilities', defined as: "[...] the knowledge and skills needed for firms to choose,

install, operate, maintain, adapt, improve and develop technologies" (Romijn and Albaladejo, 2002, p. 1054).

Commercial state of the art

Manufacturing PV products that are commercial state of the art refers, in this study, to the capability of the Chinese PV firms to produce within the dominant PV technology family (i.e. c-Si) at the same technical and qualitative level as the international technology leaders. For example, it refers to the capability of producing c-Si cells or modules with the same conversion efficiency and qualitative performance as the international competitors.

Technology frontier

Being at the technology frontier is understood by this study as:

a) the ability to undertake (or evaluating to undertake) new technological choices, within the dominant (c-Si) technology family, that would allow the firm to further improve this technology family and to take it forward by driving down the costs of the final products. An illustrative example would be the ability of the PV firms to adopt emerging and alternative c-Si production techniques, such as, for instance, growing ribbons of multicrystalline Silicon to reduce the costs of the c-Si final products

b) showing a forward view by entering or investing in PV technology families different from the dominant family (i.e. c-Si) and that are currently in their infancy (for instance some thin film technology families, organic PV but also PV under concentration) but that may well start to significantly penetrate the market after 2010-2015 (de Moor et al., 2004).

Developing and industrialising countries

According to the World Bank classification, countries with low or middle levels of GNP per capita are defined as 'developing countries'[2]. China, despite its rapid and prolonged economic growth, but because of the unevenness of its development, is classified by the World Bank as a lower-middle-income economy[3].

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[2] See http://web.worldbank.org/WBSITE/EXTERNAL/DATASTATISTICS/0,,contentMDK:20420458~menuPK:64133156~pagePK:64133150~piPK:64133175~theSitePK:239419,00.html

[3] The extent to which results obtained by studying the innovative behaviour of the Chinese PV firms could be extended to other developing countries is discussed in Chapter 9.

Industrialising countries are those developing countries that are undergoing rapid industrialization and that are technologically self-reliant in some standard modern technologies but remain dependent on advanced countries for technology, especially innovative technology.

Based on these definitions China is considered by this study as a developing and an industrialising country.

1.5 Research methods: an overview

The first step in the research method was to develop the analytical framework. An *extensive literature review* was conducted together with in-depth *interviews with key PV experts in Europe.* These have been necessary to deepen understanding of the PV sector and to adapt to the specific PV context a more general framework inspired by the theory.

The empirical part of the research has employed a *firm-level survey based on a questionnaire* administered in face-to-face interviews with a selected number of PV firms in China, during plant visits and fieldwork from May to July 2005.

Semi-structured interviews with other relevant stakeholders of the Chinese PV sector (i.e. R&D representatives, policy makers, etc.) were also conducted, to define the innovation system surrounding PV and to understand its evolution over time and how it facilitates or constrains innovation in firms.

The design of a methodology suitable to study the technological capabilities of the Chinese PV firms and the innovation systems of which they are part presented several analytical and empirical challenges. These are briefly summarised in what follows and then discussed in more detail in Chapter 3.

1.5.1 A brief note on some analytical and empirical challenges presented by the study

It is a challenging task to investigate if and how Chinese firms involved in the PV industry are accumulating technological capabilities and innovating, not least because it involves international comparison. The task is rendered difficult also because

as will be highlighted in Chapter 4, the term 'photovoltaic' ('PV') refers to a number of technology families that are at different levels of technological and commercial maturity. Assessing the complexity of the technological capabilities accumulated by firms and the role of the innovation system in promoting further advancements, means bearing in mind mature and emerging technologies alike. Moreover, different productive processes along the PV value chain present different levels of technological complexity. For example, assembling solar modules is technologically less intensive than producing crystalline Silicon (c-Si) wafers (see discussion in Chapter 4). Developing a technological assessment of this industry requires taking into account these differences.

Furthermore, what is going on in PV in China depends on developments in the rest of the world (e.g.: China relies on export markets to sell between 70 and 80% of its domestic solar cell and module production) and this should be accounted for in the analysis.

Besides the complexities determined by the technology itself, the country under analysis, China, presents several unique features. The story of PV development in China, and indeed the accumulation of technological capabilities in firms, dates back to the early 1960s, when China was a planned economy (see Chapter 5). Since the economic reforms started in 1978, the country has experienced tremendous changes that have contributed to creating an increasingly complex system within which to study PV development.

All these technology and country specific factors have contributed to enriching the context within which the analytical framework of the research has been developed and to enlarging the challenges faced by the research.

In terms of the empirical analysis it has been necessary to collect data and information at both the firm and the national levels and to gain access to the relevant sources of information. This has been particularly challenging and has required an understanding of the country and of the culture upon which the study is based. China is a country with which the author of this thesis is familiar and that has been the focus of several research projects she undertook in the past. Moreover a fluency in spoken Mandarin has been an advantage in conducting in-depth interviews, not only with industrialists but also with representatives of the R&D sector and with policy makers. This capability has allowed her to collect valuable first hand information (without the

mediation and possible distortion of an interpreter) and to develop a unique body of empirical evidence (see the thesis' empirical contribution in Section 1.6) on the sector, which is extremely rarely obtained by non-Chinese researchers.

Considerable effort and time were also spent before leaving for fieldwork, to create a suitable network upon which to rely once in China. Chinese RE associations, academics, local and international organisations with strong and far-reaching links with domestic PV firms were also contacted and engaged in the research project, to secure not only access to the necessary information but also to create a positive attitude towards the researcher and her study.

1.6 Novelty and original contribution of the thesis

This thesis makes significant novel contributions of three kinds: methodological, empirical and theoretical. While the details of these contributions are discussed in Chapter 9, we summarise here only the main points.

Methodological contribution

To understand how advanced is what the PV firms in China can do and what influences their innovativeness, this study develops an analytical framework, which departs from the existing approaches and improve them in the following ways:

- It is *specifically developed to study the PV sector.*
- It *combines and contrasts two well-defined approaches* that have been so far applied largely separately: the firm-level technological capability approach and the innovation system approach.

Empirical contribution

It is the *first time that the Chinese PV industry has been studied from an innovation view point* and that an innovation systems approach has been applied to the PV sector in China. This allows us to *map for the first time the main actors and interactions* of the Chinese PV innovation system and to study its evolution over time.

Moreover, *contemporary and primary data on the state of the Chinese PV manufacturing industry* are gathered, organised and presented for the first time (Marigo, 2007).

Theoretical contribution

The thesis makes the following contribution to the existing theory and more specifically to the technological capability (TC) and innovation system (IS) literatures that underpin this study:

- It *adds to the debate about what we mean by innovation in developing countries* and 'how' and 'why' firms in these economies accumulate technological capabilities that are specific for RET and PV.
- It also *adds to the debate on how RET emerge and diffuse* in the market, by providing specific insights derived from the study of the PV innovation system in China.
- It *provides new and enhanced policy guidelines for developing countries wishing to undertake PV component production* and more broadly, RET manufacturing. These derive from the combined insights obtained by applying both the TC and the IS analytical approaches.

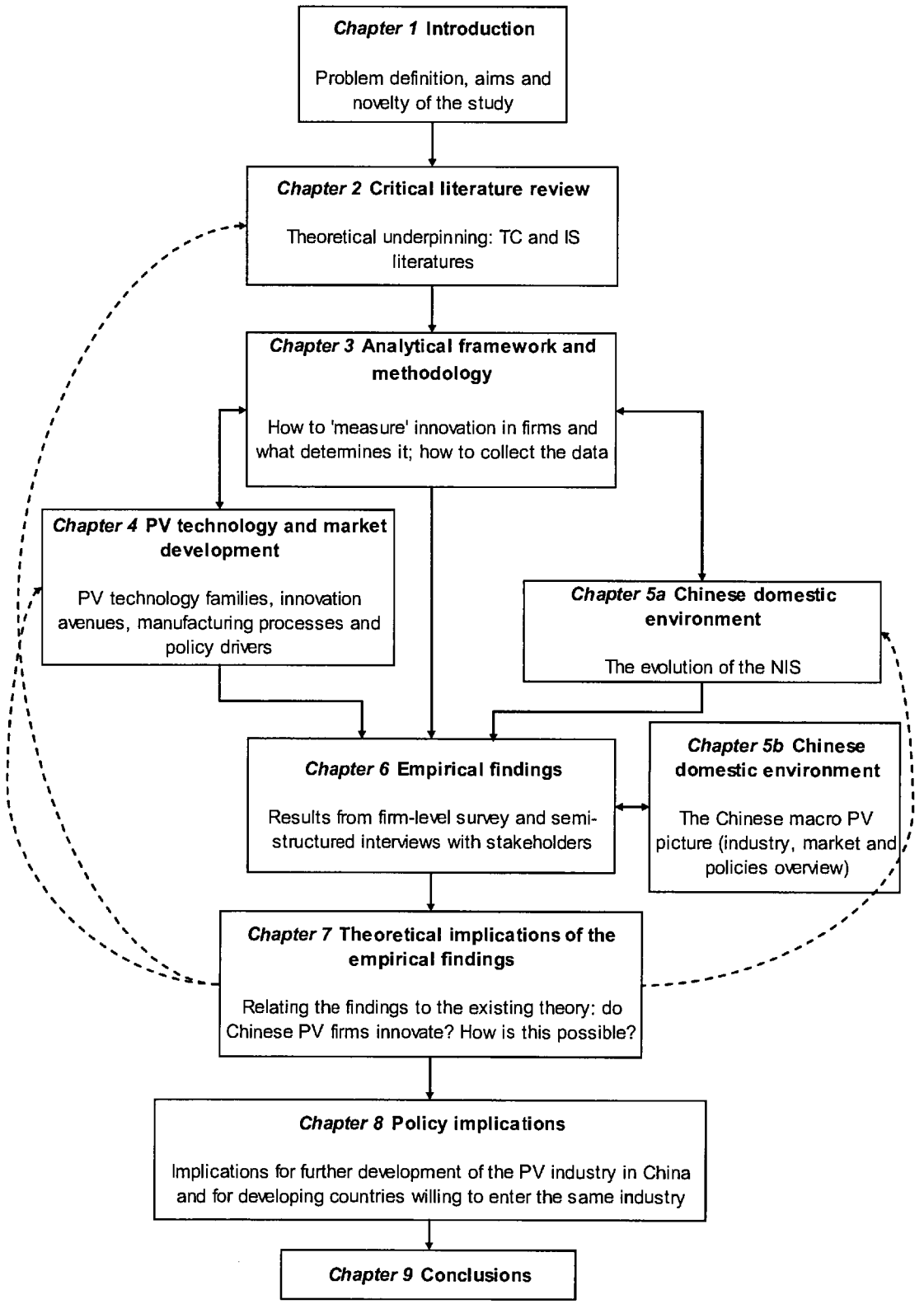
1.7 Structure of the thesis and coverage

This thesis has nine chapters. Their short titles and the main issues they address are summarised and presented graphically in Figure 2.

Although the thesis follows an apparent linear flow (as suggested by the order in which the different Chapters follow each other), the research process has been characterised by numerous feedback loops between the activities described in the different Chapters. This is better explained below and illustrated in Figure 2 by the double arrows that connect several chapters.

Following this introduction, *Chapter Two* reviews critically the two main bodies of literature that underpin the theoretical understanding of this research: studies about technological change in firms in developing countries and innovation systems studies, with a particular reference to those that have been applied to RET. This chapter discusses the main issues emerging from these literatures, their relevance to this study and their main limitations. This chapter also reviews critically alternative approaches (based on the use of quantitative indicators) to the understanding of innovation, and assesses the extent to which they are appropriate in depicting and explaining innovation in China.

Figure 2 The structure of the thesis



Note: TC = Technological Capability; IS = Innovation System; NIS = National Innovation System

Chapter Three develops the analytical framework adopted by this thesis to study technological capabilities and the innovation system that surrounds PV

technology in China. This chapter also presents a detailed description of the methodology adopted, the data collection approach and the fieldwork undertaken in China.

Chapter Four is the first of two chapters (together with *Chapter Five*) devoted to developing a better understanding of the empirical setting of the research. This chapter briefly introduces PV technology, manufacturing processes and market development. It also discusses PV-specific innovation avenues together with policy measures adopted to promote a larger diffusion of this technology.

Chapter Five is China specific. It tackles two separate topics: the evolution of the national innovation system over time and the macro domestic PV picture (these are indicated as 5a and 5b in Figure 2). Information contained in this second part of the chapter was collected, as noted, during fieldwork in China from May to July 2005 and is located here to provide a broad national PV-specific background for the understanding of the firm-level results presented in Chapter 6 and discussed in Chapter 7.

The non-linear nature of the research process mentioned above has characterised in particular Chapters 3, 4 and 5. While a preliminary version of the analytical framework was drafted earlier on in the research process, its final version came only after Chapters 4 and 5 were firmly in place. It appeared in fact rapidly clear that a thorough understanding of the PV manufacturing process and of the possible innovation avenues viable in PV technological development (all issues discussed in Chapter 4), were necessary to inform the analytical framework and to make it suitable to understand the technology under study. Similarly, in order to get deeper insights into the specificities of the Chinese context, it was necessary to have a thorough understanding (as discussed in Chapter 5) of the profound changes experienced by its innovation system over time.

Thus the final version of the analytical framework presented in Chapter 3 is the result of a great number of feedbacks with Chapters 4 and 5, which are to be considered integral parts of the analytical framework necessary to study innovation in PV firms in China. For reasons of simplicity, however, the three chapters are presented and discussed sequentially.

Chapter Six presents the results obtained from the empirical part of the study. While the first part of the chapter presents the findings pertaining to the nature of

innovation in the Chinese PV firms, the second part presents the results about the factors that affect their ability to undertake technological change.

Chapter Seven takes a critical look at the empirical results presented in Chapter 6 and pulls out the main theoretical insights by discussing how they relate to the theory that underpins this study (presented and discussed in Chapter 2).

Chapter Eight discusses the main policy implications of this thesis for China's future PV industrial development and innovation-led economic growth. Broad implications for other developing countries wishing to enter the same industry are also discussed in this chapter.

Chapter Nine concludes the thesis by summarising the principal findings, highlighting its contribution to the existing knowledge and discussing its limitations. The chapter also points the way forward in terms of further research

Appendices provide the name of the firms and people interviewed during fieldwork in China and a list of the questions asked to non-firm stakeholders. An appendix also provides the complete version of the questionnaire, as administered to the firms during the interviews.

2 CRITICAL LITERATURE REVIEW

Picture 3 The window of a cloth shop in Hangzhou, China



Source: Picture taken by the author during fieldwork in China, May-July 2005

2.1 Introduction

In this Chapter we lay down the theoretical foundation of the thesis. This research does not exist in a vacuum: there is a pre-existing body of knowledge that serves as its source of grounding and inspiration but also as its point of departure. This Chapter has hence two main purposes: (a) to illustrate and discuss what is already known about innovation for emerging energy technologies in developing countries, particularly in China; and (b) to identify what remains unexplained or unexplored in the existing (academic) literature that covers these issues. This is so because the ultimate purpose of this study is to address these limits and to take our knowledge about the topic forward.

The material in this chapter also serves as a basis for the analytical framework proposed in Chapter 3, where we will translate some of the theoretical concepts

reviewed in this chapter into observable and empirically testable variables. For example we will propose a way in which the concept of technological capabilities discussed in section 2.5 can be empirically observed and measured in firms. Moreover, in Chapter 7 we will discuss the extent to which the results obtained in the empirical analysis and presented in Chapter 6, relate to the ideas debated in this chapter.

As briefly anticipated in Chapter 1, two streams of literature form the academic grounding of this thesis and lie at the core of this chapter:

a) One stream understands technological change as a systemic process where different actors (e.g. academic and technology developers, governments, etc.) and their interactions contribute to innovation. This body of literature will be referred to in this study as the *Innovation System (IS) literature.* Within this literary tradition a group of studies that has applied the IS approach to RET (Jacobsson and Johnson, 2000, Foxon et al., 2005, Jacobsson et al., 2004), stands out for its relevance to this study and for its interest in understanding innovation in PV in the Chinese firms.
b) The other stream of literature, commonly used in studies focusing on technological development in less-developed economies, conceptualises firm-level technological change in terms of the acquisition of technological capabilities and emphasises the contribution of learning in this acquisition process. This body of literature is often referred to in the literature as 'latecomer innovation research' (Hobday et al., 2004), 'latecomer company literature' (Figueiredo, 1999) or 'technological capability accumulation' by firms in developing countries (Dutrénit, 2007). In this study it will be simply called *Technological Capability (TC) literature.*

Although these two streams of literature have been chosen to form the theoretical core of this thesis, they are not the only possible approaches that could be adopted to understand technological change. Quantitative indicators, like R&D expenditure or patents, are often adopted to describe key dimensions of technological change. This is not a formal theory or a conceptual tool, as it is the case of the TC and IS literatures, but rather a method widely used in the literature, especially when an

empirical measurement of technological change is needed[4]. Since China's innovative performance has often been explored and assessed by using quantitative indicators, we devote the initial part of this Chapter to critically reviewing this method and the picture it conveys about innovation in China.

This part of the review serves two main purposes:

a) To provide initial motivation[5] on why we decided to adopt the IS and TC literatures instead of undertaking the more conventional quantitative indicators route. In other words, although other approaches exist and could be used to enhance the understanding of innovation, we believe the combination of the IS and TC literatures better serves our purposes;

b) To sketch a picture of China's innovativeness, as it results from the use of quantitative indicators, against which the findings obtained by this study by adopting the IS and TC literatures, could be compared and contrasted[6].

The Chapter is structured as follows: Section 2.2 critically examines the adoption of quantitative indicators to understand technological change and uses them (section 2.2.3) to sketch a picture of China's innovation (i.e. how 'innovative' does China look like when conventional quantitative indicators are used?). The same section also explains why we believe this method is insufficient to understand the nature and the determinants of innovation in the Chinese PV firms and to address the research questions in this thesis.

Sections 2.3 to 2.5 constitute the theoretical core of the thesis. Section 2.3 set the theoretical scene by briefly explaining why two apparently different streams of literature have been both taken into account. Section 2.4 reviews the IS literature, its main insights and the limits in understanding technological upgrading in PV firms in China. Particular attention is given both to a variant of the IS approach - the National Innovation System (section 2.4.6) - for its relevance in the study of innovation in developing countries, as well as to the application of the IS approach to the study of RET (Section 2.4.7).

Section 2.5 critically reviews some selected strengths and limits of the TC literature as they relate to the main purpose if this study.

Section 2.6 closes the chapter, by summarising the main points discussed in the Chapter.

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[4] See Smith (2005) for a discussion of the quantitative measurement of innovation.
[5] Section 2.3 in this chapter explains in detail why this study adopted both literatures.
[6] This aspect will be specifically discussed in Chapter 7.

We start with Section 2.2, where we critically examine the approach that is most commonly used to understand technological change (i.e. the use of quantitative indicators) and assess its robustness and appropriateness in studying the innovation behaviour of the Chinese PV firms.

2.2 A critical examination of the use of quantitative indicators to study innovation in the PV firms in China

The technological change process and the driving forces that are behind it can be studied from a number of perspectives. A common approach is to develop *quantitative indicators* that could be used to measure and assess the innovation behaviour of countries, industries or firms. The importance of developing indicators rests upon the need to provide a sound enough and 'measurable' basis for comparing the innovative effort of different economies (or firms) in a range of sub-sectors (Smith, 2005) and a hands-on tool for the design of appropriate policies aimed at stimulating innovation (OECD and Eurostat, 1997).

In this and the following section we will focus on this quantitative approach and critically assess the extent to which it helps a better understanding of firm-level PV innovation in China. In Sections 2.2.1 and 2.2.2 we discuss the strengths and weaknesses of two broad and widely adopted families of innovation indicators: the so-called *input-output* indicators and *trade data*. In Section 2.2.3 we use these indicators to picture China's innovativeness and to discuss critically the extent to which they provide a sound enough analytical basis to understand innovation in the context of the Chinese firms involved in PV production.

2.2.1 Input-output innovation indicators

A common way to design innovation indicators is to reason in terms of 'input-output factors'. It is assumed that for innovation to take place a certain number of inputs are needed (e.g. funds should be put into R&D activities) and that the results of these inputs could be observed by considering, for instance, proxies like the number of patents issued by a firm or by a certain industrial sector. It follows that R&D expenditure or data on patent applications are among the major established quantitative

indicators that have been used for innovation analysis (Smith, 2005, Griliches, 1990, Hagedoorn and Cloodt, 2003)[7,8].

R&D expenditure

Innovation input measures, such as *R&D expenditure* at the national level or as a percentage of a firm's sales, have the merit of being collected through national surveys over time[9]. This can allow for time series analysis and could provide a consistent basis for comparisons across projects and industries and therefore be used as a guide for policy implementation.

Although widely adopted in innovation surveys[10], R&D data presents a number of limitations in describing innovation. First, although it is a key input to innovation and it is clearly related to technical change (i.e. one can reasonably expect that limited R&D expenditure will not create a fertile enough ground for innovation to emerge), it does not measure it. The R&D input can in fact be used more or less efficiently: a high R&D expenditure does not necessarily correspond to a lot of new products being developed and diffused on the market (OECD and Eurostat, 1997, Smith, 2005). Secondly, the indicator does not capture other inputs closely related to innovation such as design, product engineering, trial production, training of employees and technology service expenditures (Kleinknecht et al., 2002).

When this indicator is used in a developing country context, additional difficulties can be encountered. The use of R&D expenditure in fact poorly represents technology development investments in those firms (often of small dimensions and resources) that lack distinct R&D laboratories or other units with separate functional and accounting identity (Kleinknecht et al., 2002). These features tend to be common in

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[7] Keith Smith, in a comprehensive review of innovation measurement, mentions other important classes of indicators: 1) bibliometric data, that is: data on scientific publication and citation; 2) technometirc indicators, which explore the technical performance of products; 3) databases on specific topics developed as research tools by individuals or groups; 4) synthetic indicators developed for scoreboard purposes by consultants (Smith, 2005).

[8] Besides the traditional and most common innovation indicators that are discussed here, there is a recent research project (funded by the European Commission) aimed at developing indicators and statistics specific for eco-innovation. More details are available at: http://www.merit.unu.edu/MEI/index.php

[9] Eurostat regularly collects data on R&D expenditure and personnel, see: http://epp.eurostat.ec.europa.eu/portal/page?_pageid=0,1136250,0_45572552&_dad=portal&_schema=PORTAL

[10] One of the most authoritative innovation surveys (available at EUROSTAT) is the Community Innovation Survey (CSI), which, as of 2007, had been carried out five times in all the EU Member States (CIS 5). Some non-EU countries perform very similar surveys according to the methodology suggested by the OECD Oslo Manual (OECD and Eurostat, 1997). These include Canada, USA, Australia and South Africa.

firms in developing countries (Romijn, 2002), where technical change often occurs through less formal and non easily quantifiable sources like learning by doing or learning to improve at the shop-floor[11] (Lundvall, 1992, Bell, 1984, Forbes and Wield, 2002). Moreover, it has also been noted (Forbes and Wield, 2000) that what matters more for firms in developing countries, is not the *amount* of the R&D expenditure (which is unlikely to match that of firms in mature economies), but its *focus*, i.e. the purpose for which R&D is undertaken[12].

It follows that using the amount of R&D expenditure as the unique indicator to derive conclusions on a firm's or a country's innovation performance could provide only a partial picture of a more complex reality, especially in developing countries.

Patents

Innovation output indicators, like *patents* granted by national patent offices, present a number of advantages in gaining insights into innovation activities. Patents applications are regularly collected and searchable in publicly available data bases[13] (Cooper and Merrill, 1997). Moreover, the detailed classification by technical field allows some hints as to the direction of technological change.

A number of drawbacks are also encountered when using patents as an innovation indicator (Griliches, 1990, Pavitt, 1988, Archibugi and Planta, 1996), however. Not all inventions are patented because firms might, for instance, decide to protect their innovations with alternative methods, most notably secrecy (Archibugi and Planta, 1996). Moreover, "[...] many patents correspond to invention with a near zero technological and economic value, whereas a few of them have very high value; many patents never lead to innovation" (OECD and Eurostat, 1997, p. 13).

The use of patent statistics to measure innovation taking place in developing countries is even more problematic. In these countries innovative modifications may be made to foreign technologies, which may be copied or adapted to suit local conditions and specific requirements. "These minor improvements, although locally relevant and 'new', are not straightforwardly translated into patents. Local learning may exist without local patenting" (da Motta e Albuquerque, 2000, p. 1048).

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[11] Different types of firm-level learning are discussed in detail in section 2.5.4.

[12] As will be discussed in more detail in the following part of this thesis (section 2.5.4), it is suggested that firms in developing countries should direct their R&D effort towards the enhancement of independent design and product development capacity (Forbes and Wield, 2000).

[13] The World Intellectual Property Organisation (WIPO) and the European Patent Office (EPO) have up-to-date databases on all the patents filed in the USA and in Europe.

As in the case of R&D expenditure, patent data cannot provide a comprehensive picture of technological upgrading, especially in developing countries where innovation could occur in non-conventional ways that are instead common in industrialised countries (i.e. in-house formal R&D followed by patent applications).

2.2.2 Trade data as indicators of innovation

A second broad group of indicators has been developed to specifically address product innovation. *International trade statistics* could be used to "capture the upgrading performance of different economies in a range of sub-sectors" (Kaplinsky and Readman, 2005, p. 680). It is in other words possible to infer a country's technological performance by looking at the high-tech content of the products it exports.

The main limitation of looking at trade data is that they can give indication only on product innovation, for which they have been specifically designed, but not on other types of innovation such as process innovation (i.e. improvements in the way in which goods are produced) or indeed organisational innovation (i.e. new ways to organise production and distribution). Moreover the use of trade data to asses a country's high-tech endowment may well give an indication of what that specific country does at that point in time, but it cannot tell us what the country could do in the future. Today's trade figures do not capture the time and effort needed for technological change and innovation to occur because these are gradual and cumulative processes. Therefore trade data offer, at best, a snapshot of current product innovation but do not shed light on the technological accumulation path of enterprises and on their potential for innovation in the future. Furthermore, international trade statistics do little to explain the determinants of innovation (Kaplinsky and Readman, 2005).

As in the case of the two previously presented indicators, trade data are an imperfect indicator to use to derive definitive conclusions on one country's innovativeness and innovation potential.

2.2.3 Depicting China's innovative potential by using quantitative indicators

Quantitative indicators, like the ones reviewed in the previous sections, have been widely adopted in the literature to assess technological upgrading in both mature[14]

[14] As a reference, the Community Innovation Survey (CIS) mentioned at the beginning of Section 2.2.1, could be cited. The survey collects a wide number of information, including R&D expenditure and number of patents held by the firms interviewed.

and developing countries, China included (see among others: Rosen, 2003, Cheung and Lin, 2004, Hu and Mathews, 2008).

China's outstanding economic growth in the last twenty-eight years has prompted questions, both within China (Gu, 1996, Chen and Xu, 2000, Fan, 2006, Guan et al., 2006, Liu and Lundin, 2006, Shen, 1999) and among foreign observers (Rosen, 2003, Yam et al., 2004, Steinfeld, 2004, Sigurdson, 2005) about the future prospects for the country's economic development and the extent to which this will be driven by technology-based gains. Moreover, China's growing share of world exports has spurred concerns about the extent to which the country will be able to compete in international markets with high value-added products and pose, in this way, a possible competitive threat to mature economies, and to its Asian neighbours (Lall and Albaladejo, 2004). Studies addressing these issues and backing their findings with quantitative indicators have then started to emerge and to form a growing body of empirical evidence.

Table 1 Depicting China's technological progresses with quantitative indicators

Indicator	Quantity	Year	Source
% GDP spent on R&D	0.6% 1.3%	1995 2005	OECD, 2006, National Bureau of Statistics and Ministry of Science and Technology, 2002 and 2006
Annual rate of growth in government R&D budget	19.2%	2005	National Bureau of Statistics and Ministry of Science and Technology, 2006
Share of world scientific publications	2.05% 6.52%	1995 2004	Zhou and Leydesdorff, 2006
Applications for invention patents[15]	173,000	2005	SIPO, 2005
Growth rate of invention patent applications	23% annually since 2000	2005	SIPO, 2005
China's exports of high-tech products (% of all exports)	6.8% 20.8%	1995 2002	National Bureau of Statistics and Ministry of Science and Technology, 2003
China's imports of high-tech products	16.5% 28.0	1995 2002	National Bureau of Statistics and Ministry of Science and Technology, 2003

[15] There are three types of patents available in China: design, utility models and inventions. "A design pertains to the shape, pattern, colour or their combination in a product, which creates an aesthetic feeling and is fit for industrial application although it cannot be required to have a technical solution [...]. For utility models 'inventiveness' requires the utility model to have substantive features and represent progress compared with the technology existing before the date of filing. For inventions, the 'inventiveness' requirement is greater than for utility models—the invention must have prominent substantive features and represent notable progress" (Fai, 2005).

Table 1 uses some of the most recently available quantitative indicators to sketch a picture of the state of China's science and innovation and how this has changed over time.

The table reveals some interesting, yet complicated, trends, about China's innovativeness. By looking at the indicators, there has certainly been an improvement over time in China's innovation performance: the percentage of the GDP spent on R&D has more than doubled since 1995 (from 0.6% of GDP in 1995 to 1.3% in 2005) with China becoming in 2006 the world's second highest investor in R&D after the United States (OECD, 2006); the number of scientific publications has risen from around 2% of the world share in 1995 to 6.5% in 2004; China's exports of high-tech products has increased from 6.8% of all products exported in 1995 to 20.8% in 2002.

A closer look to the indicators in Table 1 provides a more complex picture, however. By analysing China's trade data, Rosen notes that, although 21% of Chinese exports in 2002 was listed as high-tech (National Bureau of Statistics and Ministry of Science and Technology, 2002), these were dominated by parts and accessories for finished information technology products (Rosen, 2003). Moreover, when looking at China's trade data by type of enterprise, 60% of China's high-tech exports in the period Jan-Aug 2003 were done by wholly foreign owned enterprises (Rosen, 2003). These findings are further confirmed by a study about technology transfer and trade specialisation in China (Lemoine and Unal-Kesenci, 2004), where the authors argue that the country's competitive industries are dominated by foreign affiliates that coexist with a traditional export sector that lags behind and is dominated by wholly Chinese firms. They claim that the links and spillovers between the two sectors are quite weak. Although the specialisation of China in assembling high-tech products has allowed the country to rise the level of its exports (from low tech content-products to high-tech ones), the dissemination of foreign technology to the rest of China's industrial capacities has been slow.

A similarly mixed picture emerges from bibliometrics data. If the number of China's scientific publications has recently increased sharply, as is illustrated by Table 1 above, China's citation rate, which is used as a proxy for the quality of the

scientific publications, is low, with only 2 Chinese scholars cited in the top 100 most cited international scientists (People's Daily, 2006)[16].

Invention patent filings, one of the three types of patents recognised by the Chinese patent law and the one with the highest innovative content, have increased in the country by 23% annually since 2000. Although 54% of all the invention patents filed in 2005 were made by Chinese firms (against 46% by foreign firms), the bulk of all the domestic patent applications in 2005 were still patents for utility models and industrial designs (i.e. the two types of patents with the least significant technical improvements). As a comparison, of the three types of patents filed by foreign firms in China in 2005, the majority (85.5%) were patents for inventions.

As far as the data pertaining to firm-level innovation are concerned, a report published by the OECD (2002a) notes that in-house R&D expenditure and personnel involved in R&D, are extremely low when compared to mature economies.

Looking at recent data on innovation inputs and outputs can hence provide useful, yet incomplete, information on how China's technological upgrading is changing. However, it is precisely by using quantitative indicators that China is commonly perceived to have a poor science and innovation performance. China's high-tech production is often described as being 'not so high-tech, nor so Chinese' [17] (Rosen, 2003, Gilboy, 2004); the country is depicted as possessing weak technological capabilities (Dahlman and Aubert, 2001, OECD, 2002a) and as having a competitive advantage based on low-end commodity manufacturing where cheap labour plays an important role (Steinfeld, 2004, Arayama and Mourdoukoutas, 1999).

These common perceptions and the data they are based upon, do not take into account that there are emerging evidence that in certain sectors China is indeed making progress towards indigenous innovation. Nanoscience and nanotechnology are two notable examples of how the scientific community in China has made: "remarkable advances across the R&D spectrum, from fundamental scientific research to studies into the potential societal implications of new nanotechnologies" (Wilsdon and Keeley, 2007, p. 24). Also in other sectors, like public digital switching systems, China has developed technological capabilities not only in production, operation and maintenance,

[16] Also this Figure does not deliver a univocal picture of the quality level of the Chinese publications because a low citation rate could be equally due to poor-quality science but also to language and cultural factors (Zhou and Leydesdorff, 2006).

[17] Recall the point made in the previous page about China's exports.

but also in innovation and creation of new technological knowledge (Shen, 1999, p. 188). China is also moving forward in more traditional sectors like textile where the PRC has established a strong competitive advantage not only because of its low labour costs but also by significant technological upgrading. "[...] Many Chinese companies are in fact already offering improved supply-chain management and value-added services in design" (Sigurdson, 2004, p. 4).

2.2.4 Concluding remarks on the use of quantitative indicators to study innovation in PV firms in China

What all the discussion done so far in this section adds up to is that taking quantitative indicators at face value tells us only part of the story about technological upgrading. This is particularly true in a country like China where differences across regions, industrial sectors and actors that take part in the economic process (i.e. state owned enterprises vs private or foreign firms) are enormous; where the speed of change is formidable and where what is true today might well be outdated in five years time. Moreover the situation is further complicated by the way in which the national economy is more and more bound up in global networks and flows of knowledge, capital and talent.

Although approaches based on quantitative indicators certainly add to our understanding of innovation, they are not powerful enough to capture a much more complex dynamic, especially in developing countries, where innovation often should be understood as a dynamic adaptation process and where formal indicators developed to depict behaviour common in mature economies (i.e. patenting, in-house R&D) do not seem always appropriate. Entire chapters could be written about China's innovativeness on the potential interpretations of each of the statistics in the Table 1, but the dominant message to convey here is just how fast the country and its innovation system is changing to be depicted by numbers alone. Based on these considerations we have decided not to follow the quantitative indicator approach but to adopt an alternative route to gauge how technological change is taking place in China. We will focus on a high-tech industry (i.e. solar PV), which has also been the fastest growing power generation technology in latest years (Martinot, 2006), and assess how China is performing here and what is driving its firms forward. We will do so by combining insights coming from both the TC and the IS literature in the hope that this could

provide a richer picture of the nature and the drivers behind technological change in the country.

The remaining part of the chapter explains in depth the theoretical point of departure of this thesis.

2.3 Technological capability and innovation system literatures: why do they both constitute the theoretical underpinning of the thesis?

When the literature review for this thesis started in 2003, it appeared clear that there was no group of studies directly and specifically addressing the same problem of this thesis, i.e. innovation for renewable energy technologies in firms in developing countries, particularly in China. Only one study existed (Dai and Shi, 1999), to the best of the author's knowledge, but it was not based on a sound analytical approach that could be used as a point of departure.

It followed that to provide the study with a suitable theoretical underpinning it was necessary to turn to the available literary traditions that more closely addressed issues similar to those of this thesis: what is the process through which RET emerge and diffuse on the market? What is relevant in their development and what can contribute to their further diffusion? How does technological change take place in firms in developing countries? How does this happen and through which accumulation processes?

As noted in Chapter 1 and at the beginning of this Chapter, two literatures appeared suitable and provided useful, yet, as explained below, partial, insights: the innovation system (IS) and the technological capability (TC) literatures.

Recently a group of studies belonging to the IS literature has started to emerge and to address the factors and forces governing the innovation process for RET (Foxon, 2003, ICCEPT and E4Tech, 2003, Jacobsson and Bergek, 2004, Jacobsson and Johnson, 2000, Foxon et al., 2005). One of the articles on the topic (Jacobsson et al., 2004), where a technology-specific innovation framework was developed and applied, among other RE technologies, to solar PV in Germany was the departing point of this thesis. Innovation is understood in this article as both an individual - at the firm level - and a

collective act, where organisations, institutions and the links between them all concur in the emergence of a new energy technology. This aspect, together with the identification of a number of factors contributing to the success of the German solar PV industry (Jacobsson et al., 2004) were all elements considered of relevance for this thesis. However, as discussed in Section 2.4.8, the article did not provide any specific insight into knowledge accumulation and technological improvement in firms, which are among the key concerns of this thesis. Firms are analysed by the article only as part of a broader innovation system and in terms of systemic dynamics. Furthermore, the fact that the technology specific framework of the article was developed and applied to RE technologies in a mature country context (i.e., Germany) prompted the author of this thesis to question its appropriateness for a rapidly industrialising country context. In developing countries it has been argued that: "[...] very few patterns of the socio-economic behaviour regarding innovation at national level can be viewed as working in a system-like manner" (Arocena and Sutz, 2000, p. 58).

For these reasons the use of the IS approach as the unique theoretical contribution on which to ground the thesis was considered not sufficient and the attention was turned to another extensive body of literature: the so-called technological capability literature where firm-specific dynamics are studied and where firm-level innovation is understood in terms of capability accumulation and technological learning.

This literature, particularly the part with a focus on developing countries (Dahlman et al., 1987, Katz, 1984, Bell, 1984, Lall, 1992, Bell and Pavitt, 1995, Mani and Romijn, 2004, Romijn, 1997), suggests that elements such as access to knowledge external to the country or the firm, the firm's endowment in terms of education and entrepreneurial culture together with the effort put in learning (via formal R&D but more often through daily improvements on the shop floor) are critical factors in the development and diffusion of new technologies in firms in developing countries.

The two bodies of literature adopt two different analytical perspectives: a systemic macroeconomic one versus a micro-economic, firm level one. They both contribute to our understanding of technological change and they are both relevant for this thesis. However, as it is detailed in the following pages of this chapter, each of them yields only partial insight towards the understanding of the nature and the determinants of innovation in PV firms in China, which are the central problems of the study. This is the reason why they both constitute the theoretical underpinning of the

research and have been used to develop the analytical framework discussed in Chapter 3.

In what follows the insights coming from these two literatures, their relevance but also their limits in addressing the core concern of the thesis are discussed in details in separate sections.

2.4 The Innovation System literature

This section presents an overview of the innovation system (IS) approach. The first part, sections 2.4.1 to 2.4.5, reviews broad analytical aspects of the IS approach: why the concept of system is useful in the study of innovation, how a system is structured and performs, how it evolves over time and what are the policy implications of a systemic understanding of innovation.

The second part of the review narrows down the discussion by focussing first on one specific variant of the more general IS approach: the national innovation system (section 2.4.6) and then on the empirical findings of a group of studies that have applied the IS approach to the study of renewable energy (section 2.4.7). Section 2.4 ends with a discussion of the limits of the IS approach in understanding the nature and the determinants of the innovation effort underway in the Chinese PV firms (section 2.4.8).

2.4.1 Why do we need a system to study innovation?

In early economic models (Schumpeter, 1934) innovation was perceived as a linear sequence of stages that starts with an invention (understood as a practical demonstration of an idea), goes through innovation (the first commercial application of the original idea in the market) and terminates with diffusion (the spreading of the innovation on a large commercial scale).

More recent approaches (Lundvall, 1985, Freeman, 1987, Nelson, 1993, Dosi et al., 1988, Carlsson et al., 2002, Fagerberg et al., 2005, Bergek et al., 2008, Edquist, 1997) have shown that this early understanding of innovation is an oversimplification and that innovation is better understood as a *process* of matching technical possibilities to market opportunities (Freeman and Soete, 1997). The innovation process involves multiple and bi-directional interactions between the different stages that contribute to

the development of new technologies: research, development, demonstration, commercialisation and diffusion (ICCEPT and E4Tech, 2003)[18]. Practical needs of the consumers, which pertain to the diffusion of technologies, affect the type of research that is conducted, for instance, by research institutes or private firms. This in turn, affects the path that is followed to disseminate new technologies on the markets (Fagerberg, 2005). Frequent overlaps and feedbacks between the different stages of technological development distinguish innovation as a non-linear, dynamic and multi-agent process where technologies are continuously adapted and improved to better fit conditions and requirements.

However, there is more to this dynamic understanding of innovation since also framework conditions affect the process through which technologies emerge and diffuse in the markets (Edquist, 2005). This is for instance the case of government policy intervention[19] or of the different investment options available on the market. Policies promoted by a government affect the behaviour of the business community, which, in turn, affect the government's action.

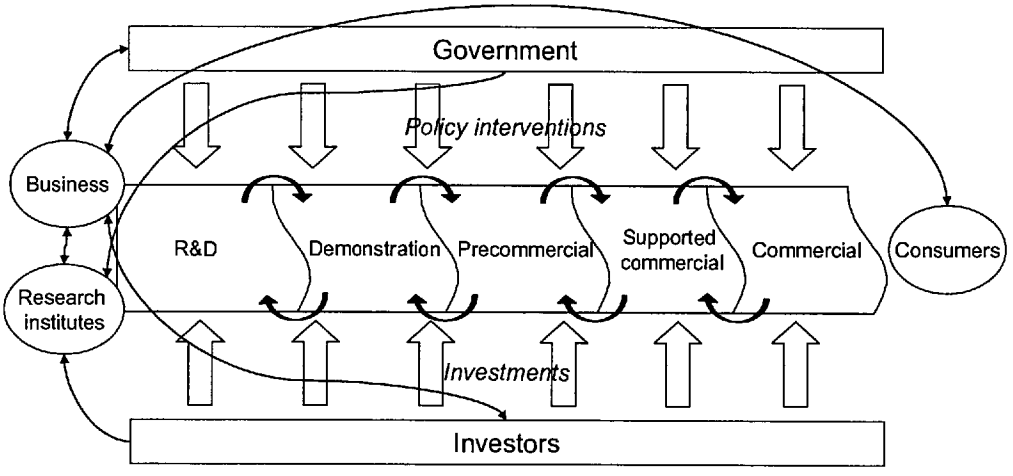
Recognition of the importance of the relationship between the many counteracting stages and elements of the innovation process suggests that innovation would be better understood within a *systems framework* (Lundvall, 1985, Freeman, 1987, Nelson, 1988, Dosi et al., 1988, Edquist, 1997). The innovation system approach can then be considered as a conceptual tool we use to better illustrate and understand complex system dynamics and performance (Bergek et al., 2008).

The understanding of innovation as a dynamic, multi-agent, non-linear and systemic process is represented in Figure 3.

[18] It should be noted that this subdivision of the innovation process in different stages is here adopted to provide theoretical underpinning to the way in which the technological maturity and the market penetration of the different PV families is presented in Chapter 4.

[19] As an example, the recent diffusion of RE technologies on the market, and in particular of solar PV, has been driven by support policies promoted in different EU countries (Blok, 2006), Japan and more recently in some states in the US (Martinot, 2005). More details on policy intervention to support PV could be found in Chapter 4.

Figure 3 Stages of the innovation process and feedback dynamics



Source: Adapted from ICCEPT and E4Tech, 2003

Two ideas are central to the innovation system approach[20] and recur in all studies: the role of learning and of institutions. The IS approach puts knowledge creation, diffusion and hence *learning* at the centre of the innovation process (Lundvall, 1992). This reflects the understanding that innovation is a cumulative process that involves: "[...] producing new knowledge or combining existing (and sometimes new) elements of knowledge in new ways as well as diffusing and utilizing it. Thereby the IS approach distinguishes itself from approaches where technological change and other innovations are regarded as exogenous" (Johnson et al., 2003, p. 6). Moreover, a wide set of sources of innovation is taken into account: innovation reflects not only formal learning that occurs via R&D, but also interactive learning taking place in connection with ongoing activities in procurement, production and sales (Johnson et al., 2003).

As explained above, the IS approach emphasizes interdependence and non-linearity (Johnson et al., 2003). This is based on the understanding that innovation is both an individual (at the firm level) and a collective act. Firms do not innovate in isolation but interact with other organizations through complex relations that are characterized by reciprocity and feedback mechanisms in several loops. These interactions occur in the context of *institutions*—e.g., laws, rules, regulations, norms and cultural habits (Johnson et al., 2003). It follow that to explore the technological

[20] The term 'approach' is here used because the IS perspective cannot be considered a formal theory, in the sense that it does not provide specific propositions regarding causal relations among variables. Edquist suggests to call IS an approach or a conceptual framework rather than a theory (Edquist and Johnson, 1997, pp. 28-29).

dynamics of innovation it is crucial to study the interplay between organizations and institutions (Balzat and Hanusch, 2003).

It should be noted that the term 'institutions' is controversial in the IS because it is used in different senses by different authors. In a narrow sense, institutions are conceived as types of organizations and include, for instance, universities or technology institutes. In broad terms, institutions include the political context, habits, practices, norms and the rules regulating relations and interactions between people as well as shaping social interaction (Johnson, 1992).

Since its first adoption in the mid 1980s (Lundvall, 1985), the IS concept has been explored and widely adopted in the literature by different scholars (Freeman, 1987, Dosi et al., 1988, Malerba and Orsenigo, 1993, Carlsson et al., 2002) as well as by international organisations, like the Organization for Economic Cooperation and Development (OECD, 1997, OECD, 1999, OECD, 2002b) which has used it to examine innovation patterns in different sectors[21], and, more recently, by the United Nations Commission on Trade and Development (Nassif, 2007).

2.4.2 How a system is structured and how it performs

The IS approach aims at improving our understanding of the innovation process and of what determines it. This goal can be achieved by the identification and study of the different *system components* and by understanding *what is going on in the system*, i.e. by identifying and studying both the structural characteristics of the system and those processes that have a direct impact on the performance of the system (Edquist, 2005, Bergek et al., 2008). In what follows we discuss in turn these two aspects by borrowing from the *technological innovation system (TIS) tradition* (see among others: Carlsson and Stankiewicz, 1991, Bergek et al., 2008). This is a variant of the more general IS approach, where the innovation system is focussed: "[...] on the development, diffusion and use of a particular technology (in terms of knowledge, product or both)" (Bergek et al., 2008, p. 408).

Since the TIS approach has been adopted by several authors interested in innovation for RET[22] and because this study has a technology specific focus, we

[21] The technological sectors include energy, pharmaceutical biotechnology and knowledge intensive service activities (OECD, 2003/2004).

[22] For the specific empirical findings of the IS approach applied to RET see Section 2.4.7.

believe the insights offered by this IS variant to study a system's structure and performance are particularly appropriate for our purposes.

System structure

An IS, and more specifically a TIS, is described in the literature (Carlsson et al., 2002, Edquist, 2005) as having two types of constituents: the components (also called 'elements') and the relations among them.

The components can be distinguished in: organisations and institutions.

Organisations can be defined as "formal structures that are consciously created and have an explicit purpose" (Edquist, 2005, p. 188). Organisations, which are also defined in the literature as *actors* (Jacobsson and Bergek, 2004, ICCEPT and E4Tech, 2003), include for instance, firms, universities, users, venture capitalists, etc.

Institutions are instead the habits, norms, routines and rules or laws that determine and affect the behaviour of the organisations or actors (Edquist, 2005, Bergek et al., 2008).

In other words, organisations can be regarded as the players and the institutions as the rule of the game[23].

Relations or networks that exist among the different system's components are created and used to transfer knowledge and information (Lundvall, 1992). Knowledge, financial inputs, people (who detains both tacit knowledge and know-how), policy regulations and market inputs are all part of the flows that connect a system together (Niosi, 2002, Jacobsson and Bergek, 2006)[24].

[23] Some authors prefer a slightly different classification of the systems components by identifying the actors according to the role they play in the system. In this case we can have actors involved in creating and/or sharing knowledge, who include academics and technology developers; actors disseminating and using knowledge in the form of intellectual property (IP) and commercial products, such as project developers and end-users; and actors setting the framework conditions. They include government departments and regulators, research founders and financial investors (Foxon et al., 2005).

[24] Bergek et al. (2008) distinguish between formal and informal networks. The former are created to solve a specific task and may include, for example, standardization networks, technology platform consortia, public–private partnerships, etc. The latter are instead formed and evolve in a less orchestrated way. Buyer–seller relationships or university–industry links could be taken as example of informal networks.

System performance: functional dynamics[25]

In terms of 'how' a system works and what can have a direct impact on its functioning, scholars from Chalmers University of Technology in Sweden, have undertaken thorough reviews of the literature (Johnson, 1998, Johnson and Jacobsson, 2001) to understand what actually 'happens' within an innovation system and more specifically in a TIS[26]. They identified (Bergek et al., 2008), following a number of subsequent refinements (Johnson and Jacobsson, 2001, Jacobsson and Bergek, 2006), seven key processes that are referred to in the literature as being important (and therefore that could be expected to occur within a system) for innovation to emerge and diffuse. They name these key processes as *functions*[27]. Whereas a system has an overall function, which can be conceptualized as the generation, diffusion and use of innovation (Edquist, 2005), the seven key processes can be understood as sub-functions that concur in the achievement of innovation (i.e. the overall function).

The seven sub-functions are (Bergek et al., 2008):

1. Knowledge development

This function is concerned about the knowledge base of the system. This is because the existence and performance of a system critically depends on the creation and diffusion of knowledge. The function encompasses different types of knowledge (like, scientific, production, logistics and design knowledge) as

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[25] The discussion of the system performance is mainly focused, as said previously, on the TIS perspective and on the analytical contributions provided by scholars of Chalmers University in Sweden (Johnson, 1998; Jacobsson and Bergek, 2004, Bergek et al., 2008). Since their insights have been applied to the analysis of emerging RE innovation systems and they are of particular relevance to this study.

[26] A review of the literature has also been undertaken by Hekkert et al. (2007b), who have identified a number of requirements (or functions) that need to be accomplished for well-performing innovations systems.

[27] Other IS studies have identified key processes that occur within a system. Edquist (2005) refers to *activities* and identifies 10 of them that he groups in four main categories: a) activities that are important to provide knowledge inputs to innovation. They include provisions of R&D, as well as education and training; b) activities relevant for the demand side of innovation and its diffusion on the market. Formation of new product markets and the articulation of quality requirements for improved or new products are all included in this category; c) activities that are conducive for the emergence of the constituents of the system. These include creating and/or changing organisations and institutions, as well as, stimulating networking through markets and other mechanisms; d) activities that can provide innovation-specific services in firms. Providing consultancy services of relevance for innovation processes (e.g. technology transfer, commercial information, and legal advice), financing innovation and offering access to facilities or administrative support are examples of the activities in this category.

Although conceptually quite similar to the functions identified by Bergek et al. (2008), the activities put forward by Edquist are structural in nature (see the activities in group c above) and, being quite specific, do not include all the more general functions found in Bergek and colleagues. For these reasons we prefer to focus on the functional approach suggested by Bergek (and by the TIS approach) rather than on the activities described by Edquist.

well as different sources of knowledge, like R&D, learning by doing or by experimenting and imitation.

2. *Influence in the direction of search*

For a TIS to work and for innovation to be achieved, a whole range of organisations, and indeed firms, have to choose to enter the system. This could be achieved if there are sufficient incentives for the firms or the organisations to do so. Incentives could include a belief in growth potential, a favourable regulatory or policy framework and demand from leading customers (Bergek et al., 2008).

3. *Supply of resources*

Similarly to the key role played by knowledge, different types of resources are needed for a system to emerge and evolve. These include, but are not limited to: human capital to be enhanced through education in specific scientific and technological fields; financial capital as well as services and network infrastructure.

4. *Creation of positive externalities*

When the system moves from an early formation period (see discussion in Section 2.4.3) to a more mature stage with a larger number of actors participating in the innovation process, networks between them are created where information is exchanged and where self-reinforcing mechanisms of cause and effect are created. These lead to positive externalities that could include both network externalities and other spillovers such as, for instance, the effect of the R&D done by one company on another one. The entrance in the system of new firms is particularly important in this process (Bergek et al., 2008). As an example, new firms entering the system contribute to the formation of markets which in turn can strengthen the technology legitimation and the institutional framework. Producer and user networks could be formed facilitating the exchange of information and the development of knowledge. "New entrants may contribute to a process whereby the other functions are strengthened, benefiting other members of the IS. This function is therefore not independent, but rather one which indicates the dynamics of the system" (Jacobsson and Bergek, 2006, p. 692).

5. *Facilitation of market formation*

For innovation to develop and diffuse, markets are needed. In an emerging TIS markets may not exist or can be difficult to access because existing and embedded technologies may prevent emerging technologies from accessing these potential markets (Hekkert et al., 2007b). New technologies need hence to be supported in their market search progression. One way of doing this is to create a protected space: the formation of temporary niche markets for specific applications of a technology (Kemp et al., 1998, Schot et al., 1994).

6. *Stimulus of entrepreneurial experimentation*

Innovation involves a high degree of technological, market and application uncertainty. As an example that will be discussed in more details in Chapter 4, not necessarily the PV technology family that now dominates the market (i.e. crystalline Silicon, hereafter c-Si) is the one that will have the largest market share in the years to come. For this reason it is important to facilitate entrepreneurial experimentations so that a wide range of ideas, designs or market applications could be tried out. Many will possibly fail along the way but some will succeed and a social learning process will be initiated (Kemp et al., 1998).

7. *The legitimation of nascent technologies or industries*

To develop well, a new technology has to become part of an incumbent regime and to gain a technological, market as well as a political space. Parties with vested interests could be expected to oppose the emergence of the new technology. Advocacy coalitions are then needed, "[...] they put the new technology on the agenda, lobby for resources and favourable tax regimes and by doing so create legitimacy for a new technological trajectory" (Hekkert et al., 2007a, p. 4679).

Functions influence each other. The fulfilment of a certain function will quite likely influence the fulfilment of other functions (Hekkert et al., 2007b, Bergek et al., 2008). It could for instance happen that an increased legitimation of an emerging technology could have a positive fall out on the creation of markets[28]. Multiple interactions between functions affect the performance of the system and can initiate a

[28] This is indeed what happened in the case of solar cells in Germany, where pressure groups succeeded in lobbying in favour of the new technology (i.e. in legitimating it) and in pushing the government towards the promotion of the feed-in tariff. This had, in turn the effect of stimulating installed capacity and the on-grid market (Jacobsson et al., 2004).

virtuous circle trough which the different functions strengthen each others and pave the way for innovation to diffuse on the market (Bergek et al., 2008).

The adoption of the concept of functions, i.e. the key processes that can be expected to occur in a system and that are conducive to the formation and diffusion of new technologies, provides a useful analytical tool in the study of the innovation process. It allows in fact to *separate the system's structure from its functioning* and to identify key issues upon which to focus in policy intervention (Bergek et al., 2008). This is analytically important because systems with similar structure could well perform quite differently. Moreover, how do we know whether the existence of a particular actor in a system is a strength (i.e. it concurs in the achievement of innovation) or a weakness? (Bergek et al., 2008).

The importance of this aspect (i.e. the distinction between structure and performance) could be appreciated by quoting a recent study on the Chinese innovation system (Liu and White, 2001). Liu and White notice that describing only the elements of a system — categories of actors, institutions and policies — poorly represents differences across systems with different departing points. They argue that: "[...] using organizational categories such as 'research institute', 'firm' or 'government' can generate more confusion than insights, since, in different national or industrial contexts, these may have very different meanings in terms of the range of activities they undertake" (Liu and White, 2001, p. 1093). In the case of China, as will be explained in Chapter 5, during the planned economy period (1949-1978), the role of actors like firms or research institutes was much more restricted than in other countries (firms did not have, for instance, the mandate nor the incentive to undertake their own R&D, but were executers of limited and specific activities – production – decided and managed by the central government). In recognition of the analytical problems that arise from comparing different innovation systems on the basis of their structure, Liu and White reach similar analytical conclusions as scholars from Chalmers University and suggest in their article to adopt a functional analysis focused on the performance implications of the system[29] (Liu and White, 2001).

The functional concept is hence a useful analytical tool especially when, as in the present research, one wants to better understand technology-centred innovation systems different from those to which the IS analysis was originally applied. The

[29] Liu and White specifically talk about five activities - R&D, implementation, end-use, education, linkages – and focus on a number of system-level characteristics, including the effectiveness of the system in introducing, diffusing and exploiting technological innovations.

emphasis on functions does not mean that we can disregard or neglect the 'components' of an IS, however. On the contrary, we need to study both the structure and the performance of a system to understand innovation processes and to design innovation policy (Edquist, 2005).

Assessing the 'goodness' of a system performance: inducement and blocking mechanisms

If we know how a system is structured and how it works (i.e. what functions are known to be conducive to innovation), we can also study the present state of a system (Johnson and Jacobsson, 2001), i.e. 'how well' a given system performs with respect to the goal of achieving innovation. Since there are many factors that can affect the functioning of a given system, scholars from Chalmers University (see for instance Bergek et al., 2008) suggest that it can be analytically useful to reason in terms of mechanisms that in a particular situation *induce or block* the system's functions. As an illustrative example, which is particularly useful in the context of RET, one can think about climate change. Concerns about environmental pollution have in fact prompted several governments in mature and developing countries alike to promote *ad hoc* policies for a wider diffusion of RET. These polices have contributed in expanding the markets for RET[30] (i.e. they have contributed to the 'market creation' function), but also in stimulating new firms in entering the RET industry because attracted by remunerative markets supported by the government (i.e. government's polices have affected the function concerning the influence on the direction of search). Climate change has thus acted as an inducing mechanism for some of the functions of the TIS that surrounds the different RET.

Clearly there could be a number of different mechanisms inducing or blocking the emergence and the diffusion of an IS and the good functioning of its internal processes (i.e. the functions). Differences could for instance depend on the specific technology one seeks to study or on the development phase the given technology is in (i.e. formative phase or market diffusion)[31].

Bergek and colleagues provide a few illustrative examples of inducing and blocking mechanisms (Jacobsson and Bergek, 2004, Bergek et al., 2008):

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[30] The effect had by the feed-in tariff promoted by the German government on wind or PV installed capacity is particularly illuminating in this case (Sijm, 2002; Agnolucci, 2006).

[31] See the discussion in section 2.4.3

1) Institutions may fail to align to the new technology. They could, for instance, not provide a favourable regulatory framework.
2) Market may not be formed; this could for instance depend on the availability of alternatives that could serve similar purposes as the technology that is trying to emerge.
3) New firms may not take part in the emerging system because of the lack of markets.
4) Networks between the different system's components can be weak or non existent.

As in the case of the functions, also the *different blocking and inducing mechanisms influence and reinforce each other.*

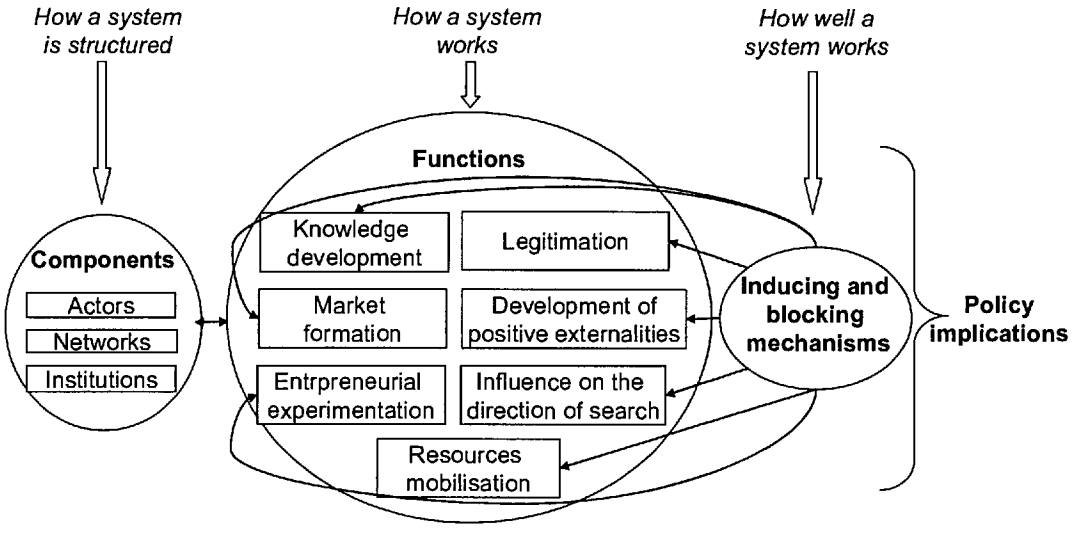
Since inducing and blocking mechanisms are system specific it is not possible to provide a general lists that encompasses all of them. In section 2.4.7 in this chapter we will specifically focus on those inducing and blocking mechanisms that have been identified in the case of RET.

What is important here to emphasise is that they provide a useful tool to study the performance of a system and to suggest appropriate policy intervention that can stimulate or remove specific inducing or blocking mechanisms[32].

Figure 4 summarises the theoretical issues we have discussed so far pertaining to a system's structure and performance.

[32] Specific policy interventions that have been suggested to remove blocking mechanisms and to stimulate certain functions in the emergence and diffusion of RET are discussed in Section 2.4.7

Figure 4 System's structure, functions and blocking and inducing mechanisms



Note 1: the conceptualisation of functions and blocking and inducing mechanisms is borrowed from the TIS variant of the IS approach.

Note 2: as specified in the text, there are numerous feedbacks between the inducing and blocking mechanisms as well as between the functions. These feedbacks are not illustrated in the Figure in order to keep it simple and readable.

Source: Adapted by the author from Bergek et al. 2008

2.4.3 Stages of system evolution over time

For analytical purposes the growth of an emerging TIS can be divided into two main development phases: a formative phase and an expansion phase (Jacobsson and Bergek, 2004).

In the *formative phases* the constituent elements of the system (i.e. actors, institutions and the networks) begin to be put into place. New firms and other actors (such as, for instance and among others, research institutes) enter the system, markets begin to emerge and a process of 'institutional alignment' (which works in favour of the emerging technology) is initiated (Jacobsson et al., 2004, Bergek et al., 2008). The literature emphasises that this formative period is characterised by a range of competing designs, small markets, many entrants and high uncertainty in terms of technologies, markets and regulations (Afuah and Utterback, 1997, Kemp et al., 1998, Jacobsson and Bergek, 2004). Moreover the rate of the technology diffusion is slow and many technological and applicative experiments take place (Bergek et al., 2008).

At some point in time, the TIS needs to 'change gear' (Bergek et al., 2008) and to move into a self-sustaining *diffusion phase*. This phase, where the TIS expands, is

characterised by large-scale technology diffusion through the formation of fast growing mass markets. A number of causal interrelationships are likely to occur as a result of positive feedback loops that involve all the functions and components of the enlarged innovation system (Jacobsson and Bergek, 2004).

The basic idea behind this evolution of the innovation system into phases is that each higher level of the system's development has: "a greater degree of stability and resistance to change, due to interactions and linkages between the elements forming that [system] configuration" (Foxon, 2003, p. 15). As explained below (section 2.4.4) higher levels of system development impose constraints on the direction of change of innovation systems at a lower level of development (this is due to lock-in mechanisms), reinforcing trajectories and consolidating path dependency (see discussion below).

It is reasonable to expect that the technological and policy requirements of the two phases will be different and that, as a consequence, certain functions, among the seven identified above, would be more important in a phase than in the other (Bergek et al., 2008). In the formative phase one could for instance expect *entrepreneurial experimentation* to be particularly important given the presence of many competing designs. Technological variety and experimentation will possibly need to be encouraged to give rise to *knowledge creation*, but at the same time the *direction of search will need to be influenced* to guide the entrepreneurial efforts (for example, a number of technological and application approaches are likely to be explored in this phase but only few of them will eventually succeed). *Resources will need to be mobilised* to encourage more firms (and in general, more actors) to enter the system and a process of technological *legitimation* (where the new technology is given a positive institutional backing) could be expected to be initiated.

In a formative phase the entry of new firms in the system could be expected to play an important role as an inducing mechanism. Firm entry is in fact crucial to kick off a positive mechanism of self-reinforcing externalities: more firms entering the system means more networks could be developed, more knowledge could be created and diffused, more markets could emerge and a stronger legitimacy could be promoted around the new technology.

In an expansion phase, the need for *resource mobilization* is likely to increase by orders of magnitude and *legitimation* may become even more important to support the growing system (Bergek et al., 2008).

As a consequence of the different stages in a system's development and of the different strength with which the different functions are likely to be served over time, also policy measures aimed at stimulating technological change and at ensuring the good functioning of the system are likely to change over time

A cautionary note is important before moving to the next section. The distinction we have presented above between the formative and the expansion phase of an IS, does not imply that all ISs follow exactly the same development pattern (Bergek et al., 2008). Indeed: "the whole point of the functional dynamics approach is that ISs differ so much that there are no 'one size fits all' policy implications. Hence, although some features in IS development are arguably common to many innovation systems, we fully acknowledge that the determining factors, time frames, etc., differ between cases" (Bergek et al., 2008, p. 420).

The identification of phases of development in an IS is rooted in the way in which a system is theoretically understood and analytically approached. As is explained in the following section, this pertains to the evolutionary and cumulative nature of the innovation process.

2.4.4 Broader perspectives in the evolution of a system: path dependency and 'lock-ins'

Studying innovation from a systemic perspective implies not only studying its structure and performance (as has been explained in the previous section), but also appreciating that *in innovation history matters.* The IS approach employs an historical and evolutionary perspective[33] (see among others Freeman and Pavitt, 2002). This means that the process of innovation develops over time and involves the influence of many factors and feedback processes (Johnson et al., 2003). The concept of *path-*

[33]Although an 'optimal' or 'best practice' system of innovation cannot be specified (because there are too many variables and dynamics involved), the evolutionary perspective allows making illustrative and instrumentally useful comparisons between different innovation systems, i.e. what has been relevant in the emergence of a given innovation system for a specific technology (i.e. solar PV, in the case of this thesis) can provide useful insights for the study of the emergence of a new IS, for instance in a different country, based on the same technology.

dependence is often used to describe innovation as a learning and cumulative process that depends on previous experience and choices. The nature of the accumulated experience, which involves technological skills as well as managerial and organisational capabilities but also depends on previous framework conditions (e.g. on policies and regulations that have been promoted, etc.), influences the learning process for the adoption of a new technology and ultimately influence tomorrow's production technologies.

As the use of technologies expands they become more and more interrelated with many other technologies but also with institutional and social factors. One could, for instance, expect networks between the different actors to become stronger and the existing system to work in favour of the established technology. This tendency of technologies to become more attractive and widespread the more they are developed and hence more intertwined with the surrounding environment, might favour incumbent technologies and make it more difficult for newcomers to catch up (Foxon, 2002). This can lead to sub-optimal outcomes when firms become *locked-in* to specific technological configurations and do not longer respond flexibly to changing circumstances.

These insights into the broader understanding of the evolution of an IS, together with the importance of studying its structural components and performance (section 2.4.2), provide important analytical tools that will be used by this study (see Chapter 3) to map the components of the Chinese IS for PV and to study its performance and evolution over time.

2.4.5 Policy implications of a systemic understanding of innovation

Although specific policy measures to strengthen innovation system performance could only be suggested after an assessment of the conditions under which emerging technologies have a high chance of becoming successful (i.e. after an assessment of system specific blocking and inducing mechanisms), several remarks could be made on the way in which policy should be understood when we adopt a systemic understanding to innovation.

Policy intervention is crucial to unleash innovation and needs to be approached from a systemic and networking perspective. Since the IS approach regards technological development and innovation as a dynamic and systemic phenomenon in

which the component parts of the economic system evolve alongside each other and affect each other, it follows that policy interventions need to be similarly viewed: "[...] unless interventions take place within a systemic policy framework the results are likely to be less than completely successful" (Juma and Clark, 2002, p. 2). Within an innovation system perspective, policy design and implementation need to reflect the systemic and dynamic nature of the innovation process (Foxon et al., 2004).

Effective policy should also recognise that technologies are diverse and face different challenges over time. "It is thus important that policy is 'joined up' and supports innovation through its various stages, targeted if necessary to address specific barriers in the innovation cycle. [...] A successfully performing technology would then be able to progress smoothly from the early stages to the final stage where it can compete without direct support (given, for example, a generally supportive environmental tax or trading scheme). Thus, there are several elements to a policy, not one 'magic bullet'; the kind of instrument needed varies with the phase of a technology's development. These policies should take into account technological and institutional factors leading to 'lock-in' of existing carbon-based technologies" (Foxon et al., 2005, p. 2134).

Moreover policy intervention should be such as to allow *continued monitoring and revision* on the part of relevant stakeholders, because economic systems are never static but continue to evolve in ways that are difficult to predict for analysts and policy makers (Juma and Clark, 2002).

What all this adds up to is that policy intervention in the area of innovation cannot be viewed in traditionally 'technological' terms but it instead needs to be seen in a wider perspective where the dynamic nature of the innovative process, the many feedback loops involved and the different technological requirements over time are also taken into account (Juma and Clark, 2002).

2.4.6 The development of the IS concept: the national system of innovation and its relevance for the study of developing countries

Since Lundvall first introduced the modern version of the innovation system concept (Lundvall, 1985), several levels of analysis within the innovation systems framework have been conceptualised.

Some scholars have delimited systems on the basis of technological, industrial or sectoral characteristics. Both the previously mentioned *technological systems* (Carlsson and Stankiewicz, 1991, Bergek, 2002) and *sectoral innovation systems* (Malerba, 2002) belong to this category. Other authors have instead adopted a spatial or a geographic point of view to study the innovation system and have taken the nation or the region as the main unit of analysis. *National* (Lundvall, 1992, Nelson, 1993, Edquist, 1997) and *regional systems of innovation* (Cooke, 2001, Braczyk et al., 1998, Asheim and Isaksen, 2002) are both part of this perspective.

Before focusing in more detail in section 2.4.7 on the findings obtained by applying a systemic approach to the study of RE technologies (under several variants that include technological and national innovation systems), here some key aspects of the national innovation system (NIS) perspective are reviewed[34]. This is necessary for two main reasons. A number of NIS studies have been applied to developing countries and reviewing them should enable us to highlight the strengths and weaknesses of this perspective in explaining technological change in a developing country context. Second, China's historic evolution in the pre and post reform period presents quite distinctive features (see chapter 5) that will need to be properly understood to asses why technological change in PV in China occurs and why firms innovate. The NIS perspective could offer in this respect a useful analytical tool because it is concerned about the country-specific factors that influence the innovation process.

Insights from wider national systems of innovation

The concept of NIS was first introduced in the late 1980s on a study of the Japanese economy (Freeman, 1988) and enhanced in the early 1990s by two major studies, which provided more detailed theoretical and empirical analysis (Lundvall, 1992, Nelson, 1993). The key idea behind the NIS concept is that the *national context made up actors, institutions and its historical evolution matters* in the development of innovation. In his study about the reasons behind differences in the rate of economic growth of several countries[35], Nelson found out that these reflected the different national institutional set-ups (Nelson, 1993) and concluded that there was need for an

[34] It is important to note that the theoretical underpinning of the NIS approach will be done in this chapter, while in Chapter 5 the approach will be used to present and discuss the evolution and the main features of the Chinese NIS.

[35] The countries included large high-income countries, like the USA, Japan and several countries in Western Europe, smaller high-income countries like Canada or Denmark, as well as lower income countries like South Korea, Taiwan or Brazil.

enhanced understanding of the national environments where technical change originates.

Although there is no a single NIS definition in the literature (Niosi, 2002), this study adopts the following:

> *"NSI is [...] a set of interrelated institutions; its core is made up of those institutions that produce, diffuse and adapt new technical knowledge, be they industrial firms, universities, or government agencies. The links between these institutions consist of flows: knowledge, financial, human (people being the bearers of tacit knowledge and know-how), regulatory, and commercial"* (Niosi, 2002, p. 291).

Similarly to the more general IS approach, the NIS concept rests upon two main building blocks: components and linkages. Understanding the linkages among the different system components (which include both organisations and institutions, as previously explained), especially how they relate to each other as elements of a national collective system of knowledge creation, diffusion and use, is a crucial instrument for the improvement of a country's innovative performance (OECD, 1997).

In recognition of the fact that *country-specific factors influence the innovation process* and that *the institutional set-up of nations matters*, a number of aspects are expected to be important and analysed in NIS. These include: provision of R&D, competence building - e.g. provision of education and training -, financial institutions and networking through markets and other mechanism, including interactive learning between organizations (Edquist, 2005).

Application of NIS to developing countries

While the NIS concept has been widely applied to comprehend technological dynamism in mature economies (see among others Lundvall, 1985, Freeman, 1987), recently a number of authors have extended the concept to developing countries (Gu, 1999, Arocena and Sutz, 2000, Cassiolato and Lastres, 2000, Hall and Sulaiman, 2002, Intarakumnerd et al., 2002, Mytelka, 2003, Johnson et al., 2003, Jacobsson and Bergek, 2006, Kiggundu, 2006, Nassif, 2007). Their insights have contributed not only to a better understanding of how technological change occurs in industrialising nations, but also to the theoretical and empirical issues one encounters in applying the NIS concept to a context different from the mature economy it was originally developed for (Lundvall, 1992, Nelson, 1993, Edquist, 1997).

The appeal of the NIS approach in a developing country context lies in the emphasis it places on the complex relations between actors, competences, policies and 'institutions'. In particular, a number of focal points of the NIS approach appear particularly relevant to understand technological change in developing countries.

First, a lot of the ideas that are central to the NIS approach occupy a predominant position also in economic development theory. As an example, the NIS approach takes into account a wide range of national institutions including those engaged in education and training which are well known in the literature for being particularly relevant in the economic development of countries and especially of the less developed (Schultz, 1988, Psacharopoulos and Woodhall, 1985). Second, the idea that institutions matter for the performance of the economy is central to the concept of NIS but is also widely recognised for economic development in industrialising nations. Third, the NIS concept, as more broadly the IS approach, allows for the inclusion not only of economic factors but also of organizational, social and political factors. It also encompasses the whole range of different innovations; minor as well as major technical and organizational (Johnson et al., 2003). This is in line with the understanding of innovation that is normally adopted in development economics studies and particularly in the technological capability literature that will be reviewed in Section 2.5. In the context of firms in developing countries innovation is understood as a continuous process to absorb or create technical knowledge (Lall, 1992).

Finally the focus on innovation as a learning process puts the emphasis on endogenous variables that should be enhanced for technologies to emerge and diffuse. This is in line with the view that technological change in developing countries occurs not only via technology transfer of hardware but is the result of a cumulative 'softer' learning process at both the firm and the country level (Lall, 2000).

Applying the NIS concept to developing countries can, however, be problematic.

NIS is an ex-post concept elaborated after having observed a number of national innovation systems in industrialised countries and having derived similarities in their behaviour (Arocena and Sutz, 2000). In developing countries, innovation tends instead to be a *process 'in the making'*, where specific elements of the system might be either missing or not-conducive for learning and innovation (Kiggundu, 2006). *Fragmentation* is a dominant feature of IS in developing countries (Intarakumnerd et al., 2002), where "very few patterns of the socio-economic behaviour regarding innovation

at national level can be viewed as working in a system-like manner" (Arocena and Sutz, 2000, p. 58). This is not to say that technical change does not occur in developing countries[36], but existing micro-innovative strengths remain isolated and many of the institutions or actors relevant to innovation do not exist (Arocena and Sutz, 2000, Kiggundu, 2006).

Several authors have added further insights by studying NIS in specific developing countries or regions.

In studying local productive clusters in Mercosur, Cassiolato and Lastres (2000) note that countries in Latin America are characterised by higher levels of *diversity and institutional instability* than advanced economies. They highlight how the instability or vulnerability of the macroeconomic, political, institutional and financial environments affects a firm's innovation behaviour more than explicit technology policies (Cassiolato and Lastres, 2000). They claim that, although the NIS approach contains the idea that differences in macroeconomic performance are related to differences in NIS, it deals little with this micro-macro relationship.

In the case of Thailand, Intarakumnerd and colleagues (2002), make two interesting remarks. First they note that studies of NIS in countries that have been less successful[37] in technological catching up (this is the case of Thailand, but also of other countries in Asia, Latin America and Africa): "[...] should focus not only on how innovation related activities start and improve over time but also, and more importantly, on factors that contributing to stagnancy and factors contributing to the long-running perpetuation of weak and fragmented NIS system" (Intarakumnerd et al., 2002, p. 1455). They then suggest that paying attention to 'blocking mechanisms' (to use the terminology adopted by Bergek and reviewed above) could offer richer and more helpful insights into the analysis of NIS in developing countries. Second, they argue that policy making to stimulate intensive learning could be hindered by *political interference from vested interest groups.* Moreover government agencies in developing countries (as has been the case in Thailand) could have *insufficient organisational and individual competencies* to initiate policies and co-ordinate with other actors of NIS (Intarakumnerd et al., 2002).

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[36] The specific understanding of innovation in a developing country context is discussed in detail in Section 2.5.2

[37] The study contrasts the Thai NIS development and performance with those more successful in newly industrialised countries (i.e. South Korea, Taiwan and Singapore)

Gu (Gu, 1999) has specifically added to the existing knowledge about technical change in developing countries by studying the evolution over time of the Chinese innovation system. Using observations she made from the Chinese case she concludes that: *NIS in a developing country is specifically related to the country's development level.* Therefore, it is important to connect level of NIS development with level of economic structural and institutional development. Moreover, in noting that extraordinary 'intensive learning' has been crucial in the successful catching-up of countries like Korea and Taiwan, Gu argues that studies of NIS in developing countries should pay particular attention to *purposeful strategic management for catching-up* (i.e. to those adaptive strategies that are promoted at both the national and the firm level to achieve performances similar, or possibly higher, to the ones of industrialised countries). Finally, unlike mature economies, *capital accumulation, rather than intangible assets,* such as knowledge and learning, is the main contribution to technical progress in developing countries. This is because: "[...] capital investment is the necessary mean by which a late industrializer acquires technology embodied in capital goods from abroad" (Gu, 1999, p. 47). A NIS analysis should hence investigate how effectively a developing country moves from a learning path based on physical capital accumulation to one based on intangible human capital.

To sum up, although the NIS approach is appealing even in a developing country context because of the emphasis it places on the complex relations between actors, competences, policies and 'institutions', it presents a number of analytical and, indeed, empirical difficulties (including the availability of data) that need to be kept in mind when approaching the study of technological change in these countries from a systemic perspective.

2.4.7 The application of the innovation system approach to the study of RET

The concept of IS was first applied to RE technologies in 2000 (Jacobsson and Johnson, 2000), further developed by the same authors in subsequent studies (Bergek and Jacobsson, 2003, Jacobsson et al., 2004, Jacobsson and Bergek, 2004) and adopted by other scholars (Foxon et al., 2005, Negro et al., 2007, Hekkert et al., 2007a, Negro et al., 2008, Kamp et al., 2004, ICCEPT and E4Tech, 2003) to highlight the success or failure of emerging RE technologies in different countries.

The point of departure of this literature is that despite the increasing role RE sources are playing in the energy mix of many countries and despite the increasing recognition of the crucial role innovation should play in taking their development further (Stamboulis and Tsoutsos, 2002, Menanteau et al., 2003, Toman, 1998) there is still limited understanding of the innovation process involved in the emergence and diffusion of these energy sources[38] (Jacobsson and Johnson, 2000, Jacobsson et al., 2004, Foxon et al., 2005, Hekkert et al., 2007a). Since RET challenge existing energy systems based on fossil fuels (Hekkert et al., 2007a, Jacobsson and Bergek, 2004), a full understanding of the systemic processes by which innovation in these technologies occur is essential to comprehend and inform the transition to more sustainable energy solutions.

This has important implications for energy policy design. In fact, without an adequate understanding of how the transformation process towards a greater share of RET in electricity consumption occurs, it is difficult to adequately inform policy makers attempting to manage the process (Jacobsson et al., 2004, p. 4).

In this context, where the real issue is not to prove the potential of RET but how this potential can be realised, an IS perspective can offer a broad and rich conceptual approach within which to study RET (Sagar and Holdren, 2002).

Scholars who have taken up the challenge to analyze under what conditions emerging RET technologies could have a high chance of becoming successfully embedded in the existing system, have done so from a number of perspectives within the broader IS approach. Some have used a NIS point of view and have highlighted country-specific features of the IS for the domestic development of RET (ICCEPT and E4Tech, 2003, Foxon et al., 2005), others have instead adopted a technological innovation system (TIS) perspective (Jacobsson et al., 2004) or, more broadly, a 'functions of innovation systems' approach (Bergek and Jacobsson, 2003, Negro et al., 2007, Hekkert et al., 2007a) to study how well the systemic functions discussed above are fulfilled in a system involving emerging RE technologies.

In what follows these studies are reviewed not for their theoretical contribution, which is in line with the more general IS literature reviewed above, but for their empirical value to the study of RET. We will in particular focus on those inducing and

[38] There is for instance not a full understanding of how the different policy instruments (prices vs quantity-type of mechanisms) adopted to stimulate an increase in RES installed capacity affect the technological learning processes and the innovation process (Menanteau et al., 2003)

blocking mechanisms that have been identified as relevant for the emergence and the diffusion of RET, as well as on the policy implications for a better functioning of the IS that surrounds RET.

Important factors in the emergence and diffusion of RET

The effectiveness of innovation systems in successfully promoting innovation in RE technologies in Europe has been analysed by researchers from Chalmers University in a series of papers (Jacobsson and Johnson, 2000, Johnson and Jacobsson, 2001, Bergek, 2002, Bergek and Jacobsson, 2003, Jacobsson and Bergek, 2004, Jacobsson et al., 2004). Two are particularly relevant here: one where the emergence of the German technological system for solar cells is examined (Jacobsson et al., 2004) and another one where the authors analyse and compare the growth of the German, Dutch and Swedish wind turbine industries (Bergek and Jacobsson, 2003). These authors argue that a number of factors have contributed to the success of these RET technologies in Europe[39].

First, the *establishment of social legitimacy* of wind and solar PV should be mentioned. These authors note (see particularly Jacobsson et al., 2004) that a number of German organisations, like the Green movement and other pressure groups, have played a key role in creating a positive momentum towards the new technologies. This has contributed in both legitimating wind and solar PV and in influencing the regulatory framework so that markets can be formed and firms have been encouraged to enter the emerging system.

A study on the UK IS for RET further supports this point by emphasising that developing a shared vision between government, industry and the research community for each RE sector is important (Foxon et al., 2005).

Second, it has been important to *stimulating technological variety* in the early phases of the system formation. The authors note that in the presence of great uncertainties over the potential performance and cost of the various competing designs, as has been the case with wind turbines (Jacobsson et al., 2004, Bergek and Jacobsson, 2003), encouraging technological variety and experimentation in the early days of the system has created a learning space for research institutes and new firms to enter the wind and PV sectors. While several wind designs or application options have failed

[39] A recently published article by Stenzel and Frenzel (2008), which analyses RE firms strategic responses to subsidy policies promoted in the German, Spanish and UK electricity markets, offers further insights into the success of RET in Europe.

along the way, stimulating technological variety and entrepreneurial experimentations have led to a 'learning selection' (Douthwaite, 2002) and have created the conditions for emerging technologies to have a high chance of becoming successfully embedded in the existing energy systems. Foxon and colleagues further corroborate this point by highlighting that RET technologies that fail along the innovation chain provide valuable learning opportunities. Support should hence be given also at the demonstration and pre-commercial stages where several attempts might be necessary by technology developers before a successful path is found (Foxon et al., 2005).

Two other important factors that have contributed to the successful development of solar and wind technologies in some European countries are the *employment of advanced market creation policies* in a later phase and the *use of industrial policy to favour the domestic industry* (Bergek and Jacobsson, 2003). This has encouraged the entry in the emerging system of local 'prime movers', i.e. actors who are technically, financially and/or politically so powerful that they can initiate or strongly contribute to the development and diffusion of a new technology.

A last point pertains to the considerable *length of the learning period* (Jacobsson et al., 2004). This includes not only the time necessary to experiment and improve the different RET technologies that have been analysed (i.e. wind and solar PV cells), but also the time needed for new firms and actors to enter the system and for new networks to be formed to enhance the learning process.

Three inducing factors have influenced the performance of the RET innovation systems in Germany, Sweden and the Netherlands (Jacobsson and Bergek, 2004)[40]: government policy, firm's entry and feedback loops from the formation of markets. In the case of Germany, *government polices*, initially in the form of R&D funding, have positively affected several functions by supporting the creation of new knowledge, supplying resources and guiding the search of various actors to the new technology (Jacobsson and Bergek, 2004). Similarly, the *entrance of new firms* has created knowledge and supplied resources but has also stimulated the creation of markets. A number of *feedback loops from the formation of markets* have resulted further affecting a number of functions. For instance, more sales have generated more resources, which have contributed in attracting new actors into the developing system.

[40] In this study the analysis, besides wind turbines, has been extended to solar cells and solar collectors.

Studies by Foxon and colleagues (ICCEPT and E4Tech, 2003, Foxon et al., 2005) support the findings of the scholars from Chalmers University in terms of the role of policies and of the importance of encouraging technological variety (and indeed of supporting technologies in the various phase of technological and market development). They also provide some further insights based on the analysis and comparisons of the different IS surrounding RE technologies in the UK. They note that *having a clear knowledge and expectations on future markets* is crucial for the successful development of these technologies. This is because market conditions fundamentally influence these technologies in all the stages of the innovation process[41].

Moreover, *developing the necessary skills in key* areas has meant that the UK has a leading research community in avant-garde technologies like high efficiency PV cells under concentration and organic PV (Infield, 2007, Marigo et al., 2007, ICCEPT and E4Tech, 2003).

In the case of cogeneration technology in the Netherlands, the key to success has been the *fulfilment of all the functions* that are known to be important for well-performing innovation systems (Hekkert et al., 2007a). Hekkert and colleagues note that: "When only a few system functions were well taken care of, no take off was observed. When a few functions collapsed, also the diffusion of cogeneration stopped" (Hekkert et al., 2007a, p. 4686). Their findings support the view that innovation in low-carbon technologies is not the result of a single magic ingredient but occurs thanks to the coexistence of many different elements and to the alignment of the government actions to the needs of the other parties in the innovation system.

Factors that can obstruct the emergence and diffusion of RET

Scholars from the Chalmers School in Sweden have also identified a number of factors which may hinder the good functioning of selected RET innovation systems (Jacobsson and Johnson, 2000, Jacobsson and Bergek, 2004). They include:

1. Uncertainty in technological, economic and market terms.
2. Lack of legitimacy of the new technology in the eye of different actors
3. Weak connectivity

[41] Foxon and colleagues specifically refer to hydrogen development, whose innovation path and technological viability depend on the expectation that there will eventually be a market, the timing of which is currently unclear (Foxon et al., 2005)

4. Ambiguous behaviour of established firms
5. Government policy

Obstacles created by the *absence of a clear and consistent policy* framework are further highlighted in a study about biomass gasification in the Netherlands (Negro et al., 2008). The authors of the study note that, despite the promises of high-energy conversion efficiency and the wide variety of applications (which could have act as inducing mechanisms), biomass has not been successfully developed and implemented in the Netherlands. According to their findings the absence of available public resources, guidance, and other forms of public support for biomass gasification have hampered the path of this low-carbon technology in the country (Negro et al., 2008).

In the case of the UK, Foxon and colleagues emphasise specific problems encountered by RET technologies along their innovation path from the R&D stages to market diffusion, i.e. they identify specific challenges encountered when technologies need a 'gear change' and begin to move from technological infancy into a growth phase (Foxon et al., 2005).

They note that the successful development and exploitation of RET (i.e. the 'goodness' of an IS for RET) in the UK have been hindered by *difficulties in moving technologies along the innovation chain* and particularly from demonstration to pre-commercial stages and from pre-commercial to supported commercialisation. This might be due to a number of factors that, in the case of the UK, have included: insufficient financing to enable scaling up to next stages; a mismatch between the skills needed for large-scale demonstration and early commercialisation; inappropriate policy support provided by generic mechanisms (like the Renewables Obligation[42]) that are unable to drive investors towards those technologies that are still in their infancy (Foxon et al., 2005); a high risk perceived by the investors and the entrepreneurs in moving technology from a pre-commercial stage to a large-scale deployment.

2.4.8 Relevance and limits of the IS approach for this study

The review of the IS literature (with insights into the 'functional approach' suggested by the TIS variant), including its NIS variant and its application to the study of RE technologies, suggests that it can provide useful theoretical insights for the

[42] For more details on the Renewable Obligation see Mitchell and Connor (2004).

understanding of innovation in Chinese PV firms. These insights are summarised in what follows.

The idea that innovation is a dynamic and multi-agent process where firms do not innovate in isolation but are embedded in innovation systems, that both guide and constrain them, provides a broad analytical understanding of technological change. It follows that, although this study will specifically focus on innovation at the firm-level (i.e. what PV firms in China can do and how they can do it) it will also need to bear in mind the broader system. This will provide a richer understanding of how PV firms in China add-value and of what affects their innovative behaviour.

Secondly, knowing how a system is structured and what processes (i.e. what 'functions' as suggested by the TIS approach) could be expected to be important in most ISs provides valuable analytical tools to map the structure of the Chinese system for PV and to study its performance and its evolution over time[43].

Third, the identification of factors that have contributed to the relative success of different RE technologies (PV included) in a number of European countries (see discussion in Section 2.4.7), provides useful insights against which to analyse the performance of the Chinese innovation system for PV.

Finally the IS approach will be useful in informing the policy suggestions that will be put forward towards the end of this thesis. These will emphasise how the dynamic and systemic nature of innovation should be taken into account together with the broader environment that surrounds it.

However the IS review also suggests that several important issues are not well addressed in the existing literature. We shall deal with two of these that will play a central role in this thesis:

1. A limited understanding of the nature of innovation and of how learning takes place within organisations like firms.
2. The use of ex-post, normative concepts to study innovation in developing countries.

[43] How these concepts have been translated into practice is explained in Chapter 3.

A limited understanding of the nature of innovation and of how learning takes place within organisations like firms

The IS approach greatly contributes to improving our understanding of 'how' innovation occurs at the system level. We know that technological change involves and emerges from a complex number of feedback loops that occur among the different agents that participate in the IS and who are both constrained and driven by framework conditions (where institutions play a key role). However the approach does not say much about the 'nature' of innovation and the extent to which technical change takes place within a country or a firm. In other words, *by adopting an IS approach we do not know whether a firm is actually undertaking technological change and the extent to which this is happening.*

Moreover, learning processes are analysed not at the level of the single system component (for instance, the firm) but at the broad system level. What really matters in the IS approach is how the whole system learns and can generate and diffuse knowledge. Although the IS approach recognises the paramount importance of learning, it does not help in understanding how learning takes place within organizations. By adopting an IS approach we cannot say much about the process trough which technological change occurs in firms, how a firm's technological capacity changes over time and what path firms follow to accumulate knowledge. In short, *we know how a system learns but we do not know how a firm, or a single organisation within the system, learns.*

Indeed Lundvall identifies this as one of the challenges the IS literature has to face: "While it is important to study national characteristics in terms of organisations that pursue R&D, it is equally important to understand national characteristics in terms of how firms interact with customers and to what degree different firms give employees access to competence building in connection with on-going economic activities" (Lundvall, 2007).

If we want to understand the process through which RET emerge and diffuse in the society we need to understand what happens in firms: "The success or failure of nascent industries is inextricably linked to actors' technological and problem-solving capabilities, and how they incorporate such capabilities into strategies for exploiting business opportunities" (Christiansen and Buen, 2002, p. 236). A poor understanding of

how knowledge and learning occurs at the level of the firms is particularly critical for two main reasons:

a. There is a lot of technological uncertainty surrounding PV (See chapter 4), hence an improved understanding of what sort of technological capabilities firms in the sector are building and how they are building them is important to understand current and future technological trajectories.
b. If the focus of the analysis is shifted from mature to developing economies, it is even more important to have a clear understanding on how a technology potentially relevant to establish a low-carbon economy is acquired and managed by firms.

The use of ex-post, normative concepts to study innovation in developing countries

The IS approach has been originally developed in mature economies. When attempts have been made to export the concept to developing countries (through the NIS perspective) useful insights into the role of institutions in unleashing technological change have been obtained but a number of analytical problems have also been highlighted. The fragmented nature of the IS in developing countries has been emphasised and discussed as a possible challenge to the IS analysis in these countries (i.e. if only few of the system components are present or seem to behave in a systemic way, is there still scope for an IS analysis?).

When knowing that a system has a certain structure and that certain processes could be expected to take place for technical change to occur, one would be tempted to find in a developing country possible analogies between functions and inducing mechanisms that have been relevant for mature economies. However, it is not necessarily the case that: "shortcomings in actor's performance or resistance to policy objectives should be seen as something to overcome. It can instead be an indication that there might be an alternative system that is equally effective and efficient in introducing and diffusing technological and related organizational innovations but more appropriate for a particular context" (Liu and White, 2001, p. 1112).

An example could be illustrative. The studies that we have reviewed with respect to the development of RET, stress the importance for a technology to gain legitimation and explain how this has occurred, in particular in the case of solar cells in Germany, through pressure groups like the Green Movement. While studying an

emerging IS in a developing country one can ask whether pressure groups are powerful enough or whether they exist at all. One can ask whether achieving legitimation is really a sine qua non condition for technological change to occur in these countries.

Overall the IS approach offers a good way to have an overview of the functioning of the whole system but it lacks depth of analysis when it comes to understand the functioning of the single parts of the system, like, for instance, a firm's TC accumulation. Empirical review of the firm-level competencies and factors of influence are usually not included in innovation system analysis. For these reasons we need to adopt a complementary approach which is discussed in the following section.

2.5 The technological capability literature

In what follows the theoretical basis for understanding the technological capability (TC) approach used in this study is outlined. This builds on a considerable academic and policy literature, some of which is critically reviewed in this section. The origin of the technological capability concept is reviewed (Section 2.5.1) together with the main insights coming from this body of literature. These include: a discussion of the understanding of innovation in a developing country context (section 2.5.2); an explanation of why it is important to focus on technological change at the firm level and what kind of capabilities do firms in developing countries acquire (section 2.5.3); a review of how capabilities are built up in firms (i.e.: how firms learn) and what important factors facilitate the process (sections 2.5.4 and 2.5.5); an analysis of the stages that a firm goes through over time to master (usually imported) technologies and to catch up with firms in mature economies (section 2.5.6). The section ends with a discussion of the contribution and the limits of the TC approach for this study's purposes (section 2.5.7).

2.5.1 The emergence of the technological capability concept

Since the late 1970s, in the debate about industrial development in developing countries, technology was often identified with the hardware of production - the knowledge about machines and processes. Developing countries were thought to advance by importing and using technology from mature economies and there was little recognition of the need to develop local technological activities (Stewart, 1977). This

understanding limited the study of technological change in these countries to technology transfer and to the choice of the most suitable technology for the development needs at the minimum possible cost (Helleiner, 1975, Eckaus, 1977).

Since then a number of authors have enhanced our understanding of technological change in developing countries (Dahlman and Westphal, 1982, Katz, 1984, Bell, 1984, Lall, 1992, Bell and Pavitt, 1995, Romijn, 1999, Figueiredo, 1999, Dutrénit, 2000, Mani and Romijn, 2004, Hobday, 1995, Kim, 1997, Kim, 1998) and have showed empirically that mere technology acquisition does not imply the capacity to master it.

This is so for two important reasons (Evenson and Westphal, 1995): technology has a strong *tacit component* and contains *environment-specific elements.* Techniques of production are often not fully embodied in manuals or blueprints but involve a tacit knowledge that can only be acquired through first-hand experience. Similarly, local conditions, shaped for instance by social, cultural or climatic factors, often determine the nature of the technology that, when used in a different context, requires adaptation.

As a consequence countries and firms *need to develop capabilities* to continually assimilate, reproduce, adapt and improve new imported technologies. Capabilities should then be understood as the ability by the firms to do things and *technological capabilities* reflect the ability to generate and master technological activities (Dutrénit, 2007, Rush et al., 2007).

Technological capabilities are the result of a constant and prolonged *effort*, that is: a purposive investment in time and resources (both physical and human) that leads to *technological learning* (Dahlman and Westphal, 1981). It is this learning effort that allows the accumulation over time of the knowledge necessary to engage in innovative activities.

These ideas constitute the theoretical core of the technological capability literature and are reviewed in more details in what follows.

2.5.2 Understanding innovation in a developing country context

A first important contribution of the TC literature (Katz, 1987, Lall, 1987, Lall, 1992, Hobday, 1995, Kim, 1997) is to have enhanced our understanding of what we mean with 'innovation' in a developing country context. When technical change is equated to major, new to the world innovation, there seems at present to be possibly

relatively little room for a contribution originated in developing countries. These countries usually lack the technical, financial and human resources to perform groundbreaking innovation and are, by definition, behind the technology frontier (Forbes and Wield, 2002). However, when technological change is understood as a *continuous process to absorb or create technical knowledge*, then the role for developing countries in innovation becomes different (Lall, 1992). This leads to a broad definition of innovation which covers all types of search and improvement efforts. An innovation in a firm in a developing country may not be new to the world but consist of a "[...] continuous search and learning process in which the generation of entirely new technology is only the most complex activity on a continuum of a much larger set of technological activities, including search for alternatives, assimilation [of technology imported from abroad], and minor and major adaptation and improvement of chosen technologies, products and organisational principles" (Romijn, 1999).

Innovation and technology management do take place outside mature economies or large, globally famous, high-tech corporations, though those activities should be perceived in a broader sense (Forbes and Wield, 2000). Although not necessarily new to the world, innovation in a developing country context can be a novelty for the firm or for the local milieu (van Dijk and Sandee, 2002).

This broad understanding of innovation does not deny that there is a difference, in terms of specific strategies, risks to be taken and resources to be invested between (a) the effort to advance the technology frontier[44] and (b) the efforts to catch up or crawl along at some considerable distance (Romijn, 2002). Indeed, these two notions of innovation imply different technological capabilities and skills required for (b) are generally less demanding then those required for (a) (Romijn, 2002).

However, a narrow focus on 'new to the world innovation' would leave aside a crucial part of our understanding of how technical change occurs in developing countries and indeed of the effort and dynamics that are behind it. There is a lot that firms in developing countries can do in terms of technological change and to: "[...] go beyond the boundaries assigned to them by their national environments and by the world's leading technology-driven firms" (Forbes and Wield, 2006, p. 2). Forbes and Wield (2002) argue that the innovation task in developing countries, and more specifically, in their firms, is indeed different from that of mature economies and that it should focus around five key areas:

[44] For a definition of technology frontier in the specific context of PV see Section 1.4.

1. *Incremental innovation.* Innovation could be classified according to how radical it is compared to current technology (Freeman and Soete, 1997). From this perspective, continuous improvements to the current technology could be defined as 'incremental' as opposed to 'radical' innovation which involves a big leap into a 'new technological paradigm' (like for instance, the introduction of a totally new type of machine – Forbes and Wield, 2002). If we assume that firms in developing countries are, in general, not concerned with: "[...] the generation of new technology [because] the technology frontier is defined by the technology-leader [in mature economies]" (Forbes and Wield, 2002, p. 15), then incremental innovation becomes key not only to keep up with continuous improvement to the technology made by technology leaders, but also to catch up at a faster pace than the improvements made by the leaders.
2. *Process innovation.* Forbes and Wield (2002) note that in the early stages of the catch up process, firms in developing countries begin with process rather than product innovation, as it is the case in leading technological countries[45]. They argue that: "[...] when an industry matures, the innovation drivers change from technical performance to cost competition" (Forbes and Wield, 2000, p. 1099). To achieve cost-saving wage competitiveness and (incremental) process innovation (i.e. making things better) are important[46].
3. *Shop-floor innovation.* Key for process innovation is the need to focus on the shop floor. This is the way in which manufacturing improvements and cost-saving could be achieved in day-to-day operations (even by simply absorbing slacks and working harder). This could help promoting the competitiveness of the firms in developing countries especially in cost-sensitive markets.
4. *Development of an innovation-conducive environment encompassing organisational, cultural and managerial aspects.* For any innovation to be successful and sustainable, it has to be widespread and continuous. This is why it is necessary to develop an innovation culture and to enhance organisational and managerial aspects to make things happen. This could be

[45] Section 2.5.6 in this chapter explores more in details the different stages developing countries tend to go through in their catching up process with industrialised countries.

[46] Odagiri and Goto (1993) note how incremental process innovation has been crucial in Japan's catching up process with industrialised countries and rapid economic growth since the 1960s.

done by embedding, for instance, in firms' routines also 'soft' elements like the development of systematic ways of capturing creativity across the organisation[47].

5. *R&D effort with a specific focus.* Firms in developing countries need to perform their own R&D but its role, it is argued (Forbes and Wield, 2000), is different from that of firms in mature economies. This aspect is discussed in more detail in Section 2.5.4

In sum, *innovation does take place in firms in industrialising countries but needs to be understood in a way that is rather different from innovation in the case of technology leaders.* Instead of a narrow focus on 'new to the world', innovation should be appreciated as the *continuous process to absorb or create technical knowledge,* where incremental process innovation (with the shop floor as source of competitiveness and a R&D focused on those activities that can force firms up the value-chain) and an effective innovation culture all play a key role.

2.5.3 Firms as the locus of knowledge accumulation and different types of TC

The technological capability literature adopts the firm as the main unit of analysis and studies it to understand the extent to which and how it develops the skills necessary to acquire, assimilate, utilise, adapt, change and create technology (Juma and Clark, 2002).

Given the specific, cumulative and partly tacit nature of technology, the most important components of technological accumulation are localized in firms (Bell and Pavitt, 1993). This is so because they are associated with learning from specific experiences in developing and operating production systems and because they need to build the necessary capabilities to maintain their competitiveness, especially in the global economy (van Dijk and Sandee, 2002). It follows that a full range of mechanisms necessary to accumulate technological capabilities (see, for example, learning by doing, reverse engineering, in-house R&D, personnel training, inter-firm linkages and networks. etc.) could be observed in firms, making them a particularly suitable place to study innovation in the making (Bell, 1984).

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[47] Open communication systems that encourage ideas or rewards systems that encourage creativity and do not discourage getting it wrong are important factors associated with creative organisations (Rickards, 1985).

The recognition that firms could make a key contribution to industrial growth has made them a central element in those government policies aimed at increasing national industrial competitiveness (see among others Lall and United Nations Conference on Trade and, 2004). As a consequence an understanding of technological capabilities accumulation dynamics in firms is necessary if we want to inform the policy process.

Different types of technological capabilities

Different types of technological capabilities, that cover the main technological activities a firm performs, are identified in the literature (Lall, 1992, Bell and Pavitt, 1995, Kim, 1999, Westphal et al., 1985). Drawing on Lall (1992) and Bell and Pavitt (1995), Romijn (2002) provides a useful synthesis:

- Investment capabilities. They refer to the firm's ability needed to choose new technology and to establish (or expand) new production facilities. They include activities related to both decision-making as well as preparation and implementation of projects.
- (Routine) Production capabilities. Consist of the skills and knowledge needed to *reproduce existing technologies* as well as to operate and maintain production facilities.
- Innovation capabilities. Are the skills and knowledge required to *make independent adaptations and improvements* to existing technologies, and ultimately to *create entirely new technologies*.

The identification of different types of capabilities[48] is analytically useful because it helps in focusing the attention on a full range of capabilities that have to be internalised by the firm to ensure successful commercial operation and to move technologically forward (Lall, 1992).

The distinction between 'routine' production capabilities and innovative capabilities is particularly important because it is based on the distinction between: "the kinds of knowledge and skill required to operate given production systems and the

[48] Two other types of 'supportive' capabilities are also identified: developing linkages and interaction with firms and institutions (Lall, 1992; Bell and Pavitt, 1995) and producing capital goods (Bell and Pavitt, 1995).

kinds of knowledge required to change them" (Bell and Pavitt, 1993, p. 165). In other words, it is the distinction between technology-using and technology-changing skills.

For analytical purposes and given the difference in the effort required to push forward the technology frontier and to catch up, Romijn suggests that a broader understanding of technological capabilities, where all the three types of capabilities identified above are included, should be preferred to a narrow one on 'innovation capabilities'.

2.5.4 Technological learning as the main means to build up technological capabilities in firms

The concept of *learning* is central to the TC literature and is regarded as the way in which organisations such as firms accumulate skills and knowledge (Malerba, 1992).

Firms are defined as 'learning organisations' (Lundvall et al., 2002) because they need a purposive effort to assimilate, adapt and modify existing technologies and/or to develop new ones[49]. Firms are "[...] skilled at creating, acquiring and transferring knowledge, and at modifying their behaviour to reflect new knowledge and insights" (Garvin, 1993, p. 80).

Firms learn at different rates and learning experiences are firm specific. Learning is a path-dependent and cumulative process and, as such, a major source of incremental technical change.

Possibly the mode of learning that is more closely associated with capability enhancement and innovation in firms is *internal R&D.*

Forbes and Wield (2002) argue that R&D in firms in developing countries is important and that its role is different from that it plays in mature economies. What, it is argued, matters for the success of industrial innovation in firms in industrialising countries is not 'how much' they spend in R&D but rather the 'focus' of their R&D. The key role of R&D in these countries could be summarised in the need to "[...] build absorptive (learning) capacity so that the firm can effectively access work done elsewhere" (Forbes and Wield, 2002, p. 18). More specifically the R&D task in developing countries' firms is suggested to be:

1. To *follow the technology frontier determined by firms in mature economies efficiently*, i.e. to support the firm's quest for long-run competitiveness in

[49] The literature on firm-level learning is abundant. Some representative authors are: Arrow, 1962, Rosenberg, 1982, Dosi et al., 1988, Lundvall, 1988, Malerba, 1992, Bell, 1984.

manufacturing. This involves, for instance, solving problems that arise in manufacturing which cannot be solved on the shop-floor and need the specific skills embodied in an R&D department.

2. To *achieve effective design leadership*, i.e. to deliver an independent product development capacity to the firm. This calls for the development of 'design capabilities' as distinct from 'technological capabilities'. The role of R&D in developing countries, as Forbes and Wield (2002) suggest, is to push the design frontier ahead while following the technology-frontier determined by firms in mature economies.

Despite the importance of in-house R&D, a substantial part of the firm's internal learning may not take the form of a formalised technological effort (Romijn and Albaladejo, 2002).

The tacit, specific and non-codifiable nature of many elements of the technology (Polanyi, 1967) and the potential to appropriate some of their benefits favour other informal and incremental problem solving strategies[50].

Forbes and Wield (2002), drawing on an abundant literature on the topic (Arrow, 1962, Rosenberg, 1982, Bell, 1984, Lundvall, 1988, Lundvall, 1992, Malerba, 1992), distinguish between the following modes of learning:

1. Learning by doing
2. Learning by investment.

Learning by doing takes place at the manufacturing stage when informal, incremental problem solving and experimentation take place on the firms' shop-floor and allows firms to get acquainted with productive processes. In other words: "learning by doing is the passive, automatic and costless by-product of production" (Forbes and Wield, 2002, p. 14).

Learning by investment involves the firm's conscious and purposive effort to enhance capabilities. This mode of learning could be further divided in three main categories (Forbes and Wield, 2002): (a) *learning by analysing*, which may include activities like reverse engineering (b) *learning by explicit action*, which includes personnel training both within and outside the firm as well as the hiring of specialists

[50] As specified at the beginning of this chapter informal ways of learning are particularly relevant for firms in developing countries, which tend to lack the necessary resources for formal and extensive R&D programmes.

(often foreign) from whom the local personnel can learn from (c) *formalised R&D activities*.

2.5.5 Factors that affect learning in firms

A variety of factors internal and external to the firm may contribute to technological learning and result in enhanced capabilities (Romijn and Albaladejo, 2002 provide a comprehensive overview).

Internal sources of technological capabilities

The *knowledge and skills brought into the firm by the entrepreneur and the workforce* significantly contribute to the firm's learning process (OECD, 2001, Romijn and Albaladejo, 2002). This knowledge is the result of both the educational background and the previous working experience. "Firms require an adequate stock of technically qualified manpower to absorb new technologies, modify them, create and transfer new technological information, particularly scientists and engineers" (Romijn and Albaladejo, 2002, p. 1054). Highly qualified workers add great value to any firm and the inability to recruit them can be a serious constraint on subsequent growth, especially when innovation is viewed as a cumulative process, critically dependent on tacit knowledge (Hoffman et al., 1998, Galende and de la Fuente, 2003).

Also the *firm's size, age and ownership* could play an important role in capabilities enhancements and learning. A large firm's size, for instance, could be positively associated with innovative behaviour in firms because it can allow achieving greater economies of scale, superior access to finance and the ability to spread risk in diverse portfolios (Galende and de la Fuente, 2003)[51]. Similarly, there seems to be a direct link between a firm's age and its ability to undertake innovative activities (Kumar and Saqib, 1996, Molero and Buesa, 1996). The age of a firm represents the experience and knowledge accumulated throughout its history and is related in the literature to: "a better management of communication and of necessary creativity to innovate, and to a more effective capacity for absorption" (Galende and de la Fuente, 2003, p. 718).

[51] It should be noted that the relationship between firm size and innovation is most controversial and arguments exist both supporting a large size and a small size. In this latter case, firms' innovative results would be favoured by greater flexibility, better communication, greater specialisation possibilities, informal and strategic controls. Galende and de la Fuente (2003) offer a thorough review of the controversies surrounding the link between firm size and innovation as well as of other internal determinants of innovation in firms.

As for ownership, we discussed at the beginning of this Chapter (Section 2.2.3) how Chinese competitive industries and China's high-tech exports are overwhelmingly produced by foreign-managed and foreign-owned firms (Rosen, 2003). In the case of China the literature seems hence to suggest that non-Chinese ownership has a positive effect on the likelihood of innovation (see among others: Steinfeld, 2004, Lemoine and Unal-Kesenci, 2004).

One further aspect that is suggested to be important for innovation but that will not be taken into account by this study because it is far beyond our scope, is *culture*, understood as 'the way things get done' (Forbes and Wield, 2002).

External sources of technological capabilities

Among the firm's external sources of technological capabilities the *access and the adoption* of the technology developed by other industries by means of license agreements or as embodied in capital equipment and intermediate inputs (Pavitt, 1984) could play an important role. This could be particularly the case of firms in developing countries where technological capability accumulation generally begins with the import of technology from an industrialised country (Forbes and Wield, 2002).

*Interaction*s with suppliers, customers, industry associations, research institutes and the alike also provide important external inputs to the learning and the technological accumulation processes. Romijn and Albaladejo (2002, p. 1055) note that "interaction may take place for the purpose of gathering information about technologies and markets, and also for obtaining various other inputs to complement the internal learning process, such as external staff training, parts and components, consulting services, and R&D grants". The type of learning that occurs as a result of the links and relations with external sources is called 'learning by interacting' (Lundvall, 1988).

Several authors (see among others: Camagni, 1991, Oerlemans et al., 1998) have suggested that interactive learning would also be boosted by the *geographical proximity* of the firms with the network of suppliers, customers and other organisations with whom they interact. This, it has been suggested[52], would happen for a number of reasons: the tacitness of new knowledge, which makes its transfer difficult across large distances (Cooke et al., 1997); the lower costs involved and face-to-face contact that

[52] See Romijn and Albaladejo (2002) for a synthesis of the main arguments about the link between geographical proximity and innovation.

would enhance the quality of the interaction (Saxenian, 1994); the importance of local knowledge spillovers, including inter-firm movement of skilled labour (Caniëls, 2000).

2.5.6 Stages in technological capability accumulation

A part of the TC literature focuses on the pathway that has been followed by developing countries in catching up[53] with industrialised countries (Kim, 1980, Kim, 1997, Lee et al., 1988, Lee and Lim, 2001, Hobday, 1995, Hobday, 2000). Kim (1980, 1997) argues that the process of innovation in catching up countries (focusing particularly on South Korea) is fundamentally different from that of mature economies.

It has been suggested (Utterback and Abernathy, 1975, Utterback, 1994) that innovation in mature economies develops along a technology trajectory that starts from a high rate of radical product innovation, where several product designs coexist and compete in the market place (*emergence stage*); it proceeds with the emergence of a dominant product design and the focus on a specific process technology (*consolidation stage*) and it ends with incremental process improvements as product design matures (*maturity stage*). When the industry reaches this stage, firms become increasingly vulnerable in their competitive position and are less likely to undertake R&D aimed at radical innovation[54].

By contrast (see Kim, 1980 and 1999) developing countries are suggested to go from acquisition of foreign technology, assimilation, where process development and product design technologies are acquired, adaptation, small modifications and eventually to autonomous innovation.

In this 'three-stages model' (i.e. acquisition, assimilation and improvement) typical of innovation in developing countries, Kim (1999) notes that the sequence of innovation is 'reversed' with developing countries (and more in particular South Korean firms upon which Kim's observations are derived) moving from mature to early stages of the innovation process, i.e. starting with process rather than product innovation as in the case of leading technological firms.

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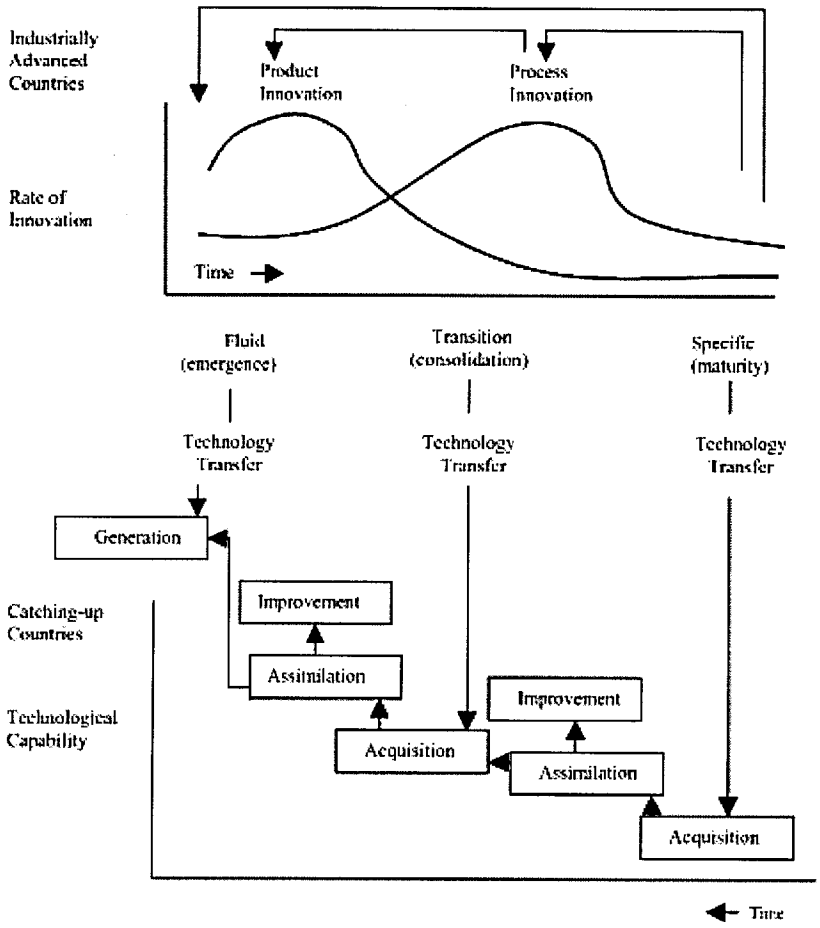
[53] 'Catch up' here refers to the processes industrialising countries could follow to accelerate their development and reduce the gap between themselves and the technologically and economically advanced countries.

[54] It should be noted that, although this trajectory mode elaborated by Utterback and Abernathy (1975) is not universally applicable (this is because differences across firms, industries and countries could determine a wide variation in the rate of accumulation – see Bell and Pavitt, 1995), it is however still useful in analysing TC building in developing countries.

Kim (1999) also notes how countries and Korea more in particular, catch up not only in mature technologies but also during the consolidation and emergence stages as they progress in their capabilities.

Figure 5 graphically represents the innovation model in mature and developing countries as it has been conceptualised by Kim (1997) drawing on previous work on technological trajectories (Lee et al., 1988, Utterback, 1994).

Figure 5 Innovation process in mature and catching up countries



Source: Kim, 1999

A similar reverse innovation model has been observed also by Hobday in the specific context of electronics in Taiwan and Korea (Hobday, 1994). He notices that firms begin their catching up process by manufacturing to the specifications of multinational companies (i.e. they start as original equipment manufacturers – OEM); they then move to their own design (i.e. they become original design manufacturers – ODM), while the multinational companies continue to carry out the marketing and

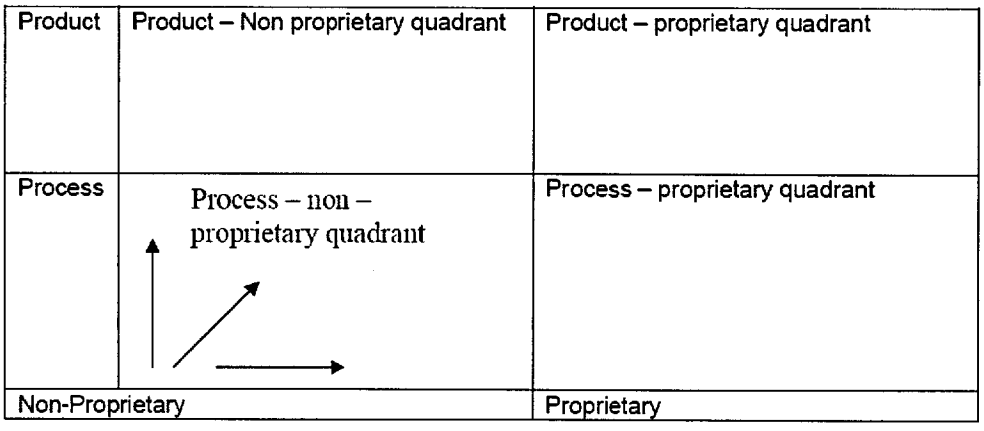
distribution under their own brand name. The catching up process is complete when the domestic firm become OBM (own brand manufacturer). In this final stage: "the firm carries out all of the stages of production and innovation, including manufacturing, new product design, and sometimes R&D for new materials and products" (Hobday and de Barros Perini, 2005, p. 19).

In line with Kim's findings, Forbes and Wield argue that, although in developing countries usually process innovation gives way to product innovation, unity between them is often crucial to move up the value-chain (Forbes and Wield, 2006). Moreover, they highlight that to develop distinctive capabilities in either or both process or product innovation another dimension is needed: *proprietary capability*. "Proprietary capability comes from knowledge that is distinctive to the firm. In some cases, this proprietary capability takes the form of intellectual property formally owned by the firm: patents, trade-marks, designs, copyright. In other cases, the intellectual property may not be formally protected through intellectual property rights (IPR) [...] but is the sum of tacit knowledge spread among the firm's employees and routines. [...] Proprietary knowledge can also take the form of management capabilities, or widespread and distinctive knowledge in the heads of a large sales force. Proprietary knowledge works when it permits the firm to stay ahead of competitors" (Forbes and Wield, 2006, p. 10).

To illustrate this point they develop what they define as the 'process-product-proprietary grids' (see Figure 6), which allow them to position firms in their catching up process but also to trace their progresses and path towards 'technological leadership' and competitiveness. At the beginning of their catching up process and when they start competing internationally, firms are in the process/non-proprietary quadrant of the grid (bottom left) where they compete on wages. Within this first quadrant firms can start improving their process capabilities by innovating at the shop-floor (by for instance absorbing slack, as explained in Section 2.5.2). Although these improvements require considerable effort and commitment on the side of the firm and cannot therefore be considered as minor, "moving up the value chain means capturing innovation rents via product innovation, or by building proprietary capabilities, or both. Crossing the quadrant boundaries requires that firms build new assets and capabilities" (Forbes and Wield, 2006, p. 14). This could happen in a variety of ways. Firms can, for instance, move from process/non-proprietary to product/non-proprietary or going proprietary by moving to the right side of the grid.

The merit of the process-product-proprietary grids is, rather than indicating one best practice, to suggest that for many firms, there are a series of possible moves to become innovative.

Figure 6 The process-product-proprietary grid to analyse firm-level innovation in developing countries



Source: Forbes and Wield, 2006

2.5.7 Relevance and limits of the TC approach for this study

The technological capabilities approach as it has been reviewed in the previous pages, offers analytical insights that are particularly useful to address some of the key issues of this study.

First the approach has been specifically developed to study and explain firm-level technical change in developing countries. It follows that, by using this approach, this study will not encounter the problems, identified instead for the IS approach, of adapting to a developing context ideas generated by observing behaviours in mature economies.

Second, the TC approach provides a practical analytical tool[55] that allows to study what kind of capabilities firms in developing countries acquire (i.e. what is the nature of their innovative effort) and what are the learning processes through which they are accumulated - all aspects that are at the core of this thesis' objectives. Moreover, a wealth of empirical evidence upon which to compare and contrast the results obtained by this study is available (Romijn, 1999, Figueiredo, 1999, Ariffin and Figueiredo, 2004, Albaladejo and Romijn, 2000, Ariffin, 2000).

[55] This will be explained in more detail in the first part of Chapter 3.

These are all important aspects, even more so, when the other approach adopted by this study, the IS perspective, has been questioned in the literature for not being practical enough and for being too conceptually heterogeneous (Klein Woolthuis et al., 2005).

However, although the TC literature has substantially contributed to our understanding of technological dynamics in firms in developing countries and on the learning processes that underpin efforts to increase value-added, it suffers from some important limitations. We shall deal below with two of these for the importance they play in this study:

1. The limited attention to the study of new emerging knowledge intensive technologies
2. The lack of systemic understanding

Limited attention to the study of new emerging knowledge intensive technologies

The process of technological capability building and the underlying learning processes have been well studied by the TC literature in industries such as, for instance, farm equipment (Mishra, 1985, Romijn, 1999), metalworking (see Katz, 1987 and Figueiredo, 2002 for specific insights into the Brazilian steel industry), rice milling (Mingsarn, 1986) and briquetting (Clancy, 2001). These are all traditional manufacturing and engineering-based industries that have been at the core of industrial development in the 20th century. Catching up strategies in these machine-based manufacturing processes were possible from a low skill base and by pursuing the previously illustrated incremental path of foreign technology acquisition, assimilation, modification and adaptation to local needs (Mytelka, 2004).

The new century is seeing instead the increasing importance of a different type of technologies. Biotechnologies, pharmaceutical, nano-technologies, fuel cells and indeed solar technologies for the production of electricity are rapidly acquiring importance. These technologies, defined by Mytelka as 'new wave technologies' (Mytelka, 2003, Mytelka, 2004) are characterised by: intense knowledge base, systemic embeddedness and patent intensity. Mytelka (2004) emphasises how processes of catching up and capability building in these technologies are bound to be different from earlier mechanically based industrial technologies upon which our understanding is

currently based. Incremental innovation strategies (i.e. from imitation, to adaptation and innovation) are bound to be not longer adequate for firms willing to take part in new wave technologies because they: "[...] have raised the barriers to entry and narrowed opportunities for incremental catching up from a low skill base" (Mytelka, 2004, p. 389).

Moreover, the technology frontier in these new wave technologies is moving quickly ahead. This is particularly relevant in the case of solar PV where, as will be explained in Chapter 4, different technological families, at different levels of technological and commercial maturity, are rapidly moving forward and are competing to dominate the solar electricity markets of the next decades. This rapid rate of technological change (in PV but also in other emerging technologies like for instance stem cell biology or nanotechnologies) casts a further doubt on whether the incremental innovation process described in the TC literature is still an adequate strategy to participate in the global markets and production. The rate of change forces firms to compete not only on prices but also on the basis of their ability to innovate.

This is why a deeper understanding of TC building in new knowledge-intensive technologies like PV is needed and should be carefully studied, both to see whether accumulation paths are indeed different from traditional technologies upon which the large majority of the TC literature is based and whether firms are taking steps to keep pace with the rapidly shifting technology frontier.

Moreover, a lack of knowledge of the extent to which, and how, firms in developing countries are building up TC in knowledge intensive technologies does not allow to shed light on the contribution these countries could give to further developing and diffusing these technologies. If: "From the firm's point of view there is little difference [...] between efforts to improve technology mastery, to adapt technology to new conditions, to improve it slightly or to improve it very significantly" (Lall, 1992, p. 166), from the technology's point of view it makes a considerable difference. This is particularly relevant for those technologies, like solar PV, that have not yet reached maturity and need innovation to develop further. Whether China is developing only the TC necessary to become a good imitator or whether it is taking steps to reach the technology frontier and possibly moving it forward could have profound implications for the future of PV diffusion.

Lack of systemic understanding

Although in identifying the factors that are relevant for technological learning, some authors (see for instance Romijn and Albaladejo, 2002) take into account also factors external to the firm and particularly those that imply interactions with customers or suppliers, they fail to study and understand the interplay between the firm and its external environment. Since firms are part of a larger system (see the discussion in the initial part of this chapter): "[...] it is simply not enough for innovation studies, in developing countries, to focus on firm-level factors without considering the relations between these and the broader institutional and organizational set-up within which firms are embedded. The dynamic capabilities for absorption and innovation are influenced by firm-level factors and competencies as well as the character and conduct of institutions and organizations defining the system" (Kiggundu, 2006, p. 33).

2.5.8 Concluding remarks on the usefulness of the IS and TC approaches for this study

Both IS and TC approaches have strengths and limitations which arise from their bounded focus. Therefore they can only yield partial insights on this study's purpose to understand more about innovation in PV firms in China.

The TC literature is interested in the determinants of firms' TC accumulation and particularly in the learning mechanisms that are behind this accumulation process. Although this is certainly crucial in firms in developing countries (even more so if we understand innovation in the broad sense so that also incremental innovation can be taken into account) the big picture remains in the background. Firms are part of a broad system that fosters and constrains innovation and capability building at the same time. It is how the different elements of the system work together that matters and determines the outcome of innovation.

On the other side, the IS literature has the merit of focusing specifically on the interplay of the different elements of the system. However, it fails to shed light on the specific knowledge accumulation processes that are so important for technological improvements in firms and even more relevant in firms in developing countries, where it is assumed that specific effort should be devoted to acquire and assimilate a technology developed elsewhere.

It is suggested here that new insights into the driving forces of firm-level competence building, competitiveness and growth in developing countries could emerge by combining the two approaches.

2.6 Conclusions

The focus of this thesis is upon the ability of the PV firms in China to innovate and on what drives them to do so. We began this Chapter by discussing a commonly used approach to understand and measure innovation in firms (or countries): the use of quantitative indicators like R&D expenditure or patents. We adopted this approach to sketch a picture of China's innovativeness and concluded that, despite being useful, quantitative indicators by no means could give a complete picture of the health or otherwise of a firm's or a country's innovativeness. Not only do they present considerable challenges when applied in a developing country context[56] but also, and more specifically, when used to understand more about innovation in China, they cannot reflect the rapid changes a country the size of China is undergoing and the time and effort needed for technological change to occur. Moreover the use of quantitative indicators cannot provide accurate insights into the many technological complexities and specificities that characterise the different industrial sectors. The nature of global innovation is changing, and we need to update our frameworks and models to take account of this.

For this reason we devoted the second part of the Chapter to review critically two strands of literature - the TC and the IS literatures - that we believed could provide a better understanding of firm-level innovation dynamics. We emphasised, however, how studies that adopt an IS perspective rarely include an empirical review of firm-level technological competences and factors of influence. At the same time, a common weakness of the TC studies is that they adopt a static view of what determines learning in firms and do not take into account the workings of the innovation system as a whole. We propose to use in this study both the approaches to see whether their joint adoption could deliver a better understanding of the innovation process underway in China in solar PV.

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[56] As explained in the initial part of this chapter formal R&D, for instance, only captures a limited part of the innovation effort undertaken by firms in developing countries.

Our task in the next chapter is to describe the analytical framework that results from combining these two literatures and to set out and discuss the methodology of the study.

3 DEVELOPING THE ANALYTICAL FRAMEWORK AND THE METHODOLOGY OF THE STUDY

Picture 4 Searching for a method: how do I eat this?



Note: the answer to the question in the caption above is provided at the end of the Chapter

Source: Picture taken by the author during fieldwork in China (May-July 2005) in a Shanghai restaurant serving southern Yunnan cuisine

3.1 Introduction

Chapter 2 discussed how technology is developed largely in firms and suggested that they need to build the necessary *capabilities* to grow value-added and to maintain their competitiveness both in domestic and international markets. The capability building process requires *effort*[57] at the level of the individual firm but also the active involvement of other elements (i.e. organisations, institutions and networks) of the system in which firms are embedded. While each of these elements is important,

[57] As discussed in the previous Chapter, the 'effort' is essentially the continuous learning that a firm needs to add value to its products and processes. Learning (which includes not only the formal in-house R&D expenditure but also other, less quantifiable, mechanisms like learning-by doing or learning by investment, see Section 2.5.4) is known from the literature (see Section 2.5.5) to be affected by previous education and working experience of both the entrepreneur and the workforce, culture, some firm-specific factors (i.e. size, age, ownership), geographic proximity with firms in similar lines of business and interaction with customers and suppliers. Since firms do not go through the same innovative process, the extent to which these factors play a role in their learning and technological capability accumulation process varies and needs to be explored.

the interplay between them and the way in which a system performs are particularly important for the emergence and the diffusion of innovation.

In this chapter we propose to design a strategy to operationalise and empirically test these concepts. The chapter has therefore two main purposes:

1. To develop an *analytical framework* to translate some of the theoretic concepts reviewed in Chapter 2 into observable and empirically testable variables.
2. To design a suitable *method to collect the data* necessary to answer the research questions (Section 1.3).

The first part of the Chapter presents the analytical framework and starts with an overview of the issues that a framework developed for this study should help in addressing (Section 3.2.1). Sections 3.2.2 and 3.2.3 discuss these issues more in detail and explain how this study 'measures': how advanced is what PV firms in China can do (Research question 1 on the nature of innovation in the PV firms in China) and how knowledge has been accumulated and what has played a part in this accumulation process and ultimately supports or inhibits innovation in the firms under analysis (Research question 2 on the determinants of innovation).

The second part of the Chapter (Section 3.3) explains the method used to address the specific theoretical, analytical and empirical requirements of the thesis. Particular attention is devoted to the empirical part of the research and to the methods used to collect the evidence necessary to understand the innovation behaviour of the PV firms in China. Sections 3.3.3 and 3.3.4 contain information on the empirical instrument used (i.e. questionnaire and semi-structured interviews); on the type of data that have been collected and on the fieldwork done in China.

3.2 Analytical framework

Before going into the details of the analytical framework, two introductory notes are important.

The analytical framework developed for this study combines two approaches – one with a TC and intra-firm learning focus and the other with a wider systemic focus,

coming from the IS literature[58]. The framework developed considerably over time and the version presented below is the result of an iterative process, in which additional pieces of information have been added as the empirical analysis has proceeded. This particularly refers to the part aimed at enhancing understanding of the systemic dynamics and of what influences innovation in PV firms. A number of factors made it difficult and possibly undesirable to tighten up too much the analytical framework before undertaking the empirical analysis: the speed of change of the Chinese PV sector since the early 2000s (see second part of Chapter 5); the fact that this sector in China had not been studied before from an innovation point of view; the rapid economic growth of the country since the early 1980s and the profound changes occurred in the Chinese innovation system over time (see Chapter 5, Section 5.2).

Furthermore, while one of the key purposes of the analytical framework is to guide the data collection, another important aspect is to explore the complementary nature of the two different approaches adopted (i.e. the TC and the IS). As a consequence it did not make sense to have a too structured framework to work with before the beginning of the data collection.

Information obtained in China has been used to further structure the analytical framework and to see how compatible the two approaches are. These issues will be discussed in more details in Chapter 7.

The second remark is that two other Chapters should be considered as an integral part of this analytical framework: Chapter 4 and 5 where the PV technology and the development of the Chinese innovation system over time are respectively discussed. As explained in Chapter 1 (Section 1.6) and further detailed in section 3.2.1 of this chapter, the reviews of these two issues are crucial not only to inform the analytical framework but also to understand the empirical results presented in Chapter 6 and discussed in Chapter 7. For reasons of simplicity we have preferred not to include the coverage of these two technology and country specific issues in this chapter but to locate them in two separate chapters that precede the presentation of the results (Chapter 6).

[58] Figure 7 provides an overview of the approaches used to elaborate the framework and the concepts it operationalises.

3.2.1 What an analytical framework designed for this study should help in understanding

The analytical framework developed for this study should help in understanding the nature and the determinants of the technological effort underway in the PV firms in China. More in particular, building on the theoretical basis reviewed in Chapter 2, it should operationalise the two research questions and a number of key concepts they contain:

1. *How advanced is what the PV firms in China can do* (research question 1).
   In this respect we need analytical tools to assess: the type of capabilities that the Chinese PV firms possess and how advanced they are (i.e. only the capabilities to assemble standard PV modules or also the ability of customising products or indeed developing fundamentally new products? Are firms developing proprietary solutions that are hard to duplicate and can guarantee a long term competitive advantage?); with respect to what and to whom should we assess how advanced these capabilities are (i.e. are the Chinese PV firms accumulating capabilities only in the PV technology family that is closer to technological and market maturity or are they entering also other emerging PV technologies? How do the Chinese PV firms perform with respect to competitors?)
2. *What factors affect the knowledge accumulation process, how they changed over time and can drive further the firms' innovation effort* (research question 2).
   To operationalise this research question we need to focus both on firm-level and wider systemic aspects. We need hence tools to: identify different types and sources of learning in PV firms (for instance: what is the role played by in-house R&D? How important is the educational/professional background of the entrepreneur in the firm's learning and innovative behaviour?[59]), but we also need to map the structure of the Chinese PV innovation system (what types of actors are there? How do they relate to each other?) and to identify what processes (i.e. 'functions') are important to the firms' ability to generate technological change and what induces and blocks them.

[59] For the theoretical underpinning of these issues see Chapter 2, Section 2.5.5.

We will also need to identify different points in time in the firms' history in order to understand the role played by the different 'accumulation factors' over time (i.e. how do the different structure and dynamics of the innovation system over time affect the innovation behaviour of the Chinese PV firms?).

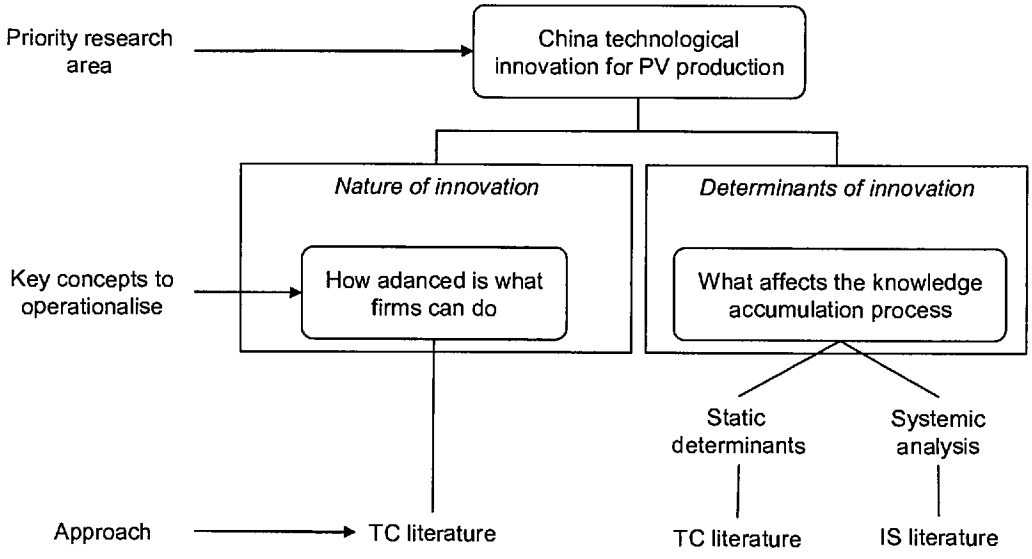
As anticipated, two different approaches suggested by the literatures critically reviewed in Chapter 2 have been used to operationalise these key concepts. The TC literature, which is more suitable to explain firm-level dynamics[60], has been exclusively adopted to frame point 1 above. Both the TC and IS literatures have instead been adopted for point 2 on the determinants. As pointed out in Chapter 2, we believe that each body of literature, when taken separately, can yield only partial insights into the factors that affect knowledge accumulation in firms, how they changed over time and what can drive their innovation effort further. In other words: why firms accumulate knowledge and innovate. To operationalise this specific aspect, we hence propose to construct this part of the analytical framework by adopting separately the two approaches to see what results they are capable of delivering. The complementarity of the two approaches and the extent to which they could be integrated will be discussed in Chapter 7.

Figure 7 summarises the two conceptual blocks that the analytical framework should address (i.e. the nature of the firms' technological effort and its determinants), the specific concepts that it operationalises and the main theoretical approaches used.

Because the analytical framework addresses a number of distinct issues (see the discussion above) it is possibly more appropriate to refer to several sub-frameworks (or 'analytical tools' as they have been called above) that have been specifically designed to address each analytical issue of interest for the study (e.g. with respect to what and whom the TC of firms should be 'measured'? How the innovation system components can be mapped and its performance be studied over time? etc.). Taken all together these sub-frameworks constitute the analytical framework of this study.

[60] See the discussion about the strengths and limits of the two literatures in Chapter 2

Figure 7 Overview of the concepts operationalised by the analytical framework



Source: Author's elaboration

3.2.2 Assessing how advanced is what the PV firms in China can do (on the nature of the technological effort)

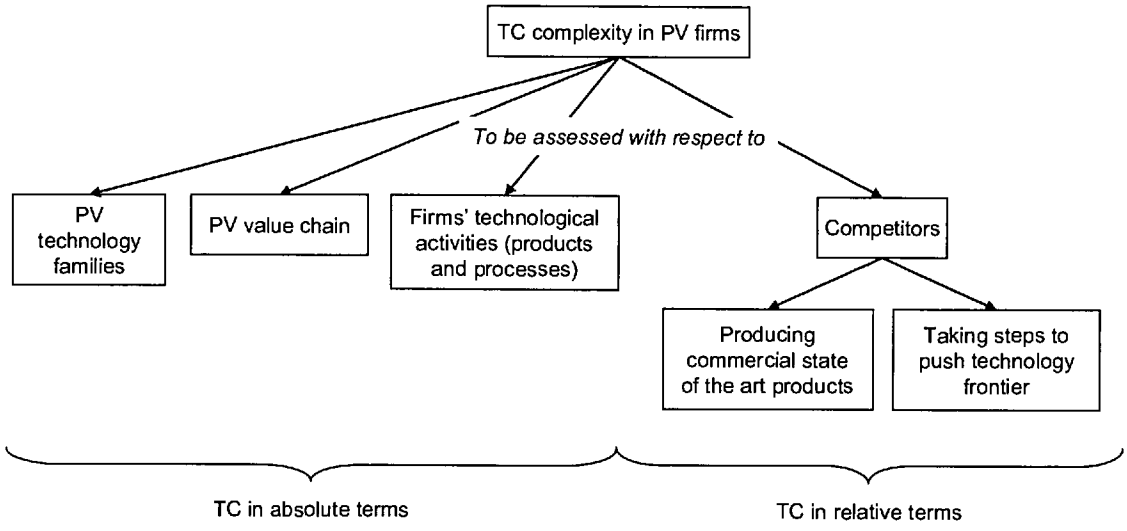
In addressing the nature of the technological effort of the PV firms in China (see the first building block in Figure 7), we need first of all to establish with respect to 'what' and to 'whom' we want to assess how advanced is what the firms can do. We argue that this should be understood not only in a narrow sense by focusing on a firm's ability to increase the value added of its products and processes, but also with respect to the firm's positioning in the PV value chain and in a broader PV technological and competitive context.

This represents an improvement to conventional approaches interested in TC in firms (Lall, 1992, Figueiredo, 2002, Romijn, 1999, Ariffin, 2000), where the degree of technological maturity firms have achieved has been assessed only with respect to the technological activities they perform (i.e. investment, product and process activities as well as developing linkages with firms and institutions)[61].

Figure 8 schematically presents the key dimensions against which the maturity of the technological capabilities accumulated by the Chinese PV firms will be assessed in this study.

[61] These aspects have already been introduced in Section 2.5.3 and will be further discussed in the following pages of this section.

Figure 8 Analytical framework for the assessment of the complexity of TC in PV firms



Source: Author's elaboration

In what follows we explain why we believe a broader focus is needed to assess technological capabilities in PV and how we intend to make these assessments operative.

A. Assessing TC with respect to the PV technological families

The generic term 'solar PV' refers to a group of technology families at different levels of technological and commercial maturity (see Chapter 4, Section 4.2.3). Not necessarily the technology that today dominates the market and that has nearly reached technological maturity (this is the case of c-Si) will be the one with the largest market share also in the years to come. Since one of the PV innovation goals is to reduce the cost of production and PV technology families that are currently in their infancy have proved they can better suit this goal, it is quite likely that c-Si will be substituted in the future by other more cost-effective and better performing technologies[62].

In assessing TC in the PV firms in China, it is hence important to position the firms within this broad technological context to understand whether they operate in a technology family with a limited innovation potential (like the case of c-Si) or whether they manifest a long term view by accumulating capabilities in technologies that are not yet commercially available (or that are approaching market diffusion) but that are likely to constitute the future PV innovation frontier. The choices made by the firms with

[62] All these aspects are discussed at length in Chapter 4.

respect to the different PV technology families will be taken by this study as a first indication of their innovation behaviour.

B. Assessing TC with respect to the PV value chain

As pointed out above, since the currently dominant PV technology is c-Si, it makes sense to give a closer look to its value chain assuming that a certain number of firms in China will be operating in this technology[63].

As Chapter 4 (Section 4.3) explains, not all the manufacturing links along the c-Si value chain have the same knowledge intensity and innovation potential towards the goal of reducing productive costs. Since the high cost of this technology family depends on the main material employed, i.e. Silicon, it follows that the manufacturing links where Silicon is employed more extensively (i.e. ingot, wafer and cell manufacturing) are the ones where more cost reduction is possible and where more innovation effort is required. Moreover these are also the links that are more knowledge intensive and where more advanced TC are required to manage the production process (see Chapter 4 for more details).

It follows that undertaking production in one manufacturing link or another along the c-Si value chain may give additional indications on the maturity of the technological capabilities of the firms under analysis. Should evidence collected for this study highlight that PV firms in China are mainly assembling modules, this result will suggest that firms are possibly doing light transformation of high-tech goods (i.e. cells and wafers) whose value is created elsewhere, possibly in mature economies.

C. Assessing TC with respect to the firm's technological activities: products and processes

Based on the idea that technological capabilities are the mastery of technological activities (see Chapter 2, Section 2.5.1), it is possible to identify those activities that are important in a firm's operations and to study the level of maturity that firms have achieved in their mastery (Lall, 1992). Lall (1992) has explored these issues and identified six different technological activities (which he calls 'technical

[63] As it will be explained in detail in the second part of this Chapter, before leaving for fieldwork, a preliminary search was undertaken to identify the main PV industrial, academic and policy players. It appeared immediately clear that the large majority of the firms that were manufacturing PV components in China in 2005, were doing so in the c-Si technology

functions'): (i) pre-investment decisions (ii) project executions (iii) process engineering (iv) product engineering (v) industrial engineering (vi) linkages within the economy [64].

The idea behind Lall's sub-division in technical functions is that a firm is unlikely to ensure successful commercial operations unless it has acquired a basic core of competence necessary for instance to decide by itself on its investment plans, to reach minimum levels of operating efficiency, to deliver products with minimum quality requirements or to establish effective linkages with reliable suppliers.

This study takes into account only two of the technical functions identified by Lall: product and process engineering. We want to establish the extent to which the PV firms in China can undertake a) changes in the products they offer (product innovation) b) changes in the ways in which these products are created (process innovation). This choice rests upon the fact that these are the aspects that are more significant to foster innovation in PV where, as anticipated here and explained in detail in Chapter 4, one of the main goals is to reduce production costs via improved or new production processes or via new applications[65].

Once the technical functions have been conceptualised, it is also possible to identify different degrees of maturity of the technological capabilities accumulated by firms in the different technical functions. Lall (1992) refers to three maturity stages: basic, intermediate and advanced (Lall, 1992)[66].

When referred to process or product engineering, the category *basic capabilities* indicates that simple routine activities, such as assimilation of standard process technology or easy maintenance to ensure product's minimum quality requirements, can be undertaken by the firm. These capabilities are the result of the experience gained by the firm in constantly repeating certain activities and do not require any significant action to foster the process of technological upgrading (i.e. they are essentially the result of learning by doing and of processes like reverse engineering).

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[64] Functions (i) and (ii) refer to the investment decisions, in terms of technology, equipment and construction sites, necessary before undertaking production. Function (v) refers to activities like inventory control, monitoring productivity, etc.

[65] Using high-efficiency 3rd-generation solar cells for building-integrated PV could be an example of a new possible application (Barnham et al., 2006)

[66] Hobday (1996, 1999) has adopted a slightly different classification framework for the technological positioning of firms. In studying technological activities in the global electronics firms, he distinguishes between: a) Changes to existing old stock through technological support and engineering services b) capability to install the latest vintage equipment c) minor adaptation and short-term (six months to a year) development of products and processes d) medium-term development and research e) 'blue sky' basic research.

Intermediate capabilities imply a certain degree of autonomous effort to adapt, for instance, the productive process to different local conditions or to undertake product quality improvements.

Advanced capabilities refer instead to the ability of substantially change or create new products or processes.

We believe the framework developed by Lall can be useful for this study because it provides a hands-on tool to study the firms' ability to increase the value added of their products and processes. The approach suggested by Lall, and its derivations (Hobday, 1996, Bell and Pavitt, 1995), has been widely adopted (and enriched) in the literature (Figueiredo, 1999, Romijn, 1999, Ariffin, 2000), so its use in this study can add to the body of evidence underpinning technological capability studies.

The following part of this Section presents in detail how this study 'measures' the different levels of complexity of the technological capabilities possessed by the Chinese PV firms in processes and products. The different degrees of complexity (i.e. basic, intermediate and advanced) have been specifically developed to study the PV industry. c-Si technology has been taken as the manufacturing value chain of reference, assuming that the majority of the PV firms to be interviewed in China operate in this technology family[67].

As explained in the methodological part of this chapter (see Sections 3.3.1 and 3.3.2) the 'complexity indicators' have been elaborated on the basis of the insights obtained from both the available literature on technological capability in firms (where the work of Romijn has been particularly useful – Romijn, 1999, Romijn, 2002, Romijn and Albaladejo, 2002) and the information collected during the in-depth interviews with the key PV experts (see Section 3.3.2).

Basic capabilities for process:

The study considers the following indicators as evidence of basic capabilities in the production processes of c-Si wafers, cells or modules:

[67] As previously pointed out, this initial assumption was indeed confirmed after a preliminary search undertaken to identify the firms to be interviewed (see further details provided in section 3.3.3).

- Conducting *routine operations* on a PV turnkey production line for the manufacturing of 'off the shelf' c-Si wafers, cells or modules. Using a turnkey production line *only* in the standard way suggested by the supplier to undertake production at the minimum efficiency level required, is considered by this study as a possible indicator of the inability of the firm to undertake an autonomous effort to modify the production process to adapt it, for instance, to specific local circumstances or market needs.
- Undertaking *only the limited maintenance* necessary to keep basic quality standards.

Basic capabilities for products

Basic capabilities for products are understood by the study as the firm's ability of *manufacturing only standard c-Si modules or other standard PV products.* A standard PV product is understood by this study as one that can be obtained 'off-the-shelf' and for which bespoke solutions are not necessary. In other words, being able to deliver only standard PV products is used by the study as evidence of the lack of more advanced capabilities that would enable the firm to customise its products.

Intermediate capabilities for processes

The study considers as 'intermediate capability for process' the following firm's abilities:

- *Intervening in the standard way in which the production line (for wafer, cell or module production) should be installed.* The user of the production line might need to modify the standard installation requirements (as for the supplier's instructions) to respond to cost savings or specific production requirements. Since these changes requires the firm to be in control of the manufacturing process and to be able to face any possible problem that can arise in the production as a consequence of a non-standard installation of the production line, they are taken by the study as evidence of intermediate capabilities for process.
- *Undertaking small modifications of the standard equipment used in the production line.* An example can illustrate this point. If the standard equipment includes a six-wafer holder, the user might prefer (to satisfy their specific production needs) to have only 4 larger wafers for which a non-

standard four-wafer holder is needed. A firm's ability to undertake such a small modification to otherwise standard equipment is used by this study as evidence of intermediate process capabilities. Moreover this ability shows the firm's technical confidence in addressing further possible issues that might arise from a non-standard use of the equipment (which will as a consequence be no longer covered by the supplier's warranty).

- *Self-constructing small parts of the equipment, such as spare parts, tools,* etc.

These are all important indicators because they testify the ability of making a non-standard use (i.e. different from that suggested by the main supplier) of the production equipment. Moreover, the ability of constructing small equipment or tools to be used to satisfy the firm's specific production needs highlights the firm's problem solving capacity.

A univocal definition of what 'small modification' means is difficult to provide. In several cases in fact even making small spare parts or some of the tools to be used on the production line's equipment (for its maintenance or more efficient use) may take the firm quite a lot of effort and time.

What is important to emphasise here is that although these modifications require the firm to have a good understanding of the productive process and the necessary technical skills (i.e. they require the firm not only to replicate the same productive process that was possibly taught by somebody else, but to add own and conscious effort to add value), they do not require the specific knowledge, the technical background and the search for specific technological solutions needed to modify production processes or even to develop new ones. Putting it differently: these small modifications and small pieces of equipment could be easily accessed outside the firm or replicated by others. If the firms decide to develop them in-house is usually because it costs less than buying them from their suppliers. This is why small modifications and the self-construction of pieces of equipment are considered by this study as intermediate capabilities.

Intermediate capabilities for products

The following firm's abilities are included by this study in this level of technological complexity:

- *Producing non-standard PV products and being able to customise them.* Taking PV modules as an example, this might refer to ad hoc changes to module size, coating and encapsulation[68].
- *Undertaking home designed/modified electric circuits.* For instance, designing protection circuits that can enable the PV module to function even if one or more cells are out of order. This could be particularly relevant for certain module sizes and installation set ups.
- *Ensuring high quality standards and procedures.* Firms' accreditation status with respect to international quality standard[69] is used in this study as an indicator of the more than basic knowledge necessary to guarantee manufacturing and quality procedures conforming to internationally approved standards.

Advanced process capabilities

They include the following capabilities:

- *Undertaking major modifications to the productive process and/or manufacturing entirely new equipment to be used in the production line.* With difference from the small modifications that have been taken as evidence of intermediate capabilities, 'major modifications' are understood by this study as those that require specific advanced technological knowledge to improve an existing production process or to develop new ones. In other words, it is not just about 'doing the same as competitors' in-house to save money on the equipment (as is the case for intermediate process capabilities), but it is about finding specific technological solutions to technological problems aimed at greatly improving or changing the technology.
- *Using (or thinking of and being able to use) alternative and advanced c-Si production technologies.* An illustrative example could be the ability of the firms to grow ribbons of multicristalline Silicon[70].
- *Adopting (also in the form of R&D or acquisitions of assets) alternative production processes belonging to emerging PV technology families* (i.e. not c-Si).

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[68] For details on the c-Si manufacturing process see Chapter 4, Section 4.3.

[69] For instance: IEC, for the performance of the components in PV modules, TUV, to ascertain the safety of the modules, CE, to declare conformity to the relevant EU directives.

[70] See the discussion on PV innovation avenues done in Section 4.4.

Advanced product capabilities

They include:

- The production of greatly modified (existing) products.
- The *use of new materials* (organics, III-V semiconductors, carbon nanotubes, etc.) to produce PV modules.
- *The adoption of alternative module designs* (like, for instance, cells embedded in glass, concentrators, etc) *to accomplish multiple functions*[71].
- *Having patents or licensing own technology to third parties*

Table 2 summarises the complexity indicators we have presented above to understand how advanced is what the PV firms can do in terms of processes and products. The columns set out the main technological capabilities by the two technical functions suggested by Lall (1992) and of interest for this study (i.e. process and products), while the rows set out the main technological capabilities by degree of complexity as measured by the activities from which the technological capability arises.

[71] A transparent module developed by Sharp to be used both for electricity generation and as an architectonic element for building integrated PV, could be taken as an example of a innovative PV product designed to meet more than one function. Developing modules for the cogeneration for both hot water and electricity production, could be another example.

Table 2 'Complexity indicators' for the study of firms' TC in PV manufacturing processes and products

		TECHNICAL FUNCTIONS	
		Product	*Process*
TC COMPLEXITY	*Basic*	Production of standard 'off the shelf' modules/cells/wafers (i.e. inability to provide bespoke solutions)	Routine operation (as for the supplier's instructions) of a turnkey production line Only limited maintenance necessary to keep basic quality standards.
	Intermediate	Production of non-standard PV products and customisation Home designed/modified electric circuits International level of quality standards and procedures	Non-standard installation of the production equipment Small modifications on the production standard equipment Self-construction of small parts of equipment (i.e. tools, spare parts, etc.)
	Advanced	Greatly modified products Use of new Materials (organics, III-V semiconductors, carbon nanotubes, etc.) Alternative designs (i.e. cells embedded in glass, concentrators, etc.) to accomplish multiple functions Patents or licensing own technology	Undertaking major modifications to the productive process and/or manufacturing entirely new equipment to be used in the production line Alternative c-Si production technologies (i.e. growing ribbons of multi crystalline Si) Novel manufacturing methods based on emerging PV technology families (i.e. non c-Si)

Source: Adapted from Lall (1992) and made PV-specific on the basis of the in-depth interviews with the PV experts

Improvement of technological capabilities over time

Borrowing from the available literature (Romijn, 1999, Romijn, 2002) and from the insights obtained during the in-depth interviews with the key PV experts, this study also adopts four other indicators to understand if the PV firms in China have improved their technological capabilities over time. The purpose here is not to rank capabilities according to the level of complexity (as was done previously following Lall's approach) but to assess whether firms have progressed over time. Two points in time are used: what a firm was able to do when it started producing and what it could do when the survey was undertaken in mid 2005.

The four indicators that have been developed are:

1. *Degree of product diversification*

The ability of a firm to manufacture an increasing range of products by entering more complex manufacturing steps along the PV supply chain over time, indicates that the firm in question must have acquired, and be able to master, more advanced technological capabilities. If, as an example, a firm started its activity by assembling solar modules and at the time of the survey is able to produce also solar cells, this will be considered an indicator of increased technological capability over time.

The ability to diversify product range over time has been widely used in the TC literature (Romijn, 1999, Mingsarn, 1986) as an indicator of enhanced technological capabilities in firms. This is an important indicator that goes beyond the understanding of TC per se. It allows in fact also getting insights into the ability to master different productive processes as well as to undertake more complex production planning and organisation.

2. *Increase product technological complexity*

Being able to upgrade the firm's product in a technological sense can also be used as an indicator of capability increase and technological deepening. For example, producing more efficient solar cells or thinner wafers over time can be considered evidence of capability increase because it is assumed that the firm must have acquired more complex skills in order to deliver more complex products.

3. *Improvements in quality and technical performance*

Similarly to the previous two indicators, improvements in quality and technical performance (for instance, an extended service life) suggest technological deepening over time. While, for example, we have already suggested using international quality certifications as an indicator of intermediate process capabilities, the ability of a firm of delivering better quality products over time is used by the study as an indication of technological progress and of the acquisition of more advance technological capabilities through time.

4. Increasing production capacity

Although this is not an indicator of improved technological capabilities per se, it is an important variable because it measures the ability of a firm to attract and mange the necessary resources (i.e. funds, personnel, equipment) to fulfil its strategic productive goals. Limited production capacity, not only greatly restrict the range of possible PV applications that the firm can satisfy[72] but can also impinge a firm's ability to secure feedstock and other production materials (for instance: glass, ethylene-vinyl acetate –EVA– sheets for encapsulation of solar cells, etc.) at discounted prices and hence endanger production.

Moreover, production capacity is closely linked to PV cost reduction, which is one of the innovation goals the PV industry should aim at. A study by NREL EIA/US (http://www.nrel.gov/pv/pv_manufacturing/cost_capacity.html) based on 14 firms with active module manufacturing lines in 2005, shows that for every doubling of production capacity an average 17% drop in direct costs of manufacturing can be achieved. Having hence a limited production capacity limits the firm's possibility of reducing production costs.

D. Assessing TC with respect to competitors

So far the construction of the analytical framework has involved analytical tools for the assessment of a firm's ability to add value in absolute terms, i.e. with respect to the firm itself as an isolated unit.

However, this study also understands innovation as a relative concept that should be studied with respect to international competitors: "Since other firms and nations do not stand still, competitiveness can only be maintained and increased

[72] Certain applications, like for instance utility scale installations that are in the typical order of about 1 MW, requires fairly large production capacity.

through continuous improvement and innovation to continuously increase value-added" (Forbes and Wield, 2002, p. 11).

The complexity of the TC in firms in relative terms (i.e. with respect to competitors) is assessed by this study for two distinct types of effort:

a) Manufacturing products that are commercial state of the art
b) Taking steps to push the technology frontier.

Since, as will be explained in detail in Chapter 6 (see in particular Table 16), the firms in the sample tend to have more than one product line, the assessment of the TC in relative terms will be done only with respect to the main product line, which is, for 7 out of the 8 firms that are in the sample, c-Si module. As specified in Chapter 6, only one firm in the sample has c-Si wafers as its main business. Since it was not possible to collect some of the necessary data relative to this firm's performance, the complexity of this firm's TC with respect to the international wafer producers is not assessed by the study.

i. Producing commercial state of the art products

According to the definition provided at the beginning of this thesis (see Section 1.4), this study has developed four indicators, to understand whether and to what extent commercial state of the art module production is achieved by the Chinese PV firms in the sample. The four indicators are:

1. Capability to deliver same technical standard as competitors
2. Capability to satisfy the largest possible range of customers' demand.
3. Capability to meet demand for utility scale installation.
4. Capability to deliver same qualitative standard as competitors

The ability to produce modules with technical standards similar to the ones of the best competitors is measured in this study by the conversion efficiency[73] of the solar module.

The number of products in range is instead used as the measure of a firm's capability of satisfying the largest possible range of customer's demand.

[73] For more information of the relevance of conversion efficiency for PV module and cell performance see Chapter 4.

The capability of a firm to satisfy not only small residential demand but also utility scale installation, is measure by the firm's production capacity. This refers to the amount of product (measured in MW) that can be produced from the firm's processing facilities. Since, as briefly mentioned before, a typical utility scale installation is of the order of about 1 MW, a firm with a production capacity of only a few MW, would be quite unlikely to be able to satisfy a large demand and to provide for utility scale installations.

The capability to deliver products with qualitative requirements similar to the ones of the competitors is measured by the number of the international certification for safety and quality needed to gain product acceptance and market share in the European and American markets.

The four indicators, and the quantitative data necessary to make them measurable, will be collected for the PV firms under analysis and compared with the 'best practice model' defined by the international competitor that was the market leader for c-Si modules in 2005. As discussed in Chapter 4 (Section 4.5.3 and in particular Table 13) the market leader in 2005 was Sharp.

Once the indicators and their respective measurements have been defined, it is necessary to assign a 'score' against the PV firms in the sample for each of the four indicators of 'commercial state of the art' that we have identified. We suggest using a 1 to 4 scale, where 4 is the 'best practice model' (so, a firm that is assigned a 4 for a certain indicator will be producing commercial state of the art for that specific indicator) and where 1 means 'very far from the production of commercial state of the art'. An example will further clarify the point. A firm that manufactures PV modules with conversion efficiency 50% lower that of Sharp (i.e. the top module producer in 2005) can be given 1 as a score. This means that for that specific indicator (i.e. technical performance) the firm is quite far from delivering commercial state of the art products as those manufactured by the best practice model.

Table 3 summarises the indicators proposed by the study to assess how close the PV firms in China are to produce commercial state of the art products, how these indicators are measured and the criteria used for each indicator to assess the scores.

Table 3 Indicators to study how close the PV firms in China are to producing commercial state of the art products

Indicator	Measurement	Score
Capability to deliver same technical standard as competitors	Module efficiency (%)	<50% of the efficiency of the 'best practice model' = 1 50%<x<60% = 2 60%<x<75% = 3 >75% = 4
Capability to satisfy the largest possible range of customers' demand	No. of products in range	<5 products = 1 <5<x<15 products = 2 <15<x<30 products = 3 >30 products = 4
Capability to deliver same qualitative standard as competitors	No. of international certification for safety and quality standards (i.e. IEC, TUV, CE, UL, etc)	No certification = 1 1 certification = 2 1 certification<x<5 certifications = 3 >5 certifications = 4
Capability to meet demand for utility scale installation.	Production capacity (MW)	<100kW = 1 <100kW<x<10MW = 2 <10MW = 3 >10MW = 4

Source: Author's elaboration

ii. Taking steps to push forward the technology frontier

In order to understand whether firms under analysis are starting to take steps to push the technology frontier, the following indicators are suggested by the study:

1. The commitment towards continuous improvement as measured by the in-house R&D expenditure on the firm's total yearly turnover.
2. The ability to produce new products, as measured by the number of new products a firm can produce in one year.
3. The ability to patent own product or process innovation or to develop other proprietary assets that are unique to the firms and that are not easy to replicate.
4. The ability to take risks and undertake strategic technological or commercial decisions:
   - Ability to move towards those links of the c-Si value chain that have strategic importance in boosting technological innovation and in greatly reducing production costs – e.g. feedstock/wafer production.
   - Investing in additional marketing and distribution channels in mature economies or where the demand is booming.

– Acquiring 'new assets' – for example, moving towards thin-film or any other acquisition of wafer/Silicon feedstock firms.

As in the case of 'commercial state of the art', the PV firms in the sample will be assessed against the best practice model provided by Sharp, which was the market leader in 2005. Table 4 summarises the indicators proposed by the study to assess whether the PV firms in China are taking steps to push the technology frontier, how these indicators are measured and the criteria used for each indicator to assess the scores.

Table 4 Indicators to study whether the PV firms in China are taking steps to push the technology frontier

Indicator	Measurement	Score
Commitment towards continuous improvement	In- house R&D expenditure (% of total firm turnover)	None = 1 <1% = 2 1-10% = 3 >10% = 4
Ability to produce new products	No. of new products during one year preceding the survey or intention to do so in the year following the survey	None = 1 In preparation = 2 Few = 3 Many = 4
Proprietary assets (e.g. patents or other assets that are unique to the firm)	No. of proprietary assets	None = 1 in preparation = 2 1 = 3 >1 = 4
	Moves towards those steps of the c-Si value chain that have strategic importance in boosting technological innovation - i.e.: feedstock/wafer production	None = 1 in preparation = 2 1 = 3 >1 = 4
Ability to take risks and undertake strategic technological or commercial decisions	Investing in additional marketing and distribution channels in mature economies or where the demand is booming	None = 1 Marginal = 2 Significant = 3 Major = 4
	Acquiring 'new assets' - i.e.: move towards other PV technology families, i.e.: thin-film, etc.	None = 1 Marginal = 2 Significant = 3 Major = 4

Source: Author's elaboration

3.2.3 Assessing what influences innovation in the Chinese PV firms (on the determinants of the technological effort)

As explained in the initial part of this chapter (see also Figure 7), to better understand what affects the knowledge accumulation process in the PV firms in China,

we combine two approaches that are suggested by the TC and the IS literatures respectively.

Both approaches contribute to a deeper understanding of innovation but emphasise different aspects of the innovation accumulation process[74]. While the TC uses a microeconomic perspective with a strong focus on firm's internal learning (and its determinants), the IS approach is more concerned about the macroeconomic and systemic perspective. We hence think it is useful to apply them separately in developing the analytical framework and presenting our empirical findings (Chapter 6). In this way we will be possibly able to gain deeper insights into the innovation behaviour of the PV firms under analysis and to explore the extent to which the two approaches can complement each other (these issues will be discussed in details in Chapter 7).

A. Using the TC approach to asses what affects the knowledge accumulation process in firms

Drawing on the TC literature reviewed in Chapter 2, the study explores six main sources of technological capability building in firms. They include both the different learning mechanisms, as they have been reviewed in Section 2.5.4, and what is suggested by the literature to have an effect on learning and on the TC accumulation process. In what follows we briefly recall what the sources of technological capability are[75] and how this study makes them operative and empirically testable.

Learning

Among the potentially important sources of TC, learning plays a crucial role. As explained in Chapter 2, learning in firms is represented not only by formal in-house R&D, but also by informal and incremental problem solving and experimentation that takes place on the shop-floor (like reverse engineering), or by sending staff to training courses or importing/hiring foreign specialists for local workers to learn from.

To explore these issues this thesis will collect information about firms' R&D investment as a percentage of the firm's total turnover, importance of R&D staff relative to total employment and training courses. Moreover, the existence of

[74] See Chapter 2 for the theoretical underpinning and Figure 7 for an overview of the different approaches that have been adopted to operationalise the key concepts of this thesis.

[75] For more theoretical background see Section 2.5.5.

shopfloor-type of experimentation and informal on-the-job training will also be explored.

This information will help in assessing the relevance of the different types of learning in unleashing the technological capabilities of the firms under analysis.

Technology access

As pointed out in Chapter 2, the access and the adoption of technologies developed by other (often foreign) industries could play an important role in enhancing technological capabilities in firms. The thesis will collect information on the source (whether they originate from imports or whether they are sourced domestically) of the production equipment used by the PV firms in China and on whether the firms under study have signed any license agreements.

Endowment

In Chapter 2 we explained how the entrepreneur and the workforce can contribute to the firm's technological capabilities by bringing a certain stock of knowledge and skills into the firm, which they obtained through earlier education and working experience (Romijn & Albaladejo 2002). Proxies used in the literature, and adopted by this study, to evaluate skills and their relevance to the firm's technological capabilities include the numbers of technicians, scientists, engineers and designers present in the firms and the number of years they have possibly worked in the PV or in a closely related sector (for instance, the semiconductor industry). Similarly, the study also assesses the relevance for the enhancement of the firm's technological capabilities of the education gained by the entrepreneur and his previous working experience.

Other firms' internal factors

We already discussed (see chapter 2) the relevance as well as the controversies pertaining to a number of firm's internal factors that showed some relevance to enhance technological capabilities. They are: *firm's age, size and ownership.* This latter aspect seem to play a particularly important role in the Chinese context where a positive correlation has been reported in several studies (Gaulier et al., 2007, Lemoine and Unal-Kesenci, 2004, Rosen, 2003, Gilboy, 2004) between the foreign ownership (also as joint ventures) of domestic firms and their ability to innovate (see the argument put forward in Chapter 2 – Section 2.2.3 - about the Chinese high-tech production as being

'not very Chinese'). These three factors, as measured by the length of the firm's commercial activity, the production capacity in MWp and indeed the firm's ownership, will be explored in the firms in the sample and their possible influence on the firm's innovation assessed.

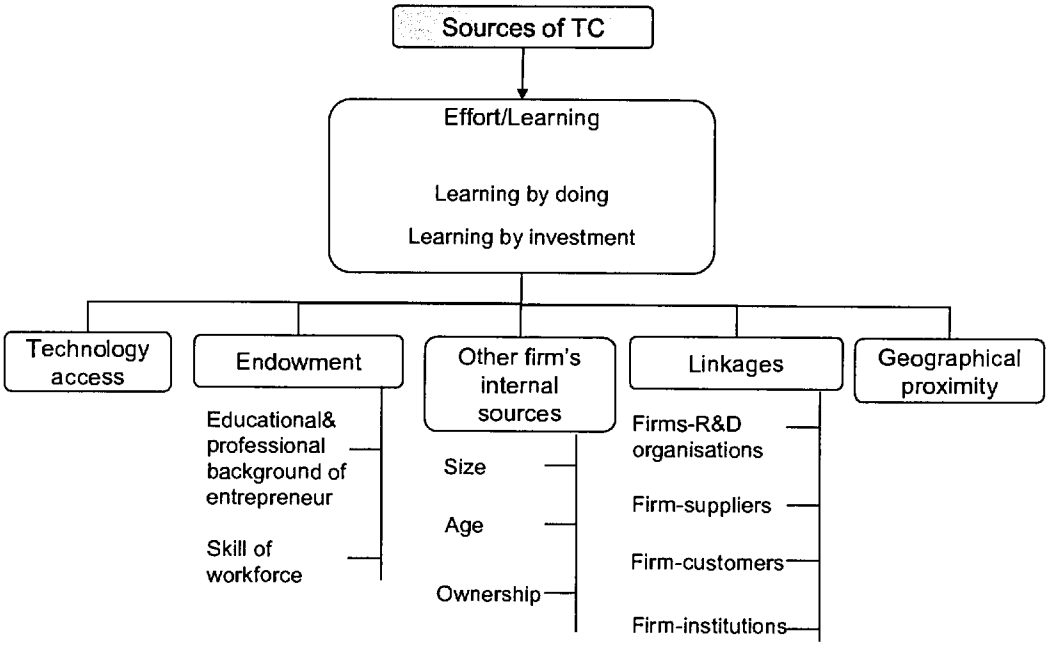
Linkages

Chapter 2 (section 2.5.5) explained as interactions with suppliers, customers, industry associations, research institutes and institutions could provide important external inputs to the learning and the technological accumulation processes of the firms. The study will assess the relevance of these linkages by exploring with how many agents a firm tends to link and which of them seem to be more relevant in the firm's learning process. Moreover the study will also explore what kind of knowledge is shared within these linkages (i.e. general knowledge form basic research, specialised knowledge to address specific problems encountered in the production, new techniques, etc.), but also what are the most important methods of sharing knowledge (for example, hiring scientists and engineers, attending specialised conferences/sectoral exhibitions, informal personal contacts, etc.)

Geographic proximity

As discussed in Chapter 2, the geographical proximity of the firms with the network of suppliers, customers and other organisations with which they interact could have a positive impact on the firms' learning and innovative performance. In exploring the relevance of the different linkages in the firms' innovative behaviour the study will also ask the firms to indicate, whether or not a proximity advantage is attached to the interaction in each network link.

Figure 9 Sources of technological capabilities in firms



Source: Author's elaboration

Figure 9 provides a synthetic view of the sources of technological capabilities as they are described in the literature and as they will be studied in the firms in the sample.

B. Using the IS approach to asses what affects the knowledge accumulation process in firms and how the different influences have changed over time and can drive further the firms' innovation effort

The assessment that this study makes of the factors that influence technological capabilities accumulation and innovation in firms draws also on the IS literature reviewed in Chapter 2 and, more precisely, on the insights coming from the application of a systemic perspective to the study of RET (ICCEPT and E4Tech, 2003, Jacobsson and Bergek, 2004, Jacobsson et al., 2004, Foxon et al., 2005)[76].

This part of the assessment should help in:

1. Identifying the key actors involved in PV development and diffusion in China and their interactions (i.e. the system's structure).
2. Understanding how the PV system performs and what processes (i.e. functions) are more relevant for innovation in firms

[76] See the critical discussion made in Section 2.4.7.

3. Understanding what induces or blocks these processes[77].

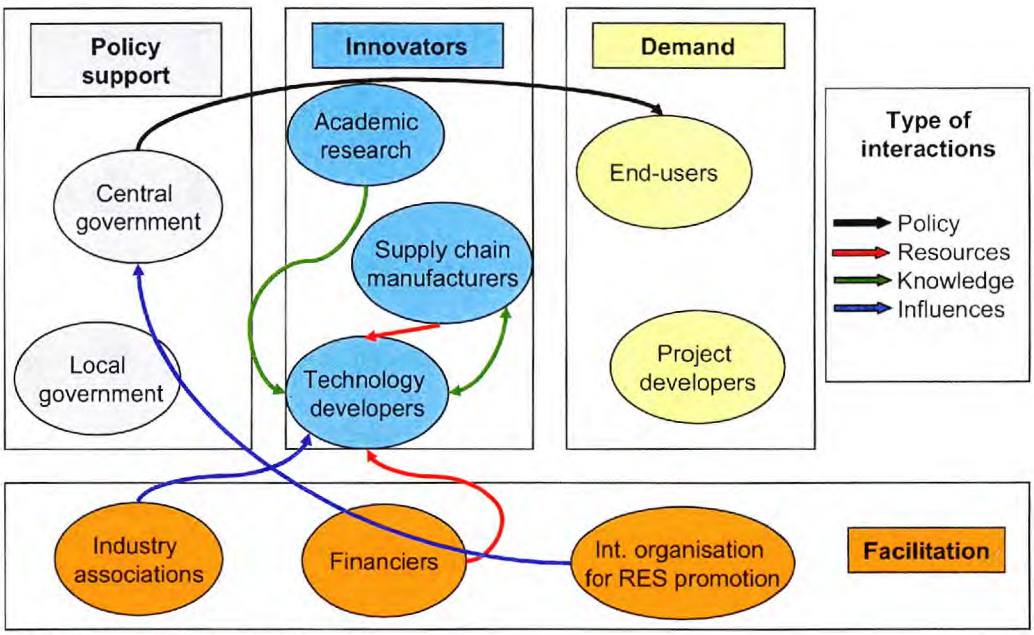
Researchers from Imperial College London have developed a generic framework for analysing IS for RE technologies, where they identify key typologies of actors and interactions (Foxon et al., 2005). They group actors in four main categories: innovators, demand, policy support and facilitators. 'Innovators' include those actors involved in creating or sharing knowledge like technology developers (i.e. firms) or academic researchers. 'Demand' includes actors involved in disseminating and using knowledge, like project developers or end-users. 'Policy support' encompasses actors that set the framework conditions like government departments and regulators. Finally 'facilitators' refers to actors like financial investors, consultants or those who can provide administrative or industrial support (for instance, industry associations and the alike).

In terms of the interactions between the actors, Foxon and colleagues (2005) identify four primary 'flows' between the actors relating to their roles and activities: flows of funding, knowledge, resources and influence. The latter may include, for instance, long term national targets set by the government to encourage a larger deployment of RET on the side of the domestic utilities and consumers.

This conceptualisation allows Foxon and colleagues (2005) to draw generic innovation systems maps where the system's main components and primary flows could be visually represented.

[77] For the theoretical underpinning of these three points see Section 2.4.2

Figure 10 Generic map to study the structure of the Chinese PV innovation system



Source: Adapted from Foxon et al., 2005

Figure 10 draws on Foxon and colleagues' contribution and provides the generic innovation system map that will be used by this study to explore who are the key actors involved in PV development and diffusion in China and what are the interactions among them. The map has been slightly modified with respect to the original template provided by Foxon and colleagues. This was done to take into account some actors, like the local governments or the international organisations involved in promoting RET in China, who resulted potentially relevant during a preliminary search conducted before the fieldwork in China. The generic system map presented in Figure 10 is not meant to be comprehensive, but only a schematic illustration of how such diagrams could be presented.

It is important to say that this map will only be used as a general guideline during data collection. This is so because we are aware that certain actors may simply be missing in the Chinese context, while others (not encompassed by the map) could be present and their role within the system could be different from the one suggested.

However, we believe that the approach of using maps suggested by Foxon and colleagues, when compared to other innovation system studies (see for instance Jacobsson and Bergek, 2004), provides a more practical, yet broad, specification of the types of actors and interactions that are likely to be relevant in RET, PV included.

The usefulness of this map for this study became apparent during the preliminary phases of the research when it was necessary to identify people with whom to conduct the semi-structure interviews and indeed the firm-level survey (see Sections 3.3.3 and 3.3.4 for more details). Guided by the framework provided by the innovation system map, industry associations, research organizations and international organisations present in China to foster the development of RET were contacted not only to secure the necessary information but also to identify further actors in the system.

Once the main elements of the system surrounding PV in China have been identified together with the main interactions that link them together we need to assess how the wider system affects innovation in the PV firms in China. This is because we want to assess the 'system' aspect of innovation and move beyond the description of specific categories of actors and the interactions among them.

From insights coming from the IS literature reviewed in Chapter 2 (Section 2.4.2), we know that a number of activities/functions could be expected to be important in most technological ISs for innovation to emerge and develop. So whether, and the extent to which, these functions affect the innovation behaviour of the PV firms in China should be understood.

The seven functions, as they have been presented in Chapter 2 drawing on Bergek et al. (2008) are:

1. Knowledge development
2. Influence in the direction of search
3. Supply of resources
4. Creation of positive externalities
5. Facilitation of market formation.
6. Stimulus of entrepreneurial experimentation
7. The legitimation of nascent technologies or industries

The study will assess the system's performance, according to the seven functions, and structure over time. This is done to enhance understanding of how the system has evolved and how influences on firm's innovation have changed over time.

Three phases of PV development in China will be taken into account: PV under central planning (1960s-1978); PV in the economic reform period (1978-late 1990s), rapid take off of the domestic PV industry (late 1990s-2005).

3.2.4 Summing up the analytical framework

The analytical framework developed for this study aims at providing guidance for a better understanding of three key areas: how advanced is what PV firms in China can do, how firms have accumulated knowledge and what factors affect the accumulation process. Two approaches have been adopted to develop the analytical framework: those suggested by the TC and the IS literatures. By combining insights coming from the TC literature and interviews with key PV experts[78], we have introduced a number of indicators that will be used to study the maturity of the firms' technological capabilities not only with respect to the technical activities, like process and products, but also in a broader PV industrial, technological and competitive context. In this way the analytical framework extends existing models of technological capability maturity where particular attention has been paid to asses TC in firms with respect to technological activities.

To understand 'how' and 'why' the current level of knowledge achieved by the firms has been achieved, we adopt both the TC and the IS approach, which are applied separately to see what results they can deliver. In Chapter 7 we will explore the complementarity of the two approaches and whether they could be integrated. We use the TC approach to explore the contribution of technological learning in determining the firms' ability to add value. We adopt instead the IS approach to see how the broader innovation system affects the firms' innovative behaviour and their ability to move forward. We have used the insights coming from the IS literature to draw generic innovation maps through which a system structure and performance can be studied.

3.3 The methodology

Four distinct methodologies were used to properly address the different theoretical, analytical and empirical requirements of the study:

1. Desk-based literature review
2. In-depth interviews with key PV experts (mainly based in the UK).
3. Firm-level questionnaire survey executed during fieldwork in China.
4. Semi-structured interviews with key representatives of the Chinese PV research community, policy-makers, international organisations and one

[78] See details in section 3.3.2.

NGO (i.e. the WWF), fostering PV development and diffusion in China (all executed during fieldwork in China).

Table 5 provides an overview of the different methods adopted, why they were adopted (i.e. to retrieve what sort of information) and for the preparation of which chapter they were mainly used.

As illustrated by the Table (third column), the *literature review* and the *in-depth interviews with key PV experts* were the main methods adopted to establish the theoretical underpinning (Chapter 2) and the analytical framework of the thesis (first part of Chapter 3), as well as to enhance understanding of PV technology and of the evolution of the Chinese NIS over time (Chapters 4 and 5).

The *firm-level questionnaire survey* and the *semi-structured interviews* were used for the empirical analysis (Chapter 6). Since the study is interested in understanding if, how and why the Chinese PV firms innovate, a firm-level survey was chosen as the key method to collect the necessary evidence. However, in recognition of the fact that firms innovate as part of a broader innovation system[79] and in order to better understand what drives or hinders their ability to innovate, semi-structured interviews undertaken at the Chinese national level were also necessary to map the different system's constituents, to understand their interactions, to appreciate what affects innovation in firms and how the system evolved over time.

[79] See Chapter 2 for the theoretical motivation of why this is the case and Section 3.2.3 to understand how the system's structure and performance are operationalised in the thesis.

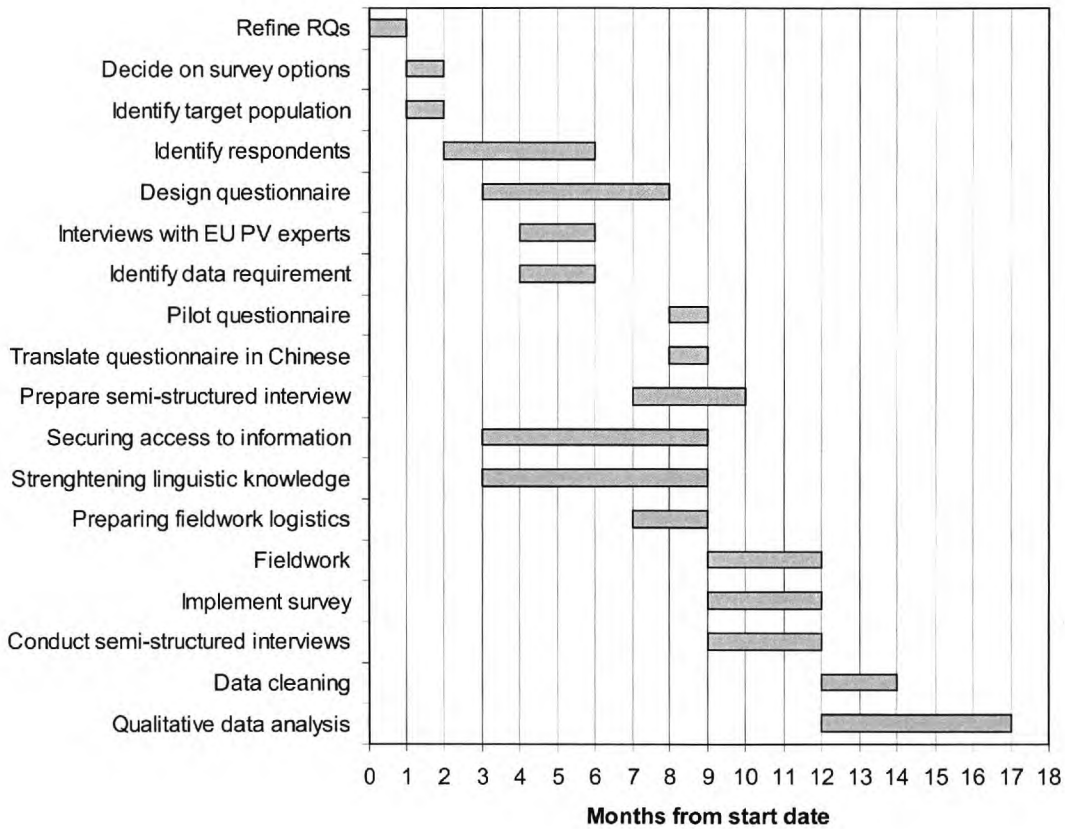
Table 5 Overview of the research methods

Method	Why the method was used	Chapter where the method was mostly used
Desk-based literature review	Understand broad context of the research Establish most suitable theoretical underpinning Develop analytical framework (i.e. how to 'measure' TC in firms, map an IS and identify system components + performance) Take decisions on the type of empirical instrument + types of questions to ask Acquire broad understanding of PV technology, production and market Understand evolution of NIS in China	Ch. 1, 2, 3 4 and 5
In-depth interviews with PV experts (mainly UK-based)	Deepen understanding of PV technological and production issues (i.e. main PV technological innovation avenues; contribution of industrial production to PV innovation, etc.) + obtain an 'insider' point of view on key technological and industrial drivers	Ch. 3 (to inform the analytical framework) and 4
Questionnaire survey with PV firms in China	Collect empirical data on TC in firms, accumulation effort and innovation drivers	Ch. 5 (for the part about PV in China), 6 and 7 (for the discussion)
Semi-structured interviews with other PV stakeholders at the national Chinese level	Identify key actors in the national PV IS in China Understanding of system dynamics + blocking and inducing mechanisms	Ch. 6 and 7 (for the discussion)

The empirical part of the research combined hence two distinct methodologies (i.e. survey and semi-structured interviews) targeting respectively firms and other relevant stakeholders at the national level.

As illustrated by Figure 11, the empirical part of the research, from initial design, to implementation and final analysis, involved several steps (all discussed in the following part of the chapter) that elapsed through a considerable number of months. Allowing enough time for these different activities was important to ensure that the empirical analysis could deliver the most accurate and comprehensive information necessary to answer the research questions. As an example, allowing six months to acquire a Chinese language terminology specific for PV and to improve overall linguistic fluency was crucial to acquire first-hand information (not mediated through the use of an interpreter) and trust among the Chinese firms and the other stakeholders that were interviewed.

Figure 11 Timeline for the empirical part of the research



The remaining part of this Chapter describes in detail the four different methodologies. Sections 3.3.1 and 3.3.2 present the desk-based literature review and the interviews with the key PV experts (and motivate why they have been adopted and useful). Section 3.3.3 presents the design and the implementation, via fieldwork, of the survey. The reasons for choosing a certain survey design versus other possible options are discussed, together with how the target population, the sample and the data requirement of the questionnaire have been decided. The measures taken to get access to the firms, the fieldwork and some practical issues encountered while administering the questionnaire to the firms are also described in this Section. Section 3.3.4 elaborates on the semi-structured interviews.

3.3.1 Desk based literature review

Extensive literature review was adopted to establish the theoretical underpinning of the thesis (i.e. which literary traditions seemed more appropriate to study innovation for RE technologies in firms in developing countries?) as well as its

analytical framework (for instance, how concepts such as the 'measurement' of technological capabilities in firms were operationalised in the literature).

Referring back to the existent studies was also important to develop a broad understanding of PV technology and market and to appreciate what was already known about the evolution of the Chinese innovation system over time.

The development of the questionnaire also required a search of the literature to check whether data and information useful for this study were available from other sources and what sort of questions and questionnaire formats had been used by other people interested in understanding innovation in firms (for example, how long the questionnaire should have been or what questions would have been most suitable to ask and how?).

Additional literature review (mainly via web search) was also used to integrate data and information obtained during the fieldwork in China.

3.3.2 In-depth interviews with PV experts

Considering the specific technological focus of this study, four in-depth interviews with key experts in the solar PV industry and research realms were conducted in the early phases of the study to deepen understanding of the technology. During the interviews, conducted mainly in the UK, experts were asked open-ended questions about their views and insights into key issues like PV R&D trends, future market development, industrial strategies for value-added and competitiveness. The information they provided helped in identifying broad categories of players that had a role in the PV sector (for example, PV cell and module manufacturers; equipment suppliers, etc.) and important aspects to include in the questionnaire, like quality issues, capacity of customising products, etc.

The analytical framework[80] was made PV specific thanks to these interviews, which also informed Chapter 4.

[80] The analytical framework is hence the result of both literature review (see Section 3.3.1) and the interviews with the PV experts.

Table 6 List of PV key experts interviewed

Area of PV expertise	Name	Organisation	Type of input provided
R&D	Dr. M. Mazzer	Imperial College London, Department of Physics (experimental solid state physics)	Insights into current and future PV R&D trends
Industry	Dr. J. Leggett	Solar Century Ltd (UK)	Industry's perspective on future PV market development, drivers and issues pertaining to the downstream of the PV value chain (i.e. PV system development and installation)
Market and industry	Michael Rogol	PHOTON Consulting	Insights into contribution of PV to future electricity-generating capacity worldwide and issues pertaining to the upstream of the PV industry (i.e. Si feedstock and wafer production)
Policy	Angus Scrimgeour	Former Vice President and Chief Financial Officer of MIGA-WB (Multilateral Investment Guarantee Agency)	Insights into renewable energy (PV in particular) support programmes in developing countries

Table 6 provides a list of the people that were interviewed, the organisation they belong to and the type of information they provided. Face to face interviews were conducted with the UK based experts between 2004 and 2005 before leaving for the fieldwork in China. Only one interview with an overseas expert occurred over the phone.

3.3.3 The firm-level questionnaire survey

Why a survey and which survey design is more appropriate for this study?

Several studies on TC and learning mechanisms in firms tend to adopt a case study strategy (Dutrénit, 2000, Figueiredo, 1999, Gao, 2003). This is an ideal methodology when a holistic, in-depth investigation of few selected cases (usually two or three) is needed (Feagin et al., 1991). As an example, Dutrénit (2000) studied the Mexican Vitro Group because she was interested in exploring the specific challenges that firms confront when moving from a minimum essential knowledge base to building strategic capabilities and leadership. It follows that, for her purposes, it was necessary to identify a firm (and indeed to interview more than one person within that firm) that was in that specific stage of development and to thoroughly investigate its behaviour during the transition process. A case study methodology was the best option to fulfil this aim.

In the case of this study, the attention is instead on how complex is what the Chinese firms involved in the PV-specific sector can do and on what factors affect their innovative behaviour. Selecting only one or two cases would have provided only partial insights into our research core problem, in fact: how could we know that the knowledge accumulated by that specific and hypothetically selected firm would have been representative of the entire Chinese PV population of firms[81]?

A *survey based on a semi-structured questionnaire* was then chosen as the most appropriate method to address the research questions specific of this study. In contrast to case studies, surveys are applicable to the entire population (or to a sample) and can allow the identification of comparison groups (Arundel, 2007). Moreover, a semi-structured survey, when compared to a structured one, has the merit of allowing for insights from the respondents and to explore 'why' and 'how' certain activities are performed (Salant and Dillman, 1994, Saunders et al., 2003). Both issues are important for this thesis because they help in understanding the extent to which and how PV firms in China innovate.

Identifying the target population

A careful identification of the target population is important because it determines the interpretation of the results (Arundel, 2007): how far it is possible to generalize from the findings? What are the policy implications that can be derived from them?

A first important ground clearing issue in the selection of the target population was to understand which PV technology families were actually manufactured in China at the time of fieldwork[82] (i.e. only c-Si that has the largest market share in global PV production or also other technology families, like thin-film?).

A preliminary search on the web and in the literature available in late 2004-early 2005 suggested that the majority of the PV firms in China were involved in c-Si technology. For this reason the target population, the analytical framework and the method to collect the data were structured around this technology. However, since this

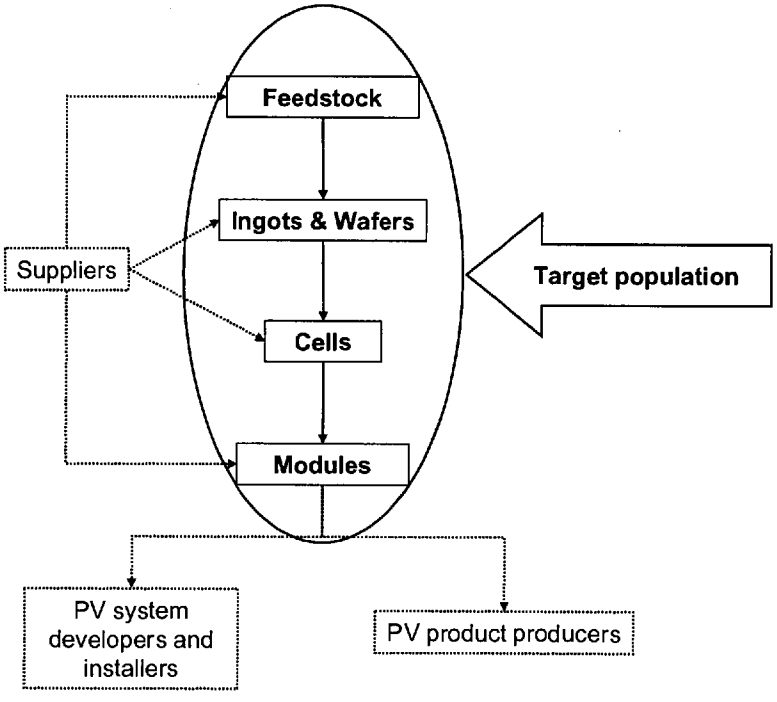
[81] For reasons that are detailed below, it has been impossible to interview all the firms that work in the PV sector in China. However all the care has been taken to select a sample that is representative of the knowledge level that the national industry has accumulated so far, of what has determined it and indeed of what can drive it forward.

[82] The existence of more than one PV technology family at different level of technological and commercial maturity has been introduced in the initial part of this chapter and will be discussed in detail in Chapter 4.

study seeks to assess firms' TC in the broader PV technological context (see Section 3.2.2), specific questions were included in both the firm-level questionnaire and in the semi-structure interviews with other PV stakeholders at the national level to explore whether other technology families with better innovation prospects were also taken into account by the firms (via, for instance, in-house R&D) or by national research institutes or indeed policy makers (via the promotion, for instance, of research programmes specifically aimed at stimulating technological variety).

The *target population of the study comprised hence all the Chinese firms involved in the core manufacturing links of the c-Si value chain.* More in particular, as it is illustrated by Figure 12, it included: Silicon feedstock (also called solar grade Silicon), ingot and wafer, as well as cell and module producers[83].

Figure 12 The target population of the study



Note: Suppliers include: suppliers of materials (for example, glass, EVA sheets, etc.), production equipment suppliers (for example, suppliers of laminators used by the PV module producers) and suppliers of BoS (balance of system) components

Source: Author's elaboration

PV system developers and PV product producers were not included in the target population despite being part of the c-Si value chain. This is not to say that the

[83] For a discussion of the crystalline Silicon manufacturing process and of the different links in the value chain see Section 4.3.

activities performed in these downstream links of the manufacturing chain cannot involve innovative aspects, but considering this study's budget and time constraint, it was decided to focus the analysis on those manufacturing links where the innovation potential and the overall impact on the industry's future development could expected to be greater. As it is discussed at length in Chapter 4 these links are: feedstock, wafer, cell and, to a lesser extent, module production (Kazmerski, 1997).

However, given that this study adopts an innovation system perspective, the roles of other actors along the c-Si value chain (i.e. equipment suppliers, PV system installers and PV product producers) were also explored by both the questionnaire and the semi-structured interviews at the national level. This was done to better comprehend the innovation system dynamics and performance.

Sample

After having determined the target population it was necessary to establish its size. This was a critical issue upon which the decision to perform a census (i.e. to survey the entire target group) or to survey only a part of the target group (via sampling) depended. Although secondary information collected before fieldwork from reports (Dai and Shi, 1999) and academic journals (Yang et al., 2003, Zhu, 2004) seemed to suggest that only 10 firms were producing c-Si feedstock, wafers, cells and modules in China (i.e. suggesting hence a census was possibly feasible), the situation at the beginning of 2005 (immediately before undertaking fieldwork) appeared to be more complex for the following reasons:

- The secondary data available in 2004 were out of date because they described the situation of the domestic PV industry and market in the late 1990s early 2000s.
- Preliminary conversation had in 2004 and early 2005 with Chinese scholars involved in PV R&D unveiled that the domestic industry was on a fast growth track and that several new firms were about to start production while others (among the 10 identified in the literature) were ceasing their activity. This aspect made the lack of up-to-date information (see previous point) even more crucial.
- Some firms had recently changed their names to reflect changes in ownership and management. This caused confusion in understanding whether 'new' firms were really new (i.e. newly established) or 'old' but with a new name.

- From a preliminary search done on the web looking for firms involved in Si feedstock, wafer, cell and module production in China it emerged that possibly many more than 10 firms were operative. However, it was extremely difficult to establish the exact business line of each of them. Although some firms were clearly involved, for instance, in cell production, for others it was impossible to establish, from the little information available on the web, whether they were producing PV modules, PV products or whether they were only installing PV systems.

All these aspects made particularly difficult to have a clear picture of the sampling frame and of the number of firms working in the c-Si industry[84] in China.

The number of module producers was particularly difficult to estimate because firms are highly dispersed across the territory and might easily have a production capacity smaller than 4 MW making their exact counting difficult even for Chinese PV experts[85].

Given the uncertainties explained above, the time available for fieldwork (two months) and the size of the country, it was decided not to perform a census but to take a sample of the population selected on the basis of the information obtained from:

a) Mr Wang Sicheng, general manager of Beijing Jike Energy New Tech. Development Co., who was interviewed at the beginning of the fieldwork (Wang, S., 2005, personal communication, 25 May 2005) and who was (and indeed still is) regarded, with more than twenty years of experience in the sector, as one of the main PV experts in China.
b) An up-to-date report published in Chinese by the NDRC/GEF/World Bank's Renewable Energy Development Program (REDP, 2004), short before undertaking fieldwork.

Both sources of information were the most comprehensive and reliable when the fieldwork took place in May-July 2005. Both the REDP report and Mr. Wang Sicheng believed 26 different companies were active in c-Si wafer, cell and module production

[84] It should be pointed out that although the PV industry has grown rapidly since the late 1990s (see Chapter 4) both in China and in the world, it remains a small industry with a limited number of firms worldwide. This particularly pertains to the upstream of the c-Si value chain where only 7 Si feedstock producers, 10-15 wafer manufacturers and 40-50 cell producers participated in the global c-Si market in 2005 (see Figure 21).

[85] This was confirmed to the author of this study several times during fieldwork.

at the time of the fieldwork. Having access to these two authoritative sources made also clear right from the beginning of the fieldwork that China's production capacity for solar grade Si feedstock was extremely limited in early 2005[86]. For this reason, and also because it was not possible to secure access to these firms, no c-Si feedstock producer have been included in the sample.

A *sample of 8 firms*, out of the 26 mentioned, was selected for the survey. The senior managers or the chief engineers were interviewed and their plants visited during the fieldwork. As suggested by conversations had in China (in particular with Mr Wang Sicheng) these companies were highly representative of Si wafer, cell and module production in China in early 2005[87]. Furthermore these firms, despite being quite far apart (sometime even some thousand kilometres) are all located along the eastern coast of China allowing to make the most of the time and the budget available for the fieldwork. A profile of the firms, their location and activities is provided in Chapter 6.

The questionnaire's design

In designing the questionnaire the first step taken was to ascertain whether the necessary data[88] were available from other sources and to what extent questionnaire's formats adopted by other innovation and technological capabilities studies could be useful for this study. A research report published in 1999 on technological innovation in PV in China (Dai and Shi, 1999) contained some information relevant for this study (for instance, the industrial organisation and structure; the government's role in supporting the industry; the in-house R&D; the manufacturing costs, etc.) but they were out of date and could only be used as an historic reference.

As for the format and for the questions to include in the questionnaire, the most consolidated survey to collect firm-level data on innovation activities is the previously (see Section 2.2.1) mentioned Community Innovation Survey (CIS)[89] (OECD and

[86] See more details in Chapter 5 (section 5.3.3)

[87] Their significance with respect to the total production capacity available in China in 2005 in each manufacturing links together with the proportion they represent on the total of the firms operating in China in the same productive process in 2005, is discussed in Chapter 6 and illustrated in Table 17.

[88] The type of data that have been collected during the survey are discussed in the following section.

[89] CIS is a survey conducted by EU member states that allows the monitoring of Europe's progress in the area of innovation. The survey was originally conducted every four years, but since 2005 has been conducted every two. See the web-site of the Department for Business Enterprise and Regulatory Reform for the UK Innovation Survey (http://www.berr.gov.uk/dius/innovation/innovation-statistics/cis/page10957.html)

Eurostat, 1997). Unfortunately this was only of limited help for this thesis' purposes for the following reasons:

a) The CIS questionnaire focuses on 'innovation activities' but not on innovation 'per se'. Its main purpose is not to study the nature of innovation and of the technological capabilities (i.e. how advanced is what a firm can do) but the activities undertaken by innovative firms (i.e. innovation outputs - in-house R&D expenditure - and inputs; aims of, and constraints to, innovation; collaborative agreements, information sources on, and public support for, innovation). The CIS survey adopts a subjective way to ascertain whether firms innovate by asking them whether they think they innovate with reference to an innovation definition provided at the beginning of the questionnaire[90].

b) The CIS survey, and the OECD's Oslo Manual upon which the data collection method adopted by the survey is based (OECD and Eurostat, 1997), has been designed to understand innovation in firms in mature economies, not in developing ones. This implies that a wide range of innovation-related activities (like reverse engineering, adaptation, etc.) suggested by the literature to be common in developing countries[91] are not explored by the CIS questionnaire. Although the most recent version of the Oslo manual (OECD, 2005) contains an appendix on how to perform innovation surveys in developing countries, the version available at the time of this study's survey did not contain any specific feature for developing countries, making the CIS format and contents of limited use for this study.

c) This study addresses a number of issues pertaining to technological capabilities, learning effort and innovation's drivers specific for solar PV. These specificities are not accounted for by the CIS surveys.

A questionnaire was then developed specifically for this study by adopting insights coming from the literature review done in Chapter 2 and insights provided by the PV experts interviewed (see Section 3.3.2).

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[90] See the CIS3 questionnaire provided at: http://www.berr.gov.uk/dius/innovation/innovation-statistics/cis/page10957.html

[91] See discussion in Section 2.2.

The type of data and information that were collected, the questionnaire's structure and how it was administered to firms during a fieldwork in China are all detailed in the following pages.

Identification of data requirements

As broadly suggested by the analytical framework it was decided to collect both quantitative and qualitative information to better understand if and how PV firms in China innovate.

Table 7 Quantitative information collected by the questionnaire

Concept to be measured	Unit of measurement	Definition
Production capacity	MW	Amount of product that can be produced from the firm's processing facilities[92].
Cell/module conversion efficiency	%	Quantity of radiated light that is converted into useable electric power by a solar cell/module
Wafer/Cell/Module size	Inches or millimetres	Typical width, height, or sometimes area of a solar wafer, cell or module
Product's lifetime	Years	The period during which a cell or a module is capable of operating above a minimum specified capacity or efficiency performance level.
Product's guarantee	Years	The period during which the quality and specifications of a cell or a module are guaranteed
Manufacturing costs	RMB/Wp	Cost of making a product, inclusive of direct costs (e.g. labour, materials) and indirect costs (e.g. overheads).
Best wholesale price of products	RMB/ Wp	Price charged to customers who buy large quantities of PV wafers/cells/modules for resale in smaller quantities to others
In house R&D expenditure	% of sales	Amount spent in R&D activities (e.g. experimental, theoretical or other work aimed at the discovery of new knowledge or the advancement of existing knowledge; searching for applications of that knowledge)[93]

Quantitative data are particularly useful to assess how technologically advanced/innovative Chinese PV firms are in both absolute terms and with respect to the competitors as well as to assess firms' technological improvements over time[94]. Quantitative data that have been collected during the survey include product's specification (cell/module size, efficiency, lifetime and guarantee), plant's production

[92] For example if a company has an end of the year cell capacity of 100MWp, and receives 100MWp of wafer supply together with all the other necessary material supplies, then it could actually produce 100MWp of cells in 12 months.

[93] http://www.hwca.com/publications/tax_treatment_of_rd_expenditure.pdf

[94] See Section 3.2.2

capacity (both current, past and expected), manufacturing costs[95] and amount of R&D expenditure.

Table 7 provides a summary of the quantitative data collected by the questionnaire, how they were defined and how they were measured.

A number of *qualitative information* were also collected to deepen understanding of both the nature of the technological effort underway in firms and of what drives firms to add value[96]. They included:

- *General information about the company*: year of establishment, ownership, location, core business (now and at the start of the firm's activity) and plans for future business expansion.
- *Entrepreneurial history*: prior working experience of the firms' manager/director, number of years spent in the PV sector, educational background and where it was acquired.
- *Production processes*: adoption of turnkey production lines; maintenance of the equipment; modification undertaken on the way in which the production line is installed; modifications on the production line's standard equipment; ability to design/manufacture entirely new equipment; existence of collaboration agreements to undertake modifications or develop new processes.
- *Product manufacturing*: main line of product (current, past and planned); product quality (i.e. products certified by different standard setting bodies); minor adaptations to products to meet market and customers needs; ability to produce entirely new products and/or engaging in products using new materials; patents and/or licences.
- *R&D*: purpose of the R&D activity and existence of protected or licensed intellectual property.
- *Manpower skills*: employees' education and qualification (i.e. existence, and number, of technicians, engineers, scientists or university-trained personnel), training activities undertaken.
- *Export*: role played (if any) by exports on total firm's sales.

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[95] Although all possible effort was made to retrieve information about manufacturing costs and product prices, the firms interviewed did not want to disclose these types of information.

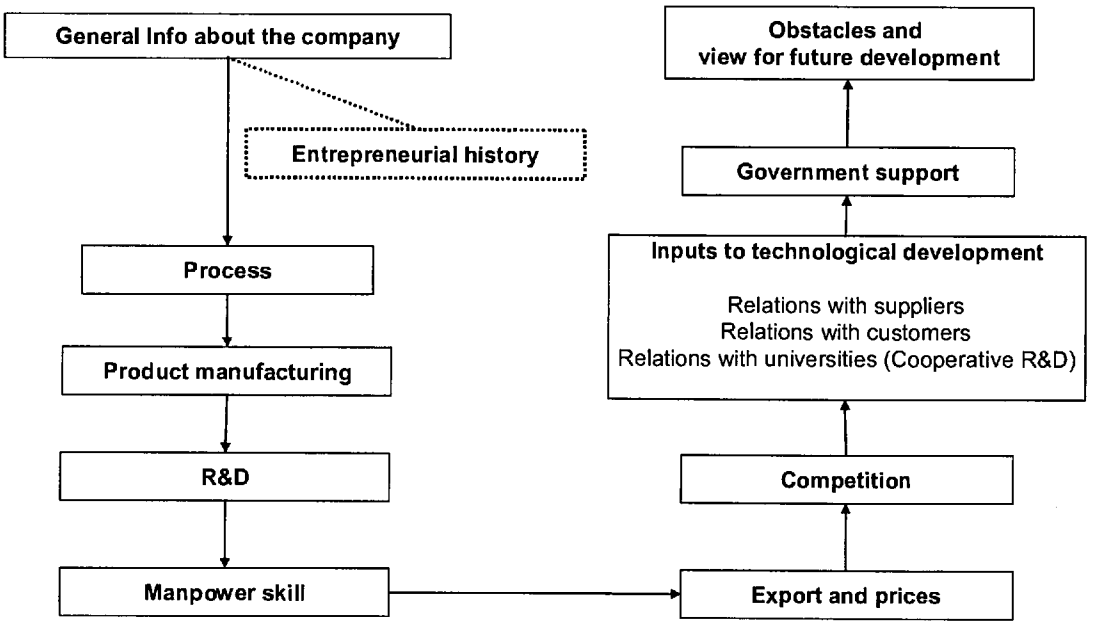
[96] For the theoretical and analytical reasons why it was decided to collect these qualitative information see the theoretical underpinning in Chapter 2 and the initial part of this chapter (sections 3.2.2 and 3.2.3).

- *Competition*: role played by competition now (i.e. when plant visits and interviews took place in May-July 2005) and at the beginning of the firm's activity and key factors that make most significant rivals more competitive against the firm's main products.
- *External inputs to technological development*: relationships with other members of the production and national innovation system (i.e. customers, suppliers and research institutes).
- *Government support*: support received (if any) from the government or other public or private organisations for innovation and RET related activities.
- *Obstacles and view for the future*: impediments and drivers for growth in the firm's main market and product segment during the last twelve months (since interviews took place in mid 2005); most relevant impediments foreseen to firm's growth in the next 12 to 24 months (until mid 2007); expected rate of growth in the firm's main market region over the next 12 months (until mid 2006).

The questionnaire structure

The questionnaire was organised into eleven sections. Each of them explored one of the issues put forward in the qualitative data requirement presented above. While the complete version of the questionnaire, as it was administered to firms during the interviews, is provided in the Appendix 1, its broad structure and the headings of these different sections are illustrated in Figure 13.

Figure 13 Questionnaire structure



Source: Author's elaboration

The questionnaire consisted of both open ended and closed questions with nominal (i.e. 'yes' or 'no') and ordinal scales. This was done to limit subjectivity in the answers but also to create opportunity to explore issues of particular relevance for the study. Figure 14 below presents an example taken from the questionnaire of a nominal question followed by an open one.

Figure 14 Example of one of the questions included in the questionnaire

Can you make minor modifications to your products to address specific requests from customers? (*For example: can you provide modules for very humid weather conditions? Or for very extreme temperatures?)*

Yes ☐ No ☐

a. If yes, please specify

b. If yes, when did you start to customise your products?

The questionnaire was prepared both in English and in Chinese to make sure that all the questions could be fully understood by all the survey respondents.

The questionnaire was piloted to make sure questions were not ambiguous, instructions were clear as well as to eliminate questions that did possibly not yield usable data.

The implementation of the empirical analysis: the fieldwork

The survey and the semi-structured interviews (described in section 3.3.4) were undertaken during a fieldwork in China, which took place from May to July 2005. Figure 15 illustrates the places that were visited during the fieldwork.

Figure 15 Places visited during fieldwork



The questionnaire-based survey was administered in face-to-face interviews with CEOs, senior R&D managers or chief engineers of the firms in the sample[97]. Interviews were conducted in the firm's sites in China and typically lasted for 90 to 120 minutes. Five firms gave also permission to visit their manufacturing facilities and shop-floors. An interview usually began with a brief introduction of the research and of its main objectives. It was also stated at the beginning of the interview that the

[97] Additional information on the interviewees could be find in Chapter 6 (Section 6.2.1)

information provided would have been considered confidential and the names of the firms would not have been disclosed in association with the information provided.

During the interviews the researcher asked the questions appearing in the questionnaire and wrote down the answers and any possible comment made by the respondents.

The fieldwork was preceded by nine-months of intense and careful preparation aimed at designing the survey (see previous discussion), preparing the semi-structured interviews (see section 3.3.4 of this chapter) and securing access to the necessary information (see Figure 11 for a complete timeline of the empirical part of the research). In what follows some of the measures taken to ensure an effective and fruitful data collection are discussed together with some first hand experience of undertaking fieldwork in China.

- Securing access to the source of the information

Obtaining a satisfactory data set depends crucially on getting access to the source of the information, i.e. to the firms that will participate in the survey and to the respondents to the semi-structured interviews. This aspect is even more critical in the case of a country with a vast territory and a distinctive cultural and business environment like China.

Considerable effort and time (see Figure 11) was spent before leaving for fieldwork to create a suitable network upon which to rely once in China. Chinese RE associations and scholars who had recently published about (a) China's PV technology and industry (b) China's technological capabilities and innovation on both international and Chinese journals were identified and contacted. International organisations[98] with strong and far-reaching links with domestic PV firms and local business organisations were also contacted and engaged in the research project. The full list of the institutions contacted before the fieldwork is provided in the Appendix 3.

This pre-fieldwork activity turned out to be crucial to identify respondents to the semi-structured interviews (see Section 3.3.4) and to secure access to the firms in the sample. With difference to survey's implementation adopted in Western countries, where respondents are often approached by letter or by phone directly by the researcher

[98] Such as the UNDP and the GEF, who together launched the Capacity Building for the Rapid Commercialization of Renewable Energy in China (CCRE); or the World Bank (WB), who launched with the GEF and the Chinese Government the Renewable Energy Development Programme (REDP)

in charge of the study (Arundel, 2007), in China being introduced by someone familiar to the firm is crucial to obtain the interview and to establish an informal and cooperative setting for the discussion.

Because the Chinese culture attaches a great importance to interpersonal relationships (called *guanxi* in Chinese) (Xin and Pearce, 1996, Park and Luo, 2001), being introduced by Chinese nationals turned out to be, in the majority of cases, more effective (and successful) than being introduced by foreigners working in China for bilateral or international organisations involved in RET and PV development. This is an important point to emphasise because researchers undertaking fieldwork in a foreign country and who do not speak the local language tend to liaise with people of the same nationality or with other foreigners (usually English speaking) working in the country to obtain access to the information of interest.

- Strengthening linguistic knowledge

An important asset in building up an effective network is the ability to speak the local language and to be familiar with the local culture. Although the author of this thesis is a fluent Mandarin speaker, the PV-specific technological knowledge required by the study presented a significant linguistic challenge. For this reason not only daily classes of Mandarin were taken for six months before departing for China to increase fluency but also a Chinese/English glossary with the main terms used in PV technology and manufacturing processes was prepared by the author.

- Creating an atmosphere conducive to fruitful discussion

It was decided not to tape record the interviews. Although this implied an intensive notes taking activity, it had the merit of putting the interviewee at ease and establishing an informal and effective setting for the discussion.

Showing interest towards the interviewee's work and the firm's activities were also important aspects to engage with the respondents.

Time spent in strengthening the links established with the firms after the completion of the fieldwork was also appreciated. For example, sending greetings to celebrate the Chinese New Year or paying a visit to the firm's booths during international exhibitions were effective ways to show commitment and continuing interest in the firm's activities.

3.3.4 The semi-structured interviews with other Chinese PV stakeholders

The aim of undertaking semi-structured interviews was to collect information pertaining to the broader Chinese PV innovation system, to understand its dynamics and evolution, as well as to appreciate closely related issues such as market prospects, PV policy measures and nation-wide R&D trends. In particular, with the help of semi-structured interviews that targeted key representatives of the PV R&D, policy and co-operation realms, it was possible to investigate the following issues:

a) Who are the main actors in the Chinese PV innovation system
b) What are the systemic interactions between these actors and how these give rise to and drive innovation
c) What has been the evolution of the system over time
d) What is (and indeed was) the performance of the system in terms of the seven functions suggested by the literature and adopted by the analytical framework of this study (i.e. knowledge development, resource mobilisation, etc. See discussion in Section 3.2.3)
e) How the system's performance affected and affects innovation in the PV firms.

Another important purpose of the semi-structured interviews was to obtain a point of view different from the one given by firms, on a number of issues. For example, while it was important to ask firms during the survey what their view was on the market prospects, it was equally relevant to hear the view of the policymakers on the same issue to appreciate (1) if and to what extent their view differed from the one of the firms (2) how the policymakers' position towards the creation of the market could affect the functioning of the system and the firms along their innovation path.

Table 8 List of organisations within which semi-structure interviews were conducted

Type of institution	Area of competence	Name of institution contacted
Academic	Innovation and management	Research Centre for Innovation and Development, Zhejiang University (Hangzhou)
	Solar energy technology and economics	Beijing Solar Energy Research Institute (Beijing)
		Solar Energy Institute of Shanghai Jiaotong University (Shanghai)
	c-Si technology	Department of Physics, Zhejiang University (Hangzhou)
NGO	PV market and development	WWF China
Industry	PV system installation and market applications	Beijing Jike Energy New Tech. Development Co.
		Bejing Corona Science & Technology Co. Ltd
International cooperation	Capability building and bilateral commercial opportunities	REDP - Renewable Energy Development Program (promoted by GEF/WB/NDRC)
		CCRE - Capacity Building for the Rapid Commercialisation of Renewable Energy in China (promoted by UNDP/GEF/ China National Development and Reform Commission
	Environmental protection and energy management[99]	GTZ – German Development Cooperation (Beijing)
Policy/business	Bridge between regulatory authorities, research institutes and industry professionals	CREIA

As anticipated above, people with whom to conduct the semi-structured interviews were selected from the contact list (see the Appendix 3) put together before leaving for fieldwork in May 2005. Once in China these early contacts gave further indications on other suitable people to interview. Table 8 provides the full list of the organisations within which the semi-structured interviews were conducted. As illustrated in the table, key stakeholders were chosen because they had an expertise on a number of innovation and PV related issues in China.

Each interview was conducted face-to-face and the answers transcribed by the interviewer. Questions were not e-mailed in advance to the interviewee because appointments to conduct the interviews were often given with a short notice. The questions that were used as a basis for the semi-structured interviews are provided in the Appendix 4.

[99] Other fields of operation of GTZ (which is an international cooperation enterprise for sustainable development) encompass: Economic Reform and Development of the Market System, Natural Resources Protection and Poverty Alleviation.

3.3.5 Summing up the methods

A combination of four different methods was adopted for this study: desk-based literature review, open-ended interviews with PV experts (mainly) in Europe, a questionnaire survey with PV firms in China and semi-structured interviews at the national Chinese level with key stakeholders involved in PV R&D, market and policy promotion. This was necessary to satisfy the different theoretical, analytical and empirical requirements of the research.

The empirical data of the study was obtained via a questionnaire survey administered to a selected sample of 8 c-Si wafer, cell and module producers in China. These data were complemented with the semi-structured interviews, which contributed in enhancing understanding of the dynamics and evolution of the PV innovation system in China.

3.4 Conclusions

This chapter has introduced both the analytical framework used by this study to understand the nature and the determinants of the technological effort underway in the PV firms in China and the method used to collect the necessary data. We have explained that the analytical framework was developed by using a combination of approaches. It adopts the insights coming from the TC literature to develop indicators of the complexity of firm-level capabilities with respect to the processes and products firms undertake as well as to the broader technological, industrial and competitive environment.

The framework adopts instead two separate approaches in order to better understand how the technological capability process occurs and what determines it. The insights coming from the TC literature have been used to explore the learning mechanisms that are at the basis of the technological accumulation in firms and their determinants. The IS literature has been used to develop a generic model of the innovation system through which to explore the system's structure, performance and the way in which it affects innovation in firms.

In terms of the empirical methods, the study adopts four distinct methodologies to address the different theoretical, analytical and empirical requirement of the study. A firm-level survey based on a questionnaire that has been administered to a selected

sample of PV firms during fieldwork in China, has been adopted as the main method to collect the necessary data. Semi-structured interviews undertaken at the national level with other stakeholders of the PV sector in China have provided further results necessary to understand firms' innovative behaviour also from an innovation system point of view.

The two Chapters that follow (4 and 5) integrate what has been discussed in this Chapter by presenting specific aspects of PV technology and market (Chapter 4), as well as issues pertaining to the evolution of the Chinese innovation system over time.

NOTE: for those readers interested in knowing how you eat the dish pictured at the beginning of this chapter (Picture 4), the dish is called *guoqiao mixian* (crossing the bridge rice noodles) and is a speciality of Kunming (Yunnan province). Diners are first given a plate (like the one in the picture) of thinly sliced raw chicken, pork, fish, bean sprouts, chives, egg and bean curd. The waiter will then serve a piping hot bowl of chicken broth and rice noodles. Put the raw meat in the broth first, then the vegetables, the fish, the remaining ingredients and lastly the noodles. Keep stirring the soup until the meat changes colour and is cooked. Your bowl of delicious noodles is now ready!

As it is often the case in the long Chinese culinary tradition, there is a legend behind this popular Yunnan dish. "Guoqiao mixian came about when a young scholar shut himself away to prepare for the imperial examination. His loving wife had to travel and cross a bridge to bring him his daily meal. Frequently, his meal went cold by the time it reached him. One day, quite by chance, his wife discovered a bowl of chicken soup could be kept warm by putting a layer of oil on top. From then on, she would serve the noodles and meat slices with the oil-layered soup and the young scholar could enjoy a warm meal every day. When the scholar did well in the examination, he credited his success to his wife's noodles and the noodle dish gained in popularity". By Tan Xiaomi at: http://paper.sznews.com/szdaily/20070321/ca2615183.htm

4 PV TECHNOLOGY AND MARKET DEVELOPMENT

Picture 5 A demonstrative PV installation



Source: Picture taken by the author at the 21st European Photovoltaic Solar Energy Conference and Exhibition, Dresden (Germany), September 2006

4.1 Introduction

This Chapter, together with the following China-specific chapter, complements the analytical framework discussed in Chapter 3 and is required to interpret the results presented in Chapter 6.

The term 'PV' groups several technology families that have reached different levels of technological maturity and market penetration and consequently different scales of potential innovation. Any assessment of the innovation behaviour of the firms involved in the solar PV industry has to be based on a thorough understanding of the technology and of what innovation means in this specific technological context.

The first part of the Chapter (Section 4.2) explains how sunlight can be turned into electricity and introduces the available PV technology families (Sections 4.2.1 to 4.2.3). Section 4.3 is devoted to the manufacturing process of crystalline Silicon (c-Si) technology, the most common PV technology family. Although several PV reviews can be found in the literature (Boyle, 1996, Archer, 2001, Luque and Hegedus, 2003, Bubenzer and Luther, 2003), the purpose here is to highlight only those aspects that are relevant for this study. It will be explained, for instance, how different links along the

c-Si value chain present different degrees of technological complexity and the implications of this for our understanding of the firms' ability to add value and innovate.

Section 4.4 explains what 'innovating' means in the context of PV and explores the possible innovation options. Section 4.5 examines PV market developments, i.e. trends in installed capacity and applications, together with production capacity and main industrial players. Section 4.6 considers the policies that have been promoted in different countries to support PV and Section 4.7 summarises the main points discussed in this chapter.

Before proceeding with the discussion, it is important to emphasise that the information contained in this chapter, which synthesises insights coming from the literature and the interviews with the PV experts (see Section 3.3.2), dates back to 2005. This is done to provide an overview of the state of the PV technology and market at the time when the Chinese PV firms were interviewed (mid 2005). Significant progress has been made since 2005, both in terms of PV installed capacity, industry development and indeed technological advancement[100]. Despite their significance for the future growth of PV, these developments are not discussed in this chapter, which only aims at providing information useful to understand and assess the innovativeness of the Chinese PV industry in 2005.

4.2 PV technology

4.2.1 How does a solar cell work?

The term 'photovoltaic' is composed of the word 'photo', meaning light, and 'volt', meaning electricity (Boyle, 1996). It refers to a family of technologies that convert sunlight directly into electricity.

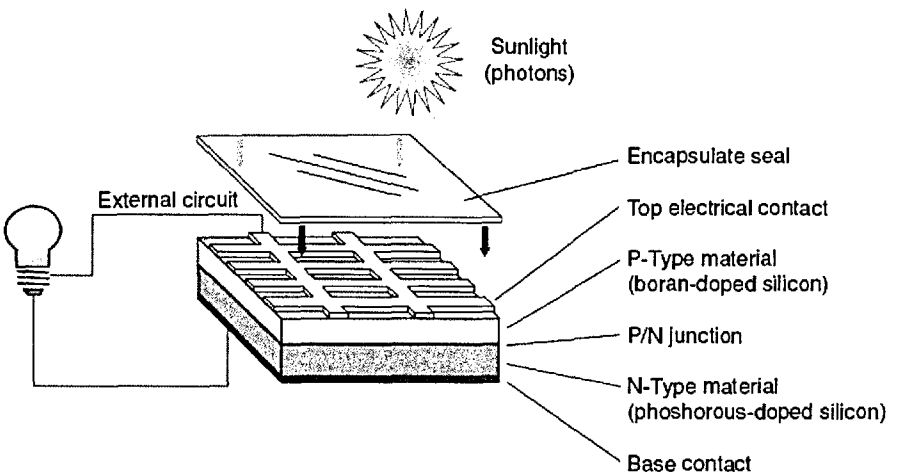
Solar cells, which are the basic element of a PV system, consist of at least two layers of a semiconducting material[101] that have been intentionally contaminated ('doped') with chemical elements to create a surplus of either positive charge carriers

[100] Some types of thin film PV modules like CIS and CdTe, that were in a pre-commercial phase in 2005, are now rapidly gaining market shares.

[101] Semiconductors are materials whose electrical properties lie between those of conductors (such as copper and aluminium) and insulators (such as glass and rubber). A semiconductor substance can conduct electricity under some conditions but not others, making it a good medium for the control of electrical current.

(p-conducting layer) or negative charge carriers (n-conducting layer) from the semiconductor material (Boyle, 1996). When sunlight is absorbed by the semiconductor, the electric field across the junction between these two layers causes electricity to flow, generating a current. The greater the intensity of the light, the greater the flow of electricity. Figure 16 illustrates the basic functioning of a solar cell.

Figure 16 Basic solar cell functioning



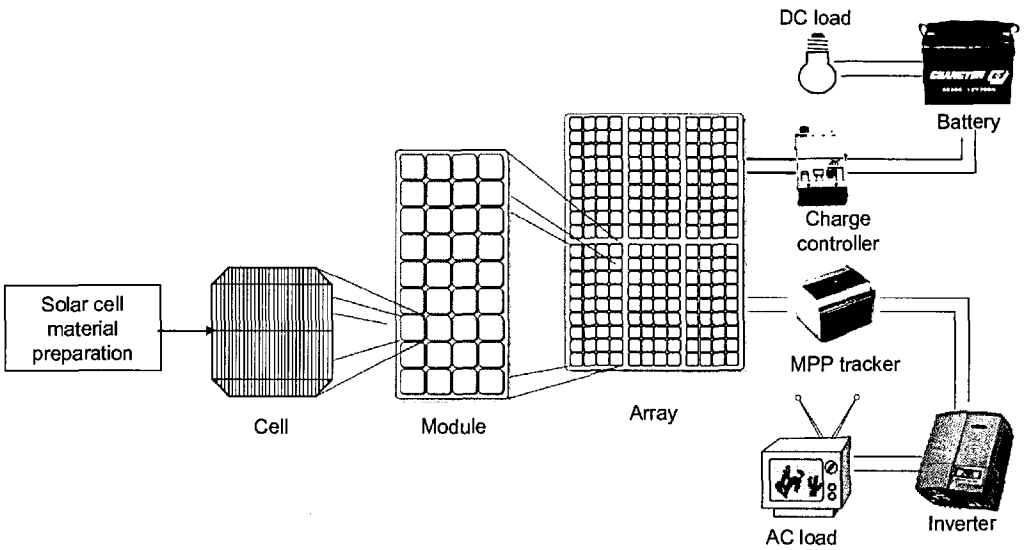
Source: State Energy Conservation Office (SECO), 2005

The quantity of the radiated light that is converted into useable electric power by a solar cell is called the cell's efficiency. Power *conversion efficiency* is the single most important indicator of a cell's performance. As discussed in Section 4.4, one of the key innovation goals of the PV industry is to improve solar cell efficiencies while holding down the production cost per cell.

4.2.2 From the cell to the PV system

Figure 17 below illustrates the main components in the typical PV system where the material preparation (dominated by two main technologies, as explained in section 4.2.3) is followed by the cell fabrication.

Figure 17 The PV system



Source: Adapted and integrated by the author from SECO, 2005

The *cell* is the basic building block of a PV system. Since the power of a single cell is small (usually 1 or 2 watts), large numbers of cells need to be electrically connected to form a single unit called a *module*. Modules can be further connected to form an array. The number of modules needed in an array depends on the amount of output needed. The module (or the array) is then completed with a number of components that enable the PV-generated electricity to be properly applied to the load. Taken together these components are called the *balance of system* (BoS). They may, for instance, include a battery, which is necessary to store and use electricity in cloudy weather conditions or at night, as well as charge controllers, used for small loads (usually in off-grid applications) to protect the battery from overcharging and also excessive discharging.

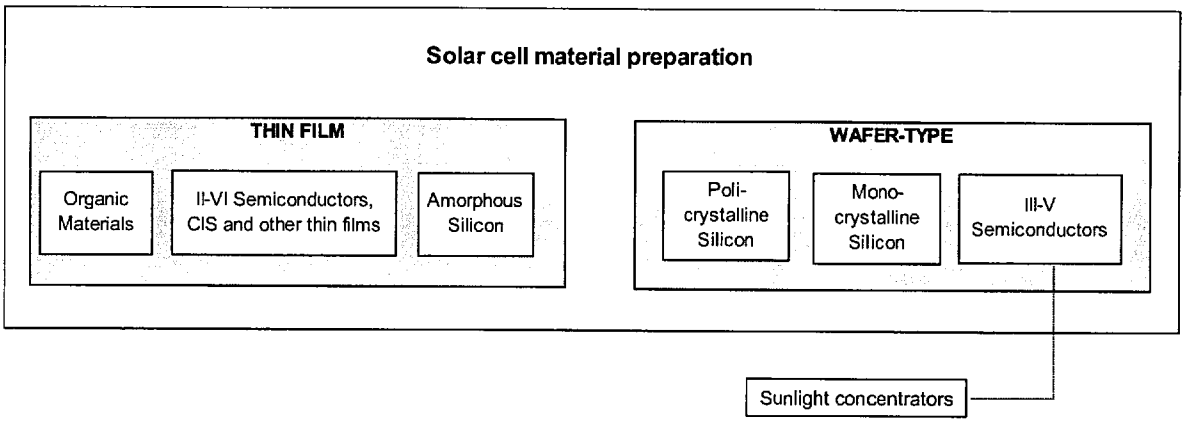
Electron control devices like maximum power point (MPP) trackers and inverters are also components of the BoS and are used to extract maximum power from the module and to convert DC power (produced by the PV module) to AC (that is used in the electric grid).

4.2.3 PV technology families

Solar cells are made of different semiconductor materials and are usually grouped in two big technology families according to the way in which the material is prepared (see Figure 18). It is possible to distinguish between:

1. Wafer-based solar cells
2. Thin-film solar cells

Figure 18 Different types of solar cells



Source: Mazzer, M., personal communication, November 24, 2004

The main difference between the two technology families is the substrate on which the solar cell is deposited and/or fabricated. Wafer-based solar cells are based on wafers of crystalline material cut from an ingot or from grown ribbons, while thin-film cells are deposited in thin layers directly onto cheap substrates like glass, plastic or steel. As explained below, the second technique allows consistent cost reductions in terms of material use

Wafer-based solar cells

Silicon (Si) is the most widely used semiconductor material in wafer-based solar cells. 93% of the solar cells that were sold on the market in 2005 were based on c-Si wafers (Greenpeace and EPIA, 2006). There are two main reasons behind the popularity of the use of this semiconductor material. First, Si is a widely available material[102] with a well-balanced set of electronic, physical and chemical properties (Green, 2000). Second, Si solar cells use the same well established knowledge base that has been developed for the semiconductor industry.

There are two types of c-Si cells: single crystal Silicon (sc-Si) and multicrystalline Silicon (mc-Si). While sc-Si cells are fabricated by slicing wafers from

[102] Silicon is most commonly found in quartz and sand and it is the second most abundant element in the earth's crust.

a single crystal ingot, mc-Si cells derive from solidifying molten Si in a container (Green, 2000)[103]. Although sc-Si cells are the most efficient cell type currently available, mc-Si cells allow a better use of the expensive Si because they can reduce waste.

Maximum efficiencies between 20.3% and 24.7% have been recorded in laboratory for cells made with mc- and sc-Si respectively (Green et al., 2006). However, commercial modules have lower efficiencies, which range between 12% and 16% for mc-Si and between 16% and 18% for sc-Si (http://photovoltaics.sandia.gov/docs/Database.htm). Table 9 compares the efficiencies of laboratory c-Si cells and commercial modules with other competing cell technologies (all presented in the following part of this section).

Table 9 Best conversion efficiency of various solar cells developed in laboratory and typical commercial module efficiency

PV technology family	Cell type	Typical commercial module efficiency (%)	Maximum recorded laboratory efficiency (%)	Area (cm^2)
Wafer-based	sc-Si	16-18	24.7 ± 0.5	4.00
	mc-Si	12-16	20.3 ± 0.5	1.002
Thin film	a-Si	5-7	9.5 ± 0.3	1.070
	CdTe	6-7	16.5± 0.5	1.032
	CIGS	9-10*	18.4 ± 0.5	1.04

Source: for commercial module efficiency (http://photovoltaics.sandia.gov/docs/Database.htm); for laboratory efficiency: Green et al., 2006

*** (http://www.semiconductor-today.com/news_items/2008/MAY/HELIOVOLT_140508.htm)**

While the main technological advantage of c-Si cells is certainly the high efficiency that they permit, the main disadvantage is the high cost of the material which has to be used in large quantities to obtain the wafer[104]. As will be explained in Section 4.4, the cost of the wafer is a substantial part of the total cost of this solar cell technology family and it constrains its further development. Moreover the process of refining Si to very high purity is particularly expensive.

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[103] The manufacturing process from the transformation of the Si raw material to the final module is explained in Section 4.3.

[104] Silicon is a poor light absorber compared to other semiconductor materials such as GaAs, CIGS or CdTe. A 50 to 100μm wafer thickness is needed to absorb a significant fraction of the incident light, while only 2 or 3μm of GaAs or CIGS would be sufficient.

Thin-film solar cells

As briefly explained above, the main distinctive feature of thin-film technology is the substrate on which the cells are grown. This is no longer a Si wafer but can rely on much cheaper materials such as glass, plastic or certain types of ceramic. The substrates are then coated and patterned with thin layers of semiconductor materials, such as Si (that can be used in much smaller quantities compared to the wafer-based technique), amorphous Silicon (a-Si) or elements of group II-VI of the periodic table such as copper-indium-gallium-diselenide (CIGS) and Cadmium Telluride (CdTe) (see Figure 18).

Solar cells belonging to this generation are highly efficient in material utilisation, and hence potentially cheaper to produce than wafer-based cells, but enjoy lower efficiencies (in the range of 5-10% when commercial modules are considered. See Table 9). Moreover their manufacturability could be constrained by the availability of some of the semiconductor materials such as indium (Green, 2000).

The market share of thin film technology was 7% in 2005, but is expected to increase in the future (Greenpeace and EPIA, 2006). Among the three thin-film cells currently available on the market (CIGS, CdTe and a-Si), a-Si are the most widespread in terms of production capacity and installation (4% of the total market in 2005 as summarised by Table 10) (Greenpeace and EPIA, 2006).

Other cell-types

There are also other types of cells that are currently at the pre-commercial stage or in their R&D infancy.

a) Sunlight concentrators. The solar cells used in this technology are wafer-based (using III-V elements of the periodic table, mainly GaAs) and are designed to operate with concentrated sunlight. These cells focus light from a large area onto a small area of PV material using an optical concentrator, such as a Fresnel lens (Boyle, 1996). The main idea is to use very little of the expensive semiconductor PV material (1/300 to 1/500 of the module area) while collecting as much sunlight as possible. III-V elements of the periodic table can allow achieving high efficiencies exceeding 30%.

Solar cells under concentration have two main drawbacks: they cannot make use of diffuse sunlight and must always be directed towards the sun with a tracking system.

This technology is at a pre-commercial stage (Barnham et al., 2006), but shows promising development prospects especially in large size utility applications.

b) Flexible cells based on organic materials. Flexible solar cells are still at a R&D stage and can be created adopting a similar production process to thin-film, by depositing carbon-based (organic) material in nanometre-thick layers. The advantages of this technique are flexibility and light weight. This opens the range of possible applications, making flexible solar cells particularly appropriate for building integration (roof tiles) or for niche applications, such as battery chargers for laptops and digital cameras (ScienceDaily, 2007).

One of the main disadvantages of this technology is that the cells produced have limited efficiency, which is currently only about 20% of that of c-Si.

Table 10 provides a summary of the main PV technology families and of the advantages and drawbacks they present.

Table 10 Overview of main PV technology families

Solar cell main tech. families		Technology market share	Technological Pros	Technological Cons
Wafer type (or c-Si)		93%	Stable solar cells and good module efficiencies (12-18%). Process technology developed from the knowledge base of the microelectronics industry	High costs of the semiconductor (c-Si wafers make up 40-50% of the cost of a finished module)
Thin film	a-Si	4%	Use of relatively cheap materials, such as amorphous Silicon (a-Si) or copper indium (gallium) diselenide.	Technological complexity. Low efficiency (production modules range from 5 to 10%). Some thin film materials have shown degradation of performance over time and stabilised efficiencies can be 20-30% lower than initial values.
	CdTe	2%		
	CIGS	1%		
Sunlight concentrators		Pre-commercial	Limited use of the expensive semiconducting material while collecting as much sunlight as possible	Modules cannot make use of diffuse sunlight. Need to use a sun tracking system
Flexible cells based on organic materials		R&D	Flexibility and light weight Particularly appropriate in building integrated applications	Low efficiencies

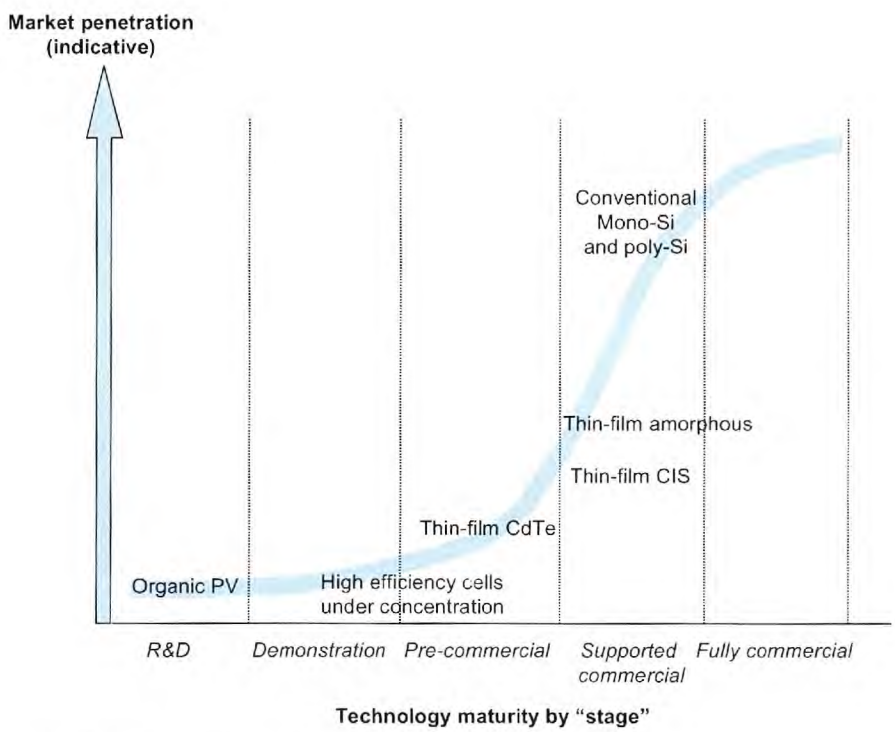
Source: Greenpeace and EPIA, 2006; SolarBuzz, 2008

Maturity and market penetration of available PV technology families

As mentioned before, the various PV technologies differ greatly in terms of technological maturity and market diffusion. While several technologies are at the

R&D or pre-commercial stage, others are sold on the market[105]. Figure 19 employs a modified version of the so-called S-shaped curve of technology development and diffusion (Tidd et al., 2005) to illustrate the different degrees of PV technological and commercial maturity. A typical diffusion curve plots the market penetration of a new product over time. Initially the rate of adoption is low; it follows a rapid take off and diffusion phase followed by a gradual slow down as the market reaches saturation. Here, following the approach adopted by scholars at the Imperial College Centre for Energy Policy and Technology (ICCEPT and E4Tech, 2003), market penetration is plotted against technological maturity. For the different PV technology families presented above market penetration increases as they become more technologically mature. For this reason c-Si technologies are plotted towards the end of the S-curve because they are approaching both commercial and technological maturity[106].

Figure 19 The technological maturity of different PV technology families relative to market penetration



Source: Adapted from ICCEPT and E4Tech, 2003.

[105] The division of technological maturity in stages has been theoretically introduced in Chapter 2 (section 2.4.1) and further discussed in Chapter 3.

[106] The Figure is only illustrative on both axis and do not intend to provide quantitative information on the future rate of adoption of technologies that are now in their infancy

Although c-Si solar cells currently dominate the market there is no guarantee that they will continue to do so. On the contrary, it is expected that they will eventually give way to other technologies that are currently in their infancy (and are plotted at the beginning of the S-curve in Figure 19) and can offer larger prospective cost reductions (Green, 2000). While these aspects, which pertain to innovation, will be discussed in more detail in Section 4.4, it is important here to emphasise that the future PV technological scenario is uncertain. This has implications for both the firms that operate in the PV industry and for the policies that are promoted by different governments to support a larger diffusion of PV.

Firms currently involved in c-Si production may well be effective in advancing the frontier of this now dominant PV technology family, but they operate in a technology that has nearly reached technological maturity and will eventually be replaced by more cost effective options.

Moreover, since the recent PV development crucially depends upon policies promoted by different governments to support installed capacity, further policy measures should ideally take into account the existence of competing PV technology families and provide incentives to both the options that are now in the early stages of development as well as to those that are approaching full commercial maturity and can provide immediate solutions.

4.3 Manufacturing process for crystalline Silicon technology

This section presents an overview of the c-Si production process. This is useful to appreciate the extent to which the firms selected for the study add value and enhance their technological capabilities[107] . Moreover the section is important to show how the different productive links along the c-Si value chain present different technological challenges and have different potentials towards cost reduction, which is the ultimate goal of the PV innovation effort (see Section 4.4).

C-Si is processed in separate steps, leading to different industries, each dependent on each other. Some firms specialise in individual links of the value chain

[107] For a presentation of the results see Chapter 6 and Chapter 7 for their discussion.

(like wafer production) while others operate in more than one link (for instance, cell and module production).

Figure 20 shows the different links of the c-Si value chain, which is characterised by:

1. *Production of solar grade Silicon.*

   This consists of the extraction of quartz sand (i.e. Silicon) from natural deposits. This raw material (often referred to as 'Si feedstock') is then purified in a metallurgical process, where the sand is melted and contamination is removed.

2. *Production of Silicon ingot / wafer.*

   This step involves placing a Si seed crystal (refined from the solar grade Si obtained in step 1) into a molten sand bath and growing it into a Si ingot (called 'Czochralski's method'). The ingot is then cut into wafers of around 260-300μm thick.

3. *Production of cells*

   In this link of the value chain, wafers are doped to create an electric field and metal contacts are added to the cell to tap the electric charge. Moreover an anti-reflection coating is applied to the cell's surface to increase the amount of light reaching the active region of the cell.

4. *Module assembly.*

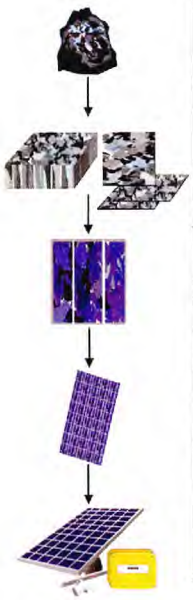
   The individual cells are assembled into strings. They are then laminated between a piece of tempered glass and a polymeric backing sheet (like ethylene vinyl acetate - EVA)[108]. Frames are then added

5. *System integration and installation.*

   In this step the different components of the BoS are added, according to the type of final application, and the completed system is installed.

[108] Solar module lamination is done for protection purposes (from mechanical damages) as well as to provide mechanical rigidity to support the brittle cells and their flexible interconnections (Luther et al., 2003).

Figure 20 The manufacturing processes along the c-Si value chain

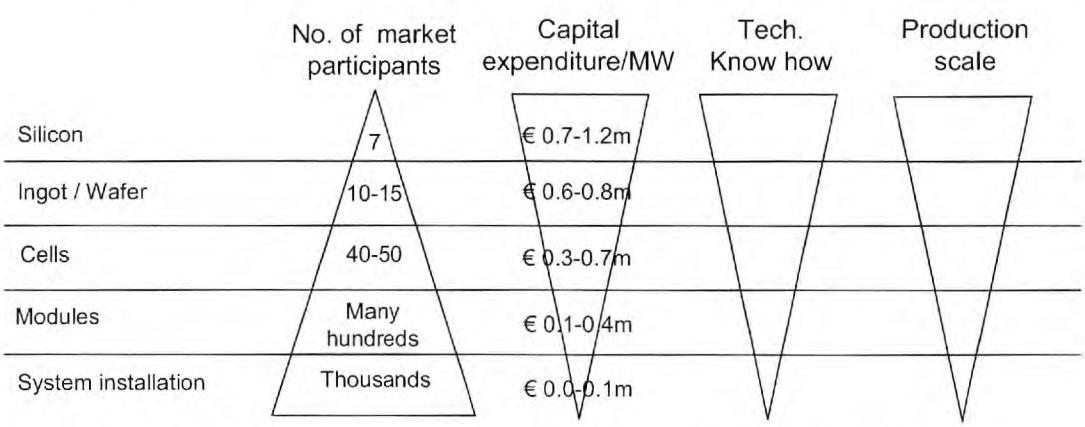


Process steps	Description
Solar grade silicon production	• Raw material extraction and refining • Processing to solar grade material
Ingot and wafer production	• Moulding of mc-Si and sc-Si ingots • Ingot cutting into wafers
Cell production	• Doping of wafers • Surface processing • Application of contacts and anti-reflex layers
Module assembly	• Connection of solar cells into strings • Module lamination and framing
PV system installation	• Application of BoS components • Installation of the completed PV system

Source: Adapted from Grøner, 2007

The c-Si value chain can be represented as a pyramid (see Figure 21) with only a limited number of solar grade Si suppliers at the top and a very large number of module assemblers and system installers at the bottom (Kluftinger et al., 2005).

Figure 21 Knowledge intensity of the different links of the c-Si value chain and barriers of entry



Note: data on the number of market participants and capital expenditure are for 2004

Source: adapted from Kluftinger et al., 2005

Segments in the upper part of the pyramid (in particular Si feedstock and ingot/wafer production) are capital and knowledge intensive and require large production volumes to be competitive. These factors constitute high barriers of entry

into the industry and explain why few firms in the world can transform quartz into solar grade Si or undertake ingot and wafer production.

In moving down the value chain (i.e. towards module production and PV system installation) barriers of entry become lower because the capital and the technological know how required are less demanding. Putting it differently: module assembly is technologically less complex than solar wafer or cell manufacturing and production capacity can be expanded in a relatively short time due to the limited capital intensity of the process.

These are all important aspects to bear in mind in assessing if and how the Chinese firms are able to innovate in this industry. Perspectives emerging from the literature (see among others Rosen, 2003, Steinfeld, 2004) would suggest that the Chinese firms are concentrated in those productive segments that require less know how and capital (i.e. module assembly and PV system installation)[109]. Moreover, segments in the lower part of the value chain tend to be more locally focused (i.e. usually PV system installers tend to serve the local market) and this seems to be more compatible with the prevailing view of a domestic industry that adapt imported foreign technology to specific national circumstances and requirements. Should the Chinese firms be involved also in the upstream segments of the value chain this would be a first broad indication that they might well have the necessary know how to handle processes more complex than module assembly or system installation. Moreover, trying to add value in wafer manufacturing has different implications for the technology's further development than adding value in module assembly. Since the bulk of the c-Si technology cost is due to the cell's material (see Table 11 in the following section) and the industrial effort should be directed towards reducing the production cost, a module manufacturer can contribute little to PV innovation because the most critical component of the system in terms of cost efficiency ratio is the cell.

4.4 PV innovation avenues

PV is an emerging industry and, in pursuit of profits its goal should be to become cost competitive with other technologies for electricity generation as quickly as possible and without the many governmental schemes that currently sustain its market

[109] See also the discussion in Chapter 2 (Section 2.2.3) about how China innovativeness is commonly perceived in the literature.

growth (see section 4.6). Therefore innovating in PV essentially means *reducing production costs while maintaining or enhancing useful cell efficiencies* (Green, 2000, Anderson et al., 2006).

The main bottleneck for cost reduction is the cost of the material of which the solar cells are made and that constitute a substantial part of the total production cost, particularly in the case of c-Si (Green, 2001). This is illustrated in Table 11 that presents the cost structure along the different manufacturing links of the c-Si value chain. As illustrated by the table, the component that uses the material intensively represents the bulk of the cost for each productive link.

Table 11 Cost split along the PV value chain for Si wafer-based technology

Wafer	Cells	Modules	System installer
>95% Silicon <5% other	60-70% wafer 10-20% pastes <5% chemicals 5% other	60-70% cells 10-15% EVA 10-15% glass 10-15% frame <5% cable, other	80-90% module 5-10% inverter 5-10% mount <5% cables

Source: Kluftinger et al., 2005

Material cost reduction could be achieved in two main ways (Green, 2001):

1. Within the dominant c-Si technology family by finding ways of using less of the expensive Si.
2. By adopting other PV technology families, like thin film, sunlight concentrators, etc., that are more efficient in material utilisation or use other cheaper semiconductor materials.

These two options are discussed below in more detail.

4.4.1 Innovation avenues within the crystalline Silicon technology family

Cost reduction in wafer-based Si cells can be achieved via:

a) Increases in cell efficiencies.
b) Reduction of the Si used in the manufacturing process.

Increases in cell efficiencies

The selling price of solar modules is determined by the price per unit of peak power delivered by the module (€ /Wp). Since cell's efficiency enhancements translate

into a higher output per area, they help in reducing the specific material consumption (Goetzberger et al., 2002).

Commercial mc-Si cell efficiencies have increased since the early 2000s from 10-11% to14-16% (see Table 9).

Although there is a theoretical maximum efficiency that c-Si cells could achieve (this is approximately 28%)[110], improvements can still be expected at least to fill the gap between record efficiencies achieved in laboratories (24.7% for sc-Si cells, see Table 9) and those, lower, currently sold on the market.

The structuring of the cell's surface to reduce reflection loss[111] is an example of innovative steps to increase efficiency. This can contribute to about 1 % cell efficiency increase (Rohatgi et al., 2003)

Reductions in the use of Silicon

While nearly two thirds of the PV costs are directly related to Si material, as highlighted before, there is no overwhelming single cost reduction factor (Schott, 2003). There are hence several ways to reduce costs all along the PV value chain:

(a) Develop a dedicated 'solar-grade' Si process independent of the electronic industry.

The semiconductor and the PV industry use the same feedstock: high grade Si. Traditionally and while the global solar electricity demand was small, the solar industry used the rejected and out-of-specification Si from the semiconductor industry. This is indeed still the main source of supply for the manufacture of solar cells. However with the recent rapid increase in PV demand this conventional route of supply is becoming tighter[112] and with total Si demand greater than supply in 2004, this shortage could prevent the sector from achieving its plans for expansion. Since the quality and purity requirements needed for solar wafer and cell production are slightly lower than those for the semiconductor industry (Sarti and Einhaus, 2002), there are several initiatives for developing an independent and

[110] PV cells that are constituted by only one type of semiconductor can all reach a theoretical maximum efficiency of about 30%. This is because the more one seeks to increase the voltage that a cell can generate the more the cell's capacity to absorb the sun's radiation and hence to generate electric current, is reduced. Vice versa, the more light is absorbed the less voltage is obtained. Since what counts for the final use is the peak power that is generated (the result of the voltage times the current), the best one can aim for is to chose a material for which the result of voltage times current is the highest possible under the sunlight spectrum. This maximum peak power corresponds to a maximum cell efficiency of about 30%. To do better, researchers and manufacturers stack materials with different bandgaps in so-called 'multijunction cells' (Mazzer, M., 2006, personal communication, 23 April).

[111] For example, the cell surface can be constructed in a pyramid structure, so that incoming light hits the surface several times.

[112] Indeed solar demand now accounts for ~45% of total Si usage (Rogol, 2005)

dedicated energy efficient Si feedstock supply chain that can secure low cost Si to the PV industry (Sarti and Einhaus, 2002, Woditsch and Koch, 2002)[113].

(b) Adopt different lower cost Si manufacturing processes.

As shown in Table 9, while sc-Si solar cells are more efficient than mc-Si cells[114], they are more expensive to produce[115]. Several different processes can be used to grow both sc- and mc-Si cells. Some of these processes are more cost effective then others. For instance, in sc-Si development, the production process known as *'ribbon growth'* is less costly than other techniques because it produces Si directly into thin wafers instead of thick ingots that need to be cut into wafers, causing a consistent Si waste (Surek, 2005). This alternative production process can reduce the waste of the Si material of as much as 20% (Boyle, 1996). Another emerging technology for improving mc-Si production techniques, involves a *casting process that originates square ingots*: this allows cells to be cut into squares that can fit more compactly into a PV module, permitting savings in the original material (Energy Information Administration, 2005).

(c) Produce thinner wafers and reduce the sawing material loss.

Most Si wafers are currently 250-300μm thick (Chopra et al., 2004) to compensate for the fact that Si is a poor absorber of light. However, wafer thickness of about 50μm - 100μm would be sufficient to absorb most of the incident light (Kluftinger et al., 2005)[116]. The innovative challenge aims at reducing the wafer thickness without increasing wafer breakage.

Further reductions in costs can be achieved by moving to thinner saws used to cut wafers from ingots. This has the merit of reducing the sawing material loss. At present about 150-180μm are lost per slice - this could be reduced to 100μm or less (Kluftinger et al., 2005).

(d) Manufacture larger cells

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[113] The overall advantage in terms of cost is difficult to assess because it depends on the different routes taken for Si production to be used by the PV industry. However a cost target below 20€, maximum 25€ per kg (20cent Wp) is referred to in the literature as feasible (Woditsch and Koch, 2002). Note that the Si produced for the semiconductor industry and used by PV producers, is currently sold at a price of around 50€/kg, while the Silicon offcuts for the PV industry is now sold at around 30-34€/kg.

[114] This is because the single crystal allows a better and more efficient transfer of the electrons through the material

[115] In general they involve a 25–30% higher wafer price in comparison with mc-Si (Nijs et al., 1999).

[116] Moving from a 300μm to a 200μm wafer (with unchanged cutting losses of about 180μm) would save 26% of material per MW output, reducing the final system price by 2% (Kluftinger et al., 2005).

An increase in cell size has a similar effect to that of thinner wafers. Although larger amounts of Si need to be used, the output per MW increases linearly with the increase in the cell area. This makes production faster and more efficient. Technological advances have already succeeded in increasing the cell area from 4x4inch, to the current industry standard of 6x6 inch (Swanson, 2006). Although, like in the case of wafer thickness, there is a limit to how large a single cell can be built due to the physical properties of these cells, the manufacturing industry claims that they have recorded limited early success with 8x8inch cells (Kluftinger et al., 2005).

Table 12 summarises the main innovation options available along the different links of the c-Si value chain.

Table 12 Innovation targets along the crystalline Silicon value chain

	Si feedstock	Wafers	Cells	Modules	System installation
Innovation focus	Dedicated 'solar-grade' Si process independent from electronic industry	Larger wafers; Thinner wafers; Improved wire saw processes	Larger cells; Alternative cell production techniques (i.e. Si ribbon cells)	Less material usage; Higher automation	Standardisation; Increase system integration; Faster installations

Source: Kluftinger et al., 2005

4.4.2 Innovation avenues via other PV technology families

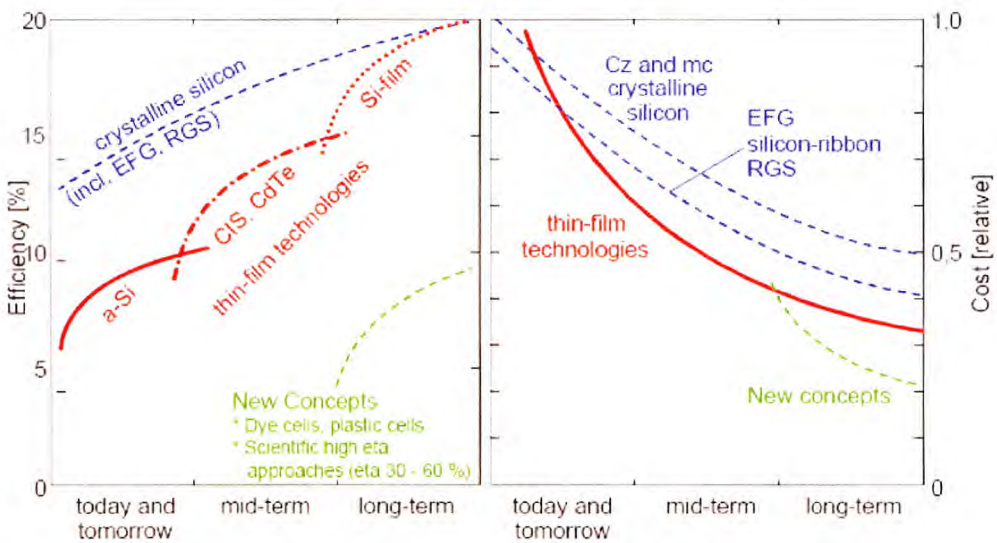
The innovation avenues described in the previous section to achieve cost reduction and to make PV competitive with existing electricity options have inherent limits. Eventually material costs will dominate further cost reduction potentials because, for instance, a minimum wafer thickness is required to absorb most of the incident light or cell efficiency could not be higher than 28% due to the physical proprieties of Si (Green, 2001, Goetzberger et al., 2002).

Although there will be further improvements in the c-Si technology, which is expected to dominate the market demand for another decade and probably longer (Kluftinger et al., 2005), alternative technologies requiring less raw material and offering further potential for cost reduction, while guaranteeing good efficiencies and performance, will become critical in the mid-, long-term (Green, 2001). This is

illustrated in Figure 22, which is the PV technology roadmap elaborated by RWE Shott, one of the biggest world PV industrial players.

Although, lower cost technology families such as thin films or dye cells based on organic materials are still in their commercial or indeed technological infancy, they will require the innovative effort of both the PV industry and the research community to drive further down the technology cost and the price of the PV module.

Figure 22 An illustrative PV technology road map



Source: Hoffmann, 204

4.5 The world market for PV

4.5.1 PV installed capacity growth and contribution to global electricity generation

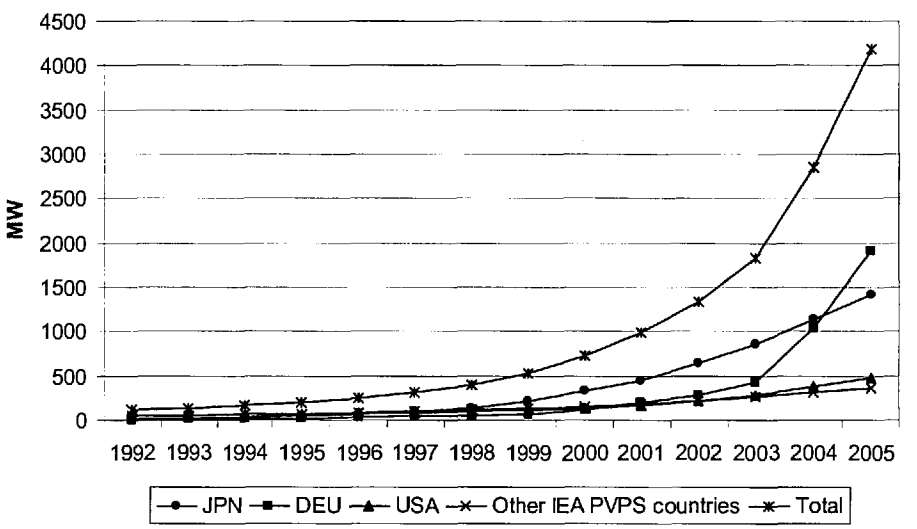
The solar PV market has been booming since the mid 1990s and is forecast to confirm this trend in the coming years (Greenpeace and EPIA, 2006). Global solar electricity demand has grown consistently by 20-25% per annum over the past 15 years (Solarbuzz, 2005) and reached 4.2 GW in 2005 (IEA-PVPS, 2005) (see Figure 23). This rapid increase made solar PV the fastest growing technological sector in the world (Martinot, 2006).

Although the bulk of the PV capacity installed since the 1990s occurred in the OECD countries (Greenpeace and EPIA, 2006), PV is becoming a mainstream power

option also in developing countries, where off-grid PV electricity is becoming integrated into rural electrification planning (Martinot et al., 2001).

Among the OECD countries, leaders in terms of installed capacity are Germany with 1.9 GW at the end of 2005, Japan with 1.4 GW and the USA with 479 MW. Together these three countries accounted for more than three quarters of the total installed capacity in 2005 (see Figure 23).

Figure 23 Cumulative installed PV power in IEA countries



Source: Based on data from IEA-PVPS, 2005

As will be explained in more detail in Section 4.6, PV market deployment is to a large extent dependent on the support schemes implemented by several countries. Germany, Japan and more recently also the US with the California Solar Initiative (Barros and Segerstrom, 2007), have been particularly active in this respect. However, despite these support programmes and the rapid growth in PV installed capacity that has followed, the present contribution of solar PV to global electricity production is still limited. To put recent developments in context in terms of scale it is sufficient to think that 4 GW of PV (roughly the total PV cumulative capacity installed in 2005) are equivalent to eight 500MW gas turbines used for peaking power (at 20% capacity factor[117]).

[117] Since the capacity factor depends on the location, the comparison provided here should be taken as only indicative.

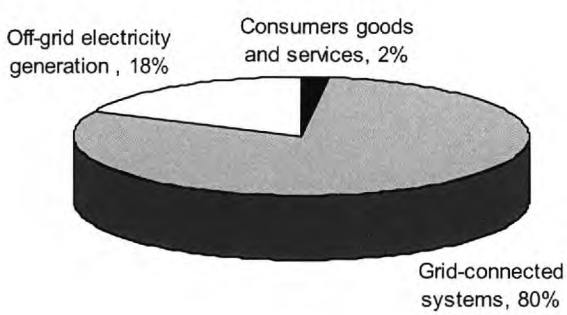
4.5.2 Main applications

PV system applications basically fall into one of three main categories (Greenpeace and EPIA, 2006):

1. Consumer goods and services
2. Grid-connected systems
3. Off-grid electricity generation (also referred to in the literature as 'stand alone applications').

Consumer goods and services include products like pocket calculators, watches, toys and power for services such as garden lights, road signs and water sprinklers. Off-grid applications pertain to systems operating independently of the national grid network, while on-grid applications refer to PV systems connected to the public electricity grid via a suitable inverter (Luther et al., 2003). These include PV systems installed on top of a roof or integrated into the facades of houses or public buildings (PV building integrated – BIPV). Grid-connected applications are the motor of the recent fast growth in PV installed capacity.

Figure 24 PV market applications in 2005



Source: Greenpeace and EPIA, 2006

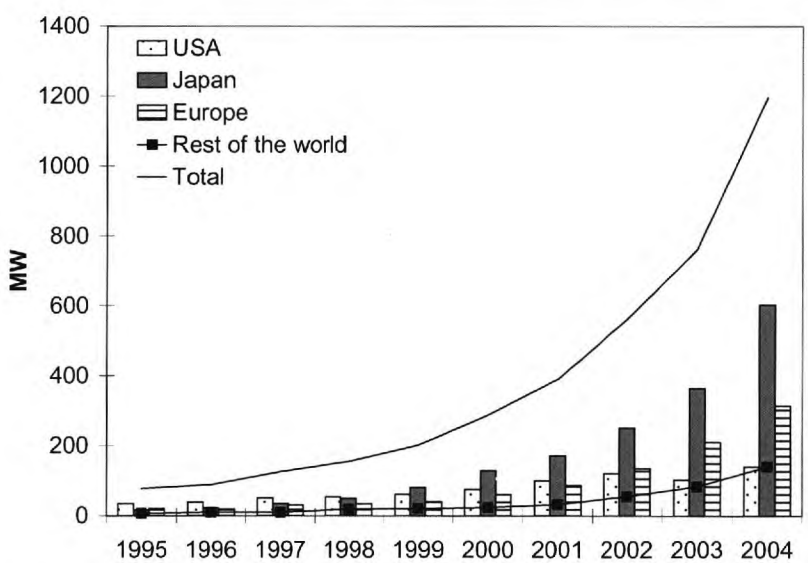
As illustrated by Figure 24, in 2005 80% of the solar electricity installed worldwide came from grid-connected systems. Support schemes promoted particularly by mature economies (see more details in Section 4.6) greatly contributed to the boom in grid-connected PV electricity. While in 1994 only 20% of new capacity was grid-connected, in 2005 the figure had grown to over 80% (Greenpeace and EPIA, 2006).

4.5.3 Production capacity development

The dramatic growth in the demand described above has been matched through time by an expansion of solar cell and module production capacity (Figure 25). Maycock refers to a world PV cell and module production of 1195 MW in 2004 representing a 57% increase on the previous year (761 MW) (Maycock, 2005). Half of the world's cell and module production in 2004 originated in Japan, where the national and local governments, the utilities and the PV manufacturers have all been actively working on the development of PV systems (Ikki, 2004).

Although the bulk of the remaining supply comes from Europe (mainly from Germany) and the USA, it is interesting to note that the manufacturing production of the rest of the world has been growing at an annual rate of 38%, the second fastest growth rate after Japan (50% annually since 1995) (Aratani, 2005). Among the emerging producing nations, China's Si cell producers increased their capacity from 19 MW in 2000 to 70 MW in 2005[118].

Figure 25 World PV cell and module production in 1995-2004 (MW)



Source: Maycock 2005

Table 13 provides the list of the world's top 10 manufacturers of solar cells in 2004 and their ranking in 2001.

[118] Data collected during interviews in China (May-July 2005) and confirmed by data available in Zhao, 2005. For more information on China's specific market and production developments see Chapter 5.

Table 13 Top 10 solar cell and modules producers in 2004

PV cell/module producers	Production in MWp (2004)	Rank in 2001 world PV cell/module manufacturers
Sharp (Japan)	324	1
Kyocera (Japan)	105	3
BP Solar (Spain)	85	2
Mitsubishi (Japan)	75	9
Q-Cells (Germany)	75	--
Shell Solar (Germany)	72	4
Sanyo (Japan)	65	7
RWE Schott Solar (Germany)	63	6
Isofotón (Spain)	53.3	8
Motech (Taiwan)	35	--

Source: Maycock, 2005

Although until the early 2000s the market was dominated by Sharp and BP Solar (Greenpeace and EPIA, 2006, Maycock, 2005), the situation has radically changed with the entry of new Japanese and European players.

4.5.4 Forecast for future PV development and contribution to (a) global electricity generation (b) emission reductions (c) employment

A recently published study (Greenpeace and EPIA, 2006) highlights the contribution PV could make to future global electricity supply, climate change mitigation and employment. The study suggests that in twenty years' time enough solar power could be produced to satisfy the electricity needs of 20% of the entire EU-25[119]. This would imply a 353 million tonne reduction in CO_2 emissions, equivalent to the emissions of both Australia and New Zealand combined. On the supply side PV module shipments have been forecast to increase by a factor of 40 by 2025 and more than 3.2 million jobs might be created along the PV value chain around the world (Greenpeace and EPIA, 2006).[120]

[119] Provided that a number of conditions are met, including the continuation of the existent (or the establishment of new) national and regional market support programs.

[120] The largest employment opportunities are expected in the installation and marketing of PV systems (Greenpeace, 2006).

4.6 PV policy drivers

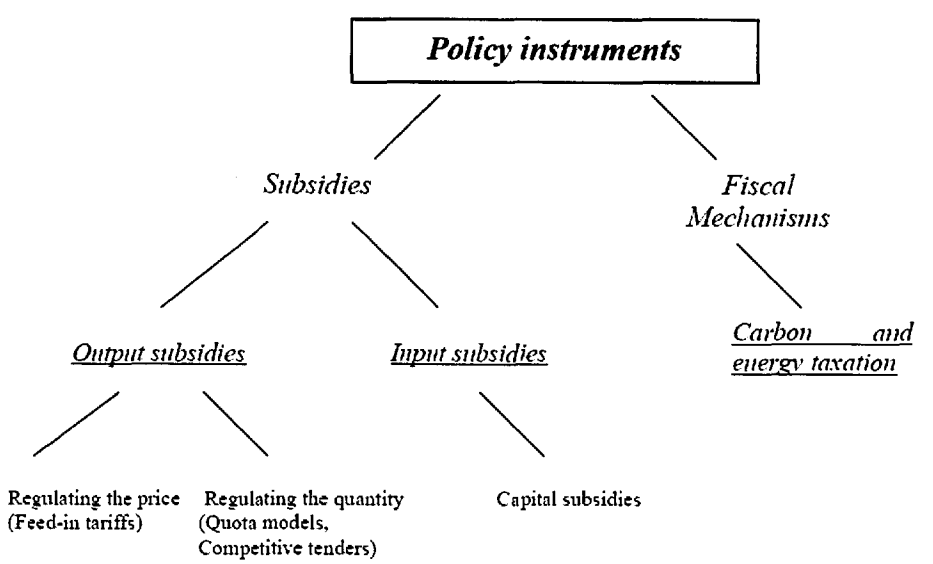
This section provides a brief overview of the policy drivers that are behind the recent development and diffusion of solar PV. This is useful to help in assessing the possible policy measures that the Chinese government is putting in place to support PV[121] and to suggest policy recommendations for the future development of the PV industry in the country.

As explained before, PV is not cost competitive with conventional electricity generation technologies based on fossil fuels and benefits from public supporting schemes. These are required to increase solar electricity installed capacity as well as to incentivise widespread investment in PV and to allow the industry to develop scale effects that in turn should allow players to bring down prices (Kluftinger et al., 2005). The two main drivers behind public support to PV development are climate change and security of energy supply.

At present, policy instruments that contribute to PV worldwide expansion are part of broader schemes aimed at supporting RET.

Two main policy instruments can be identified: subsidies and fiscal mechanisms (see Figure 26).

Figure 26 Policy options to stimulate PV



Source: Anderson et al., 2006

[121] These aspects are all presented and discussed in Chapter 5.

Subsidies, which have been quite successful in encouraging a wider diffusion of RET, fall in two categories: capital investment subsidies and subsidies directly aimed at stimulating installed capacity. Subsidies for the installed capacity may focus on quantities (i.e. a national target of RET diffusion could be established together with tender or quota systems providing for green certificate trading), or on prices, where electric utilities are obliged to purchase electricity from green power generators at guaranteed prices (i.e. fixed feed-in tariffs). It is this latter support mechanism (widely adopted in Germany, but also in other EU countries) that has triggered major investments in solar electricity, and RET more in general (EPIA and Greenpeace, 2007, Ragwitz and Huber, 2005). Fixed tariffs, over a clear timeframe, provide certainty of income, which is a key issue for investors, and encourage the entry in the market of entrepreneurs (Sijm, 2002). When tariffs are differentiated to take into account technological maturity, technological differentiation in the RET available portfolio is encouraged. Moreover feed-in tariffs seem to be more favourable than mechanisms regulating the quantity, in stimulating technological innovation because they reduce revenue risks and enable manufacturers to invest more heavily in R&D and to consolidate their industrial base (Menanteau et al., 2003, Mitchell and Connor, 2004, Gross et al., 2007).

However, to spur technological development and diffusion of solar PV technology more technology specific policy instruments are required (Sandén, 2005). These would need to include not only R&D funding but also market creation and especially the stimulation of niche markets to encourage learning.

As pointed out before a successful policy support should take into account not only market diffusion (by targeting installed capacity) but also the fact that the future PV technological landscape is uncertain and that, as a consequence, technologies in their infancy should be promoted by appropriate R&D schemes to guarantee technological variety and to prevent a country from becoming locked-in to technologies that in 15-20 years may well become obsolete.

4.7 Conclusions

Knowledge of specific technological and market aspects of PV is essential if we are to assess the innovativeness of the Chinese firms operating in this sector. We have

argued that there is technological uncertainty surrounding the future of PV development and that the technology family that dominates the market today (i.e. c-Si) will not necessarily be that with the largest market share in 10-15 years time. This has implications for firms' future competitiveness, for the development strategies they set up today and for the learning effort that will allow them to add value. We have also argued that PV will need to reduce its production costs to compete with other electricity generation technologies based on fossil fuels. In order to do this, the innovation effort of firms (and more broadly of the research community) should focus on both those links of the c-Si value chain, like wafer, cell or indeed feedstock production, that can contribute more to cost reduction or on investing in alternative PV technology families that can offer brighter prospects towards cost reduction (i.e. thin-film technologies or new concepts involving organic materials or concentrators).

We have explained how the recent expansion of world grid-connected solar electricity would not have happened (at least not at the current speed) without public subsidies, which are still concentrated in a limited number of countries (mainly in Germany, Japan and the USA)[122]. This makes firms highly dependent on, and potentially highly vulnerable to changes in, markets commercially supported by government policies. On the positive side the uncertainty that surrounds the durability of current policies acts as a driver for the industry, which is put under pressure to find innovative solutions to reduce technology costs before state subsidies phase out.

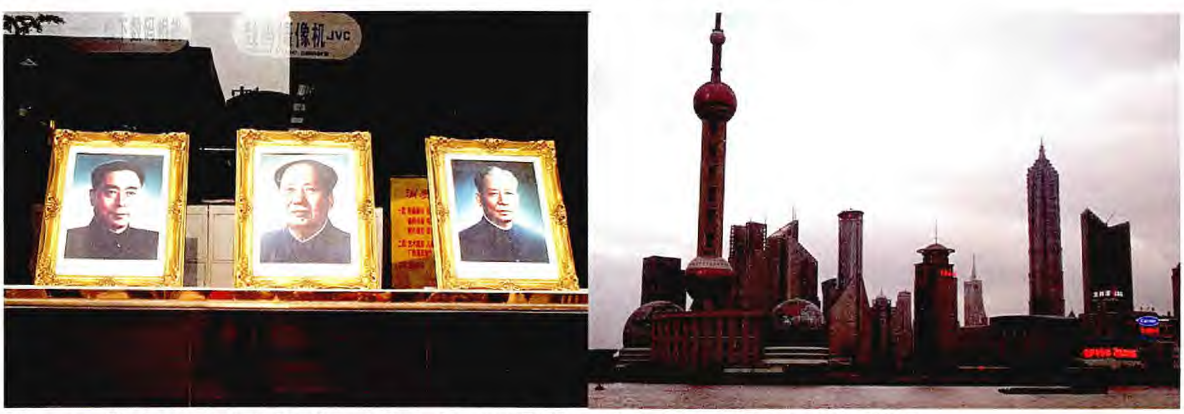
These issues play a significant role in determining the Chinese firms' ability to undertake technological change and will be further discussed in Chapters 6 and 7.

[122] The concentration of the PV on-grid market in a few countries has rapidly changed since 2005 with more countries, like Italy, Spain (Jäger-Waldau, 2007) promoting supportive polices to encourage PV installed capacity (Blok, 2006).

5 THE CHINESE DOMESTIC ENVIRONMENT: THE EVOLUTION OF THE NATIONAL INNOVATION SYSTEM AND THE MACRO PV PICTURE

Picture 6 Old guard Chinese leaders in a shop window in Beijing

Picture 7 The new China: the Pudong area in Shanghai taken from the Bund



Source: Pictures taken by the author during fieldwork in China, May-July 2005

5.1 Introduction

In Chapter 4 we provided a PV technology-specific profile and explained why the information provided in that chapter was required for an understanding of the innovation dynamics in the Chinese PV firms.

In this chapter we focus on some China-related innovation and PV specificities that need to be appreciated to deepen our understanding of micro-level and systemic dynamics in PV in China.

The chapter contains two distinct parts. Section 5.2 investigates the structure of the Chinese innovation system[123] and its evolution over time. Moreover, it includes some of the measures recently introduced to transform China into an innovation-driven economy (Section 5.2.3). We argue that capturing the main features of the Chinese NIS

[123] A theoretical underpinning of the NIS concept has already been provided in Chapter 2 (section 2.4.6)

and its evolution over time will be useful to better understand the determinants of the innovative behaviour of the PV firms in China.

Section 5.3 uses information collected in 2005 during fieldwork to introduce the Chinese macro PV picture. Sections 5.3.1 to 5.3.3 discuss PV current and future contribution to the domestic electric demand, the structure of the national industry (i.e. not the innovative behaviour of the firms, which is the object of this study and is presented and discussed in Chapters 6 and 7) and the policies promoted by the government to boost the domestic PV market and industry.

We decided to include this macro PV picture in this chapter, rather than, for instance, in Chapter 4, because we want to highlight some features of PV development that are specific to China (for instance the priority given by the government to off-grid rural applications and the striking disparity between the country's installed capacity and production capacity) and because this will provide a useful macro introduction to the PV micro aspects that are discussed in Chapter 6 that follows.

As it has been the case for Chapter 4, the information contained in this chapter has informed the analytical framework and is required for an understanding of the results presented and discussed in Chapters 6 and 7. Moreover, similarly to Chapter 4, the information refers to 2005. This is done to sketch the NIS and the PV macro picture at the time when the empirical part of this study was undertaken (mid 2005).

5.2 The evolution of China's innovation system: from plan to market

China has a long history of innovation and progresses in science and technology. The seminal work of Needham shows that China made great advances centuries before the West in many important fields: gunpowder, silk and printing are only few of the many examples (Needham, 1954-). Table 14 provides a snapshot of when some selected innovations have been introduced in China and in the West.

Table 14 The timeline of China's technological advances

Type of innovation	First introduced in China	First introduced in the West
Silk	1300 B.C.	582 A.D.
Paper	105	1150
Porcelain	851	1709
Printed book	868	1456 (Gutenberg's Bible)
Compass	1050	1190
Explosive	1151	16th century

Source: Adapted from Columbia University, 2004

However, during the Industrial Revolution that occurred in Europe in the 18th century, China started to lag behind Western countries and for three hundred years contributed little new to the world's science and technology[124].

In the twentieth century China entered a new phase of technological development when it started to catch up with the rest of the world by increasingly using western technology.

Since the beginning of the PV story in China dates back to late 1950s (see Chapter 6 for more details) and this is when the innovation system for this technology started, it is useful to recall some key features in the structure and dynamics of the Chinese innovation system over time. This should enable us to better appreciate whether the Chinese system's structure, dynamics and performance, together with the innovation policies put in place, have affected the development of the domestic PV industry over time and the firms' ability to move forward.

5.2.1 The Chinese national innovation system during the planned economy

In the 1950s a centrally planned economic regime was established in China along with extensive imports of technology from the former Soviet Union (Naughton, 1995, Nolan, 1995).

In this period the industrial organisation was highly centralised and under complete state ownership (Garrett-Jones and Liu, 2002). There were functionally specialised organisations whose activities and interactions were managed by the central government directly or by governmental industrial bureaux, such as the different

[124] An investigation of why China did not experience an industrial revolution despite its previous contribution to the world science and technology is beyond the scope of this study. The issue is however widely debated in the literature. Nolan (1993) and Balazs (1964) offer interesting points of view.

Ministries (Liu and White, 2001). The government decided what to produce, in which quantity, how and what resources to allocate to these functionally specialised organisations.

There were government research institutes (such as the Chinese Academy of Science - CAS) whose only role was to conduct research according to the priorities identified by the government. They produced research reports with limited applied industrial use because their understanding of manufacturing requirements was limited (Liu and Lundin, 2006).

Similarly, firms were only in charge of manufacturing and had, as a driver, not the market demand but the production targets set by the government. Moreover, important elements for industrial technological change and innovation[125], such as creating links with suppliers or final customers were dealt with by government's bureaux and not by the firms (Liu and White, 2001).

During the planned economy period, the Chinese innovation system was hence characterised by a *linear and hierarchical model of innovation* (i.e. research was detached from production and priorities, as well as resources, were allocated 'from above' by the government) with a *clear division of labour*[126] (Liu and Lundin, 2006).

This industrial organisation structure had at least two important implications for innovation and for our understanding of how the PV firms' capacity to add value over time could have been affected. First, *firms had neither interest nor incentive* (not even under the government's mandate) *to upgrade their capabilities or to innovate* (i.e. to introduce, adopt or diffuse innovation proactively). The innovation system not only provided few incentives for innovation but also created barriers: "knowledge in many cases accumulated on the shop floor from daily operations on how to improve technology in use. However factory managers could not take initiatives because innovation decisions had to be made by the planners following the yearly or five-year plan procedure" (Gu, 2001, p. 207).

Second, the innovation system had a *limited number of actors* so feedback and interactions for the exchange of knowledge and information were extremely limited. Moreover, as pointed out above, the government and its industrial bureaux were responsible for linkage activities and directed the technology developed by research institutes to manufactures. Firms, research institutes, distributors and users had no

[125] See chapter 2 (section 2.5.4)

[126] R&D was undertaken by research institutes, manufacturing by factories and linkages by industrial bureaux (Liu, 2007).

incentive to initiate linkages with other actors in the system because they "[...] depended on top-down allocations for necessary inputs, whether personnel, technology, capital, intermediary inputs or other resources" (Liu and White, 2001, p. 1098).

5.2.2 The evolution of the innovation system since 1978

In 1978 China entered a period of extensive reform and opening to the outside world. This market-oriented economic reform had significant effects on the structure and dynamics of the Chinese IS. The number and the relative importance of key actors have significantly changed together with the forces that drive the development of the IS. Thanks to the reform, not only there are more actors in the IS but also more functions (i.e. knowledge creation and diffusion, etc. See Sections 2.4.2 and 3.2.3 in Chapters 2 and 3 respectively) can be satisfied by a larger number of agents.

In what follows selected aspects of the IS, as it started to emerge since the late 1970s, are discussed for their particular relevance for this study.

First, after the beginning of the economic reform in the late '70s, a drastic *reduction in the direct state involvement* occurred and state-owned enterprises (SOEs) were granted more autonomy and took more responsibility (Gu, 1995, Nolan, 2005). Firms were given the freedom to take decisions on production planning, investment, marketing, acquisition of technology and personnel recruitment.

Moreover the *involvement in the industrial production of non-state enterprises has been encouraged.* China's non-state sector, which comprises collectively-owned enterprises, private businesses, foreign investment firms and joint ventures has been the engine of the country's rapid economic growth in the past three decades (Marigo, 2004).

The entrance into the Chinese IS of new actors with a greater functional diversification and autonomy has *increased knowledge and information flows* between the different system components (Liu and White, 2001).

Second, *funds and resources* granted to SOEs and the R&D institutions by the government *have been drastically reduced* and research funding, together with employment, have been made contingent on performance: scientists have to show they are able to acquire funds or to commercialise their research results (Garrett-Jones and Liu, 2002, p. 34). Some commentators note that, although this competition-based funding system created incentive for innovation and for a faster commercialisation of the research results, at the same time: "[...] it increased pressure on scientists and led to short-term research projects for pursuing more immediate economic returns" (Liu and

Lundin, 2006, p. 4). Moreover, to speed up the process from research to commercial products, the government also prompted research institutes and universities to set up their own spin-offs and encouraged scientists to leave their research position and engage in commercial activities.

Third, as a consequence of the open door policy, *China's international links have been substantially intensified* in terms of the inflow of investment, technology and capital goods. Although imports have become the most important source of industrial technology they have also created fierce competition for domestic suppliers who are under pressure to improve performance and quality of the products they sell in both the domestic and the international markets.

Despite the increased role of market forces in the Chinese economy, the government still plays a significant role in the development of the domestic innovation system. Since the economic reform of the late 1970s, the Chinese government has consciously *invested considerable resources in building different aspects of its NIS* to accelerate the pace of local generation of technology. These steps include the efforts to develop human resources (i.e. education and beyond), the promotion of specific policy and measures to foster science and technology (i.e. government direct support of national R&D and in particular of technology related research), as well as measures to promote industrial innovation (for instance, the establishment of high-tech zones and the support of technology-based SMEs). More recently, the government has been encouraging the development and the utilization of indigenous technology. We discuss below the major initiatives taken in each respect and devote a separate section (5.2.3) to the latest developments in terms of indigenous innovation.

Developing a human resources with a particular focus on science and engineering

In recognition that a good tertiary education and an adequate supply of well trained scientists and engineers are considered essential to assimilate technology and to propel innovation (Yusuf and Evenett, 2002), China has set up a system of higher education that has produced, only in 2002, more than 300,000 scientists and technologists (National Science Board, 2002). Science and engineering (S&E) degrees represented 73% of total first university degrees awarded in China in 2002 and greatly outnumbered the number of S&E degrees in mature economies (Figure 27).

Figure 27 Ratio of science and engineering degrees in selected countries, 2002

	ALL 1st UNIV. DEGREES	TOTAL S&E DEGREES	% OF S&E DEGREES ON TOT 1st UNIV. DEGREES	DETAIL OF S&E DEGREES		
				Natural sciences	Social & behavioural sciences	Engineering
Total, all regions	***6,781,885***	***2,649,460***	***39***	***917,721***	***872,629***	***868,340***
Brazil	245,401	78,049	32	32,556	27,421	18,072
China	**440,935**	**322,769**	**73**	**59,804**	**67,611**	**195,354**
EU	1,908,967	439,171	23	182,089	122,390	134,692
Hong Kong	11,362	5,425	48	2,370	1,233	1,822
India	750,000	176,036	23	147,036	NA	29,000
Japan	532,436	350,535	66	32,718	214,377	103,440
Malaysia	10,511	4,760	45	1,685	2,198	877
South Korea	204,390	91,296	45	29,527	16,624	45,145
Taiwan	87,421	34,722	40	12,911	5,173	16,638
United States	1,199,579	384,674	32	144,441	185,263	60,914

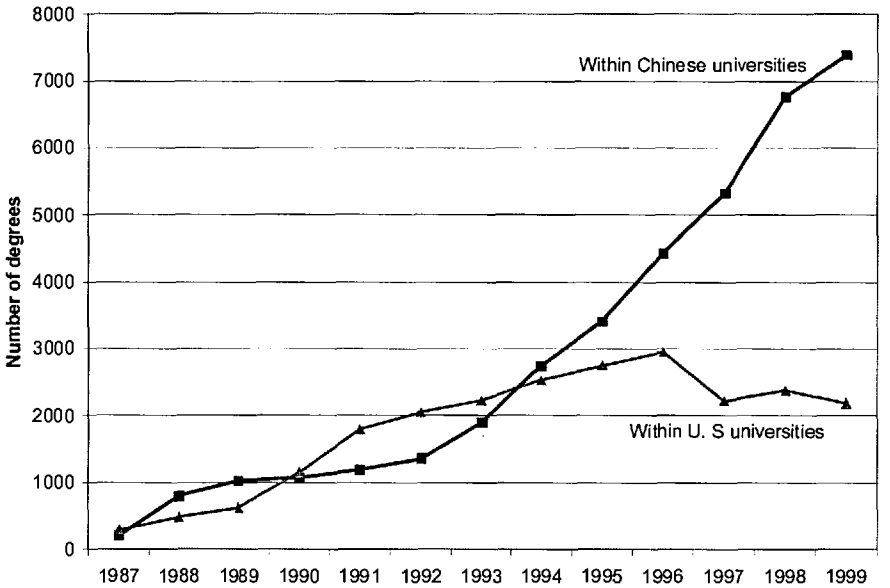
Source: National Science Board (2002)

Moreover, starting from a very low base in the 1980s, China has been able to increase the number of its S&E doctoral students[127] and also to invert a trend that, until the mid 1990s, saw students preferring to go abroad (mainly to the USA) to obtain their doctoral degrees (Figure 28)[128].

[127] According to the National Science Board, by 2002 China had the largest capacity for S&E doctoral degrees production in the Asian region and ranked fifth in the world (National Science Board, 2002).

[128] China's capacity to increase its number of doctoral students could be the combined result of: China's ability to deliver good quality S&E higher education, the increasing attractiveness of the country as a place where to work and live (see following section on attracting back talents), and the increasing difficulty to enter the USA that has followed the September 11th terrorist attacks (Broad, 2004).

Figure 28 Doctoral S&E degrees earned by Chinese students at home and USA universities, 1987-1999



Source: National Science Board (2002)

Development of science and technology

National R&D expenditure is an important indicator that shows the importance (and indeed the commitment) given by a country to scientific and technological activities and to innovation.

Since 1995, China has more than doubled its R&D spending (understood as a percentage of GDP) passing from 0.6 to 1.3% of GDP in 2005 (EurActiv.com, 2006). By the end of 2006, China was expected to overtake Japan and become the world's number-two R&D investor after the United States

The importance attached by China to R&D spending as a means to promote technological development, has been visible since 1986, when China promoted the high-tech R&D programme, better known as the *'863' programme*. The aim of the programme, which is still running, is to enhance China's international competitiveness by promoting R&D in selected high-technology areas. The six areas at the core of the programme are: information technology (IT), biological and advanced agricultural technology, advanced materials, advanced manufacturing and automatic technology, energy technology and environmental technology. The programme, which is directly

financed by the Ministry of Science and Technology (MOST)[129], has received approximately 10 billion RMB (about £970 million) from 1986 up to the end of 2001 (Sigurdson, 2005).

Attract talents back home

An important policy set up by the government to enhance creativity focuses on attracting back to the country Chinese nationals who have been trained overseas and who can bring with them modern technology and concepts. There are many different types of *returnees*: entrepreneurs, multinational managers, academic researchers and investors. "For those wanting to work in academic research, there are attractive governmental schemes such as the '100 Talents' programme, which offers high salaries and generous research budgets to promising scientists under the age of 45" (Wilsdon and Keeley, 2007, p. 30). The Chinese National Natural Science Foundation (NSFC) in 2005 also promoted a scheme where annual grants of up to 1 million RMB (about £97,000) for four years were offered to overseas Chinese scientists willing to return (Jia, 2005)[130].

Special support for technology-based firms

In 1998 the State Council established the National Foundation for Technological Innovation aimed at supporting technology-based SMEs through grants, low-interest loans and funds for capital investment (Garrett-Jones and Liu, 2002, Sigurdson, 2005).

Moreover "high-tech enterprises are now required to spend no less than 5% of their annual sales volume on R&D. A company's investment in S&T can be written off as production costs" (Garrett-Jones and Liu, 2002, p. 35).

Another key measure taken by the government to specifically promote industrial innovation has been the development of high-tech zones. They have been created to

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[129] MOST was created in 1998 out of the former State Science and Technology Commission and is responsible for science and technology strategy. Besides the 863 programme for high-tech R&D, it finances also a large amount of research through other programmes such as the Basic R&D programme (also known as the 973 programme) and the Spark programme for the support of rural industries and the diffusion of technology to township-village enterprises. MOST also administers development zones and oversees international collaboration.

[130] Despite the positive attitude of the government towards returnees, there is a widespread sense of resentments on the side of the local research community who feel they are overpaid or unfairly promoted ahead of local talents

serve as a platform for innovation activities and interactions, via the establishment of clusters to promote close cooperation among firms. Moreover they provide preferential treatment to high-tech firms in the form of a broad range of tax incentives (Liu, 2007).

5.2.3 Latest developments in the innovation system: from imitation to indigenous innovation

In 2005 China launched the National S&T Development Plan for the 2006-2020 period (Erawatch and CORDIS, 2006). While the formulation of long-term science and technology programmes has a long standing tradition in China dating back to 1956 (Sigurdson, 2005), this most recent strategic plan contains a new noteworthy element: the *need to re-focus the development model and to strengthen 'independent' or 'indigenous' innovation.* Several reasons demand for a change in the existent development trajectory.

China's rapid economic growth has been driven by a combination of low-cost manufacturing, imported technology, substantial flows of foreign investment and growing demand for China's exports (OECD, 2007). Such growth model is now under scrutiny. Years spent in attracting foreign technology and capitals have not resulted in the knowledge and technological spillovers the Chinese policymakers had hoped for (Liu and Lundin, 2006).

A culture of imitation and copying is common not only in product development and design, but also in the field of scientific research[131]. Hence, even if manufacturing will remain crucial in the future economic growth of the country, it will not be sufficient to carry China through the next stage in its development (Wilsdon and Keeley, 2007). Challenges ahead include securing energy and resources, reducing the levels of environmental pollution (the strategy 'grow first, clean up later' is increasingly challenged) and enhancing capabilities for innovation, which includes new managerial skills and new organisational practices. These challenges, which point in the direction of a more sustainable and harmonious development, demand a new focus

[131] Plagiarism affects China scientific research. In an interview given by Prof. Ze Zhang, the vice president of Beijing University of Technology, to Wilsdon and Keeley of Demos, he declared: "[...] There are policies to encourage people to generate publications and patents and prizes. You get a score and if you are an 'A', you get 25 per cent more salary. It's easy to understand why this leads people to plagiarise results. Every university has this problem. I've suffered from it myself. Some ex-students of mine took my data and published it in Science. This happened only five months ago" (Wilsdon and Keeley, 2007).

on indigenous innovation (Gu and Lundvall, 2006, Liu, 2007, Wilsdon and Keeley, 2007) and for a 'high-performing enterprise-based innovation system' (OECD, 2007).

Ad hoc policies and new measures are being introduced to pursue the government's indigenous innovation goal. These include: increase in R&D expenditure in science from the current level of 1.3% to 2% of GDP in 2010 and 2.5% in 2020 (Liu and Lundin, 2006); favourable tax policy for firms' R&D expenditure; public procurement of indigenous technology; new banking policies and fiscal incentives to support innovative start-ups.

We move now to the second part of this Chapter, which will serve as a macro PV picture to the firm-level analysis that will follow in chapter 6.

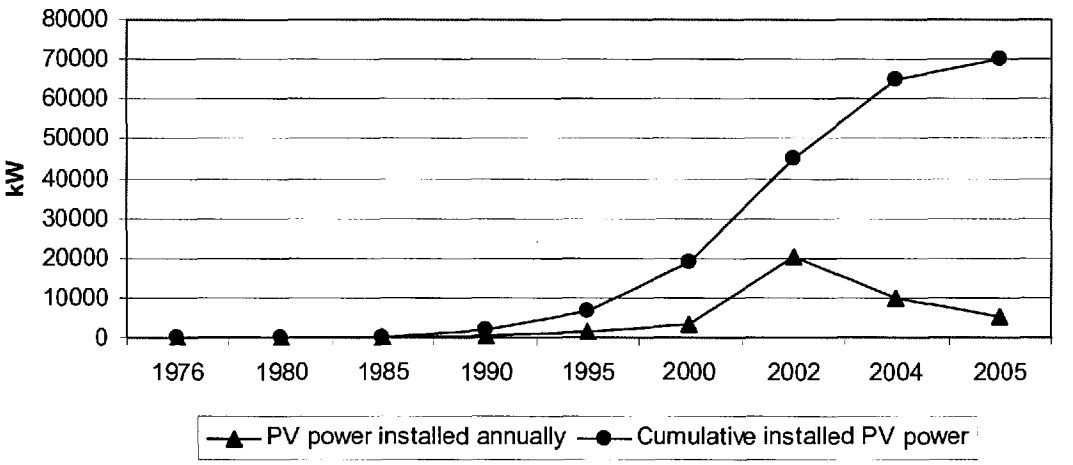
5.3 The Chinese macro PV picture: market, supply and PV role in the current and future China's electricity demand

The Chinese PV macro picture presents some distinctive features that are important to understand to appreciate the domestic context within which the PV firms undertake technological change. In the following pages we explore specificities pertaining to both the domestic PV market and industry.

5.3.1 PV demand in China: installed capacity and market applications

At the end of 2005 China's total PV installed capacity was about 70MWp (see Figure 29). Although this represented a small amount when compared to other countries that lead in terms of installed capacity (Germany had 1.9 GW at the end of 2005, see Chapter 4), it was nevertheless an important result considering that in 1995 China had less than 7 MW installed (REDP, 2004).

Figure 29 China's PV installed capacity (1976-2005)



Source: Wang, 2006

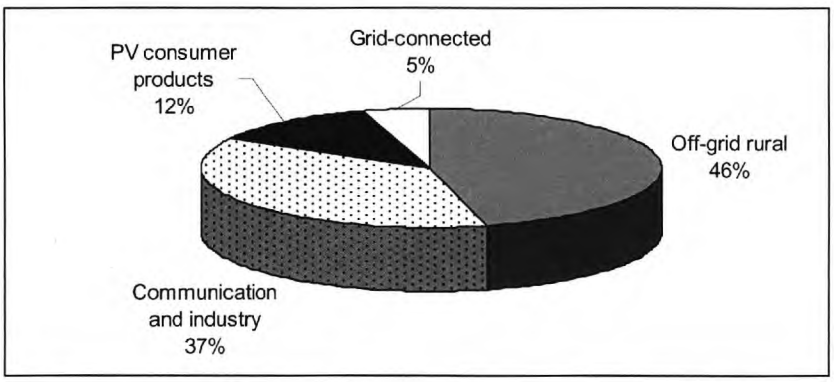
The recent rapid growth in PV installed capacity occurred mainly in off-grid rural applications (they represented nearly half of the installed capacity in 2004 as it is illustrated by Figure 30) driven by the massive rural electrification programme launched by the government in 1998 and better known under the name of the 'brightness programme' (Ma, 2004 and 2005).

The overall target of the programme is to provide electricity for 23 million people in remote areas by 2010 using PV modules and wind power systems (Marigo, 2007)[132]. If the government's rural installation schedule is going to proceed according to plan, by 2010–2015 all Chinese households should be electrified.

So far the programme has succeeded in electrifying rural population and in increasing PV installed capacity at an average annual rate of 27% since 1990 (Ma, 2004, Ma, 2005). However the programme has not provided a long and good enough incentive to local firms interested in expanding their presence in the domestic market. This is illustrated in Figure 29 by the blip in PV power installed in 2002. In late 2001 the government launched a new phase of the Brightness programme (the Township Rural Electrification Programme, see footnote at the bottom of the page), which lasted for just 20 months. The programme was too short and failed to have a long term impact on the industry that remained along the same growth path initiated in the late 1990s.

[132] The Brightness Programme includes the Township Electrification Programme and its follow up, the Village Electrification Programme, that have been adopted by the government (since 2006) to provide electricity access via solar energy to remote rural areas.

Figure 30 China's main PV applications (2004)



Source: Wang, 2006

Besides rural applications other potentially promising markets, such as on-grid applications, are at little more than a demonstration stage (see Figure 30).

It is worth recalling that the recent boom in the global PV installed capacity described in Chapter 4 has occurred in residential grid-connected applications supported by stable market support mechanisms. Moreover several studies have shown the big potential and economic rationale for an increase in grid connected applications in China (Byrne et al., 2001, Zhang, 2005, Li et al., 2007). It is therefore reasonable to expect that, as soon as the rural electrification programme is over, the main opportunity for PV in China will be in grid connected applications and this will require a stable and rewarding policy scheme, as it happened in other markets like Germany or Japan (see Chapter 4). However, the director of renewable energy at the Chinese National Development and Reform Commission (NDRC) has recently declared that: "[...] China has decided that grid-connected PV is too expensive for incentive support, with projects only being considered on a case-by-case basis" (Photon International, 2006).

5.3.2 PV's role in future electricity demand

Despite the scarce attention of the government for the PV domestic market (off-grid rural applications aside), a study by the Chinese Electrical Power Research Institute (CEPRI) has shown that PV is bound to play a larger role in the Chinese electric supply in the future (REDP, 2004). According to the study China's electricity demand is expected to rise 5.6% annually, from 357GW capacity in 2002 to 950GW in 2020. Since conventional energy sources (i.e. coal, nuclear and hydro) will not be sufficient to satisfy the increasing demand, RET like biomass, PV, small hydro and

wind, are expected to fill the gap and to provide nearly 11% of the total electricity needs by 2020 (see Table 15)[133].

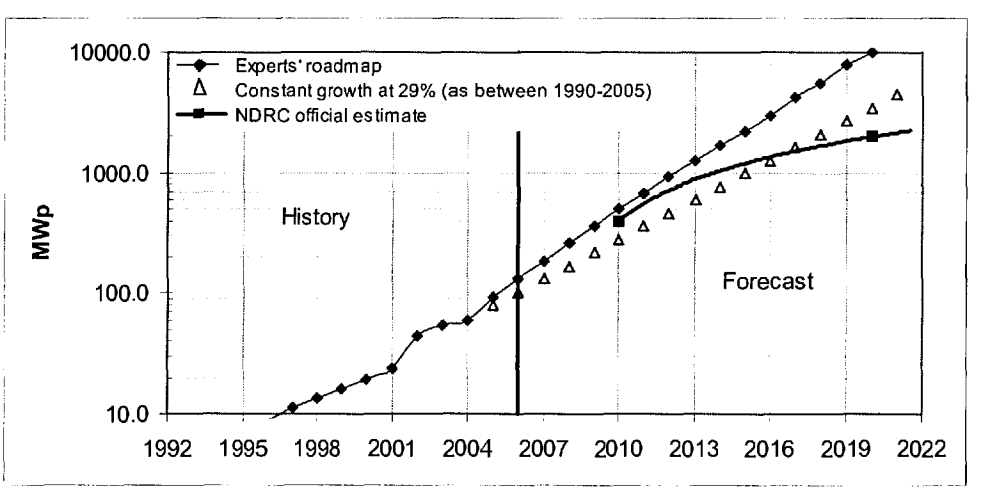
Table 15 China: electricity generation capacity in GW and as a percentage of the total in China in 2002 and projection for 2010 and 2020

Mode of electricity generation	2002		2010		2020	
	GW	*%*	*GW*	*%*	*GW*	*%*
Coal	266	74.5	400	68.40	592	62.3
Hydro	86	24.1	135	23.10	220	23.2
Nuclear	4.5	1.3	12.5	2.10	36	3.8
Renewables	0.5	0.1	37	6.40	102	10.7
Total	**357**	**100**	**584.5**	**100**	**950**	**100**

Source: REDP (2004) for 2010 and 2020 projections; Wang, 2006 for 2002 data

PV will certainly play a role in closing this gap but how significant this role will be remains an open question. Solar energy R&D representatives and experts interviewed in China in mid 2005 seem to believe that a 41% per year expansion of PV installed capacity until 2010 followed by a 36% rate of growth until 2020, can be achieved. This would bring PV from the 2005 level of 70MW to 500MWp in 2010 and 10GWp in 2020 (see Figure 31).

Figure 31 Three possible scenarios for China's PV cumulated installed capacity



Source: for experts' roadmap: Wang, pers. comm. 25 May 2005; for NDRC official estimate: REDP, 2004, Wang, 2006

[133] Although a more recent Figure by CEPRI seems to suggest that the gap to be filled by renewables in 2020 may be smaller (8.2%) due to a larger role to be played by gas generation of electricity (Wang, 2006), the government's commitment towards a greater reliance on renewable energy by 2020 seems firm (Watts, 2005).

A recently published report (Wang, 2006) suggests, however, that the National Development and Reform Commission (NDRC) might have far less ambitious expectations, not as much as for the short term, where 400MWp by 2010 are foreseen, but for the medium term where only 2GWp by 2020 are expected.

If the experts' roadmap, which is quite likely based on the hope for a long term incentive scheme, possibly a feed-in tariff for grid-connected PV electricity, appears to be ambitious, the new government forecast for 2020 appears even lower than what would be achieved by following the current business as usual scenario. It is worth noting that the total internal installed capacity has grown at a constant rate of about 27% between 1990 and 2005. If this trend is confirmed during the next 10 years, the total installed capacity would reach 1 GWp in 2015 and would fall just short of 3.5 GWp by 2020. Figure 31 summarises the three possible scenarios.

5.3.3 PV industry in China: an overview

The details provided in this section about the PV industry are the result of the information and insights obtained during fieldwork in China in 2005. Before undertaking the empirical part of this research little was known about the PV industry in China, who the main industrial players were and in what segments of the value chain they were involved (not to mention their ability to innovate, which is indeed the object of this study). The only information available at the beginning of 2005 was contained in a few articles and reports (Yang et al., 2003, Zhao, 2004, Zhu, 2004, Zhao, 2001, Dai and Shi, 1999), which were either out of date or reflected only partially the changes underway in the industry since the early 2000s[134].

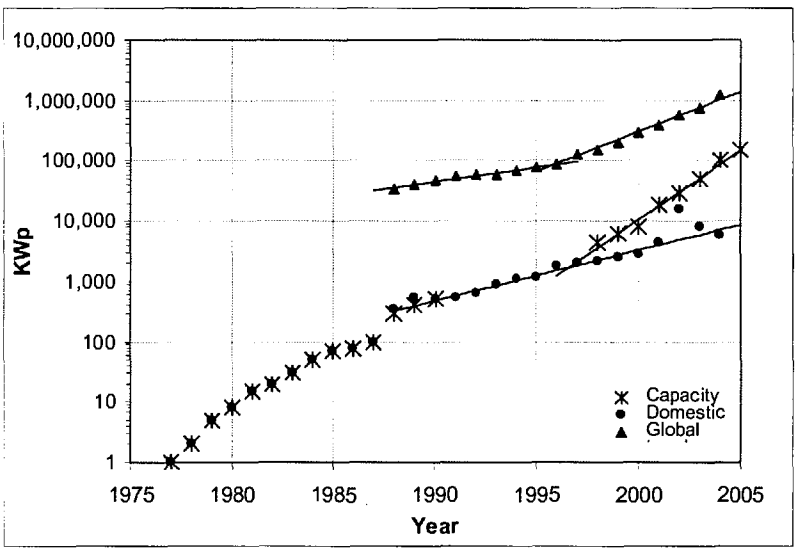
What follows presents a broad overview of the Chinese PV manufacturing industry as it was at the end of 2005 (soon after the completion of fieldwork) and summarises some of the findings recently presented by the author of this study in a journal paper (Marigo, 2007). It is worth emphasising that all the issues pertaining to the firms' ability to enhance their technology capabilities and add value are presented and discussed in Chapters 6 and 7.

Since the early 2000s, when two new cell and module manufacturers, Suntech Power and Tianwei Yingli New Energy Resources, began production, China's PV cell

[134] As discussed in Chapter 3, the limited information available before undertaking fieldwork in 2005, made the selection of the target population to be included in the survey quite challenging.

and module production has been growing rapidly. Domestic capacity has increased from 14 MW in 2003 to over 64 MW in 2004 (Zhao, 2005) and in the first half of 2005 the country ranked no. 5 in world PV production (Chen, 2004).

Figure 32 China: total PV production capacity (asterisks) and production only for the domestic market (small dots) compared to global production (triangles)



Source: Compilation of data from: Ma, 2003 for China's early total production capacity; Maycock, 2004, for global production; REDP, 2004, for domestic (no export) market production; Zhao, 2005, for 2005 China's total production capacity

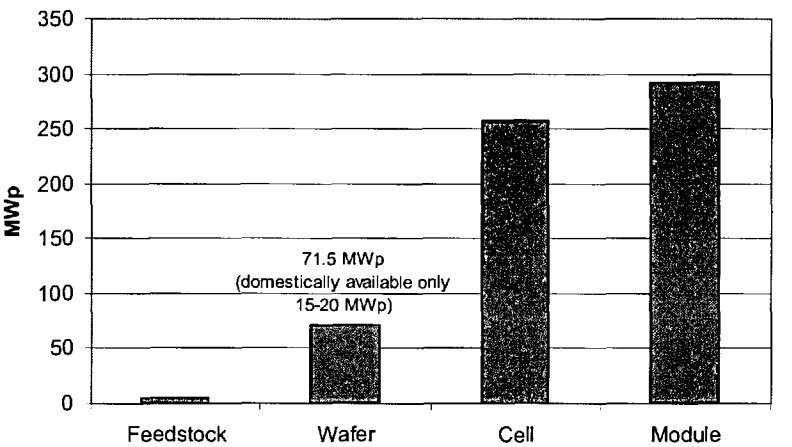
Figure 32 shows the evolution of both the total Chinese PV production capacity and the production only for the domestic market, together with the growth of global production capacity. As illustrated by the Figure Chinese PV production capacity follows the global trend quite closely but with a noteworthy difference: while global PV production has been growing at an average annual rate of 36% since 1997, the annual growth of production capacity in China has been nearly double this, 70%, during the same period.

Another striking fact emerging from the data plotted in Figure 32 is the existence of a growing gap between the real production sold in the domestic market and the industry's production capacity. As emerged during the fieldwork interviews, on average between 70 and 80% of the modules produced in China are exported.

As pointed out previously, the vast majority of the Chinese PV industry is based on c-Si technology. Solar presence on the value chain is from wafering to cell production, module assembly and PV system installation (REDP, 2004).

Figure 33, compiled by the author from information collected during interviews, provides an overview of the domestic capacity along the c-Si production chain in 2005.

Figure 33 Capacity along the c-Si production chain (2005)



Source: Wang, 2006 for data on feedstock and wafer production. Cell and module data have been collected by the author during interviews in China, May-July 2005

Silicon feedstock

China's PV industry depends almost entirely on imports of Si feedstock from abroad. Despite having a domestic semiconductor industry that supplies electronic grade Si, its production capacity is very limited (less than 200 tons/year) and almost entirely devoted to the integrated circuit industry (REDP, 2004, Wang, 2006). Currently between 30 and 40 tonnes/year of the domestically produced Si feedstock is for the internal PV market; this translates to a mere 3 to 5 MW of c-Si solar cell production. Some relief from the heavy dependence on imported feedstock could come between 2007 and 2010 as a consequence of a planned expansion of the domestic Si production capacity, which could possibly reach 1500 tons/year. However, it remains to be seen how much of this expected expansion in production will go to the PV industry and how much will be provided to the national and international integrated circuit industry.

Wafer production

There were fewer than ten sc-Si and mc-Si wafer manufacturers in China with a total capacity of 71.5 MWp by mid 2005. They were unable to satisfy the whole domestic demand coming from cell producers not only because their capacity was

limited, but also because they exported the majority of their production mainly to Japan[135].

New wafer manufacturing capacity was expected for 2006 and the years to follow. New anticipated additions in capacity may well help in re-balancing the domestic c-Si value chain that is currently skewed towards module assembly (Figure 33), and so ease the dependence on imports.

Cell production

Cell production in China has surged recently from a 64 MW capacity in 2004 (56 MW of mc-Si and 8 of sc-Si) to a probable 257 MW at the end of 2005. This is due to both the expansion plans undertaken in 2005 by nearly all the existing cell producers and the emergence of a new actor on the Chinese solar cells scene: Nanjing PV-Tech. Co., which was expected to come on line with 30 MW by the end of 2005. When fieldwork was undertaken in mid 2005, the largest cell manufacturer (producing both sc-Si and mc-Si) was Suntech Power with a capacity of 120 MW.

Module production

Module production in China offers a scattered picture, with a lot of producers with less than 5 MW capacity. Total module production capacity was expected to reach nearly 300 MW by the end of 2005. The largest module producer at the end of 2005 was Suntech with a capacity of 180 MW, followed by Tianwei Yingli, which in the same year was completing a new line with 100 MW production capacity. The multitude of module producers with limited production capacity is not surprising. Assembling cells into modules does not require the same level of technical expertise needed in cell production and putting in operation a module assembly line is technically easier and faster than setting up a cell production line. This is particularly true if the module assembly line is partially or even fully manual, which is often the case with Chinese module producers. The vast majority of the modules produced in China are based on c-Si and only a very limited number of producers specialise in amorphous Silicon (a-Si) modules.

[135] Less than 20% - between 15 and 20 MW - of the wafers they produced were for the internal market.

5.4 Conclusions

The first part of this chapter presented the transformation over time of the Chinese NIS. This evolved from a linear model where few functionally specialised actors were strictly guided by the government's decisions, to a non-linear and multi-agent model where the government has a less pervasive role, the actors are more autonomous and functionally diversified and where more information can flow horizontally.

These different system configurations had profound implications for firms' innovative behaviour. During the planned economy period, the role played by firms in the innovation system was limited and they functioned only as manufacturing or/and sales units. They were output-oriented, strictly separated from innovative activities and were not supposed to undertake any R&D or to look, for instance, for the most suitable resources to feed their productive needs. National research institutes by performing R&D under the government's guidance were closer to an innovator's role than firms.

Since the late 1970s, a recombination of competences, where research institutes are encouraged to undertake commercial activities and where firms are supposed to respond to market inputs, has granted firms a central position in the innovation system. Firms are now free to invest and innovate based on their own strategic decisions and are bound to become a key pillar in the new development trajectory based on indigenous innovation that the Chinese government intends to undertake.

The second part of the Chapter instead focussed on the macro PV picture, which, since the early 2000s, has been dominated by the rapid take off of the domestic c-Si industry. This has resulted in substantial export towards those EU and USA markets where PV installed capacity is supported by rewarding public schemes.

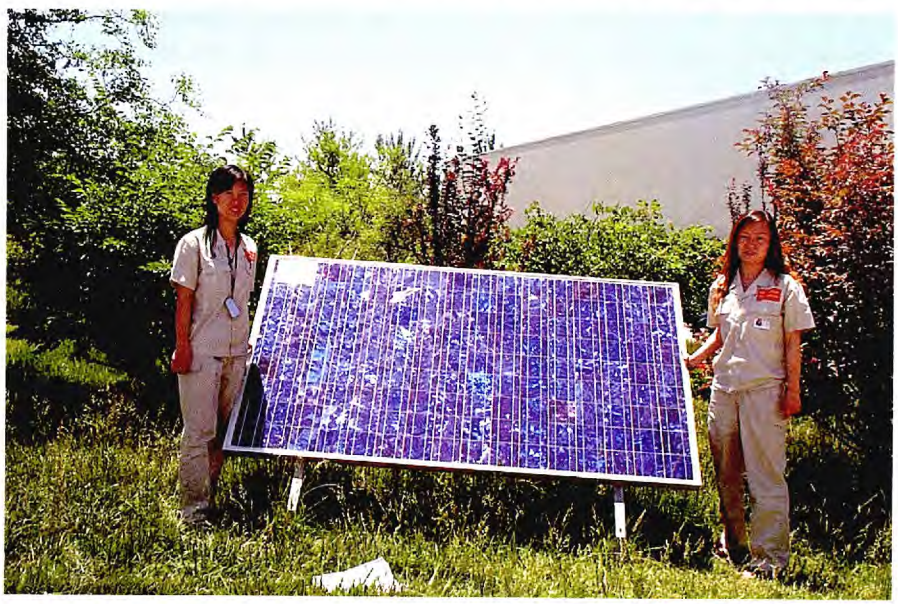
By comparison, the development of the domestic market and the goals set by the Chinese government for future PV deployment, are quite modest. Contrary to what has been happening in the rest of the world, the Chinese PV market remains dominated by off-grid applications and for the time being there is no government intention to support the untapped potential of the on-grid market[136]. This delay in promoting policies that can create larger opportunities in the domestic market means that the

[136] A few weeks before submitting this thesis the Chinese government announced its intention to promote incentive policies to support the domestic on grid market (http://progettonuovaenergia.blogspot.com/2009/03/cina-mette-in-campo-incentivi-per.html).

entrepreneurial spirit of the domestic industry is poorly mobilised and exploited to serve domestic environmental and development purposes. The extent to which this domestic industry has been improving its technological competence and has undertaken a purposive effort to add value is the object of the following two chapters.

6 EMPIRICAL FINDINGS FROM THE QUESTIONNAIRE WITH THE PV INDUSTRY AND THE INTERVIEWS WITH OTHER PV STAKEHOLDERS IN CHINA

Picture 8 A 340 watt module of one of the Chinese firms visited during the fieldwork



Source: Picture taken by the author during fieldwork in China, May-July 2005

6.1 Introduction

In the previous Chapters we laid the theoretical, analytical and methodological foundations of this study, which aims at understanding if, how and why PV firms in China innovate. We decided to focus on the firms' technological capabilities and on the innovation system that surrounds them, to explore the nature of their innovation, how it came about (i.e. how the technological capabilities had been accumulated) and what affected it. In this Chapter we present the results obtained by applying the framework described in Chapter 3, while undertaking two months of fieldwork in China from May to July 2005.

As explained in Chapter 3, two main methods were adopted to collect the necessary empirical data (see sections 3.3.3 and 3.3.4): a questionnaire survey

administered to a selected sample of 8 PV firms in China; and semi structured interviews conducted at the national level with key representatives of the Chinese PV research community, policy-makers, international organisations and an NGO (the WWF) that foster PV development and diffusion in China.

The results presented in this Chapter synthesise the information obtained by applying these two methods. They are organised, as suggested by the way in which the analytical framework has been developed (see in particular Figure 7 in Chapter 3), in two main sections. Section 6.2 presents how advanced is what the Chinese PV firms can do (i.e. it provides information about the nature of innovation useful to address research question 1). Section 6.3 is about the determinants of the technological effort in the PV firms (i.e. it contains the findings functional to answer the research question 2)[137]. In particular, section 6.3.1 presents the results obtained by applying the approach suggested by the TC literature, where the focus is on firm-level technological learning and what affects it. Section 6.3.2 is devoted to the systemic analysis and presents the evolution of the PV innovation system over time and its influence on the firms' ability to undertake technological change[138].

When fieldwork for this study was undertaken in mid 2005, little was known about the PV industry in China, particularly about the technical competence of the firms and their efforts to acquire, assimilate and manage a knowledge-intensive technology such as solar PV. What was known was that a domestic PV industry existed but, at least until the late 1990s, was producing low efficiency c-Si solar cells and modules and was far from being globally competitive (Dai and Shi, 1999). At the end of the 1990s several barriers (i.e. small market size, high production costs, capital shortage, unfavourable tax policy and limited R&D funding) were known to prevent this sector's growth and its capacity to enhance technological capabilities and add-value (Dai and Shi, 1999). What was also known was that in the early 2000s, only few years before the fieldwork took place, a few new cell and module producers had started to emerge and produce in the domestic market (Zhu, 2004). Very little was known about their activities and technological performance, however.

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[137] The specific questions that were asked during the survey at the firm level and the semi-structured interviews can be found in the Appendix 1 and 4 respectively.

[138] See Section 3.2.3 for details on how the analytical framework to explore these issues has been developed.

With this limited information available it was clear that a thorough investigation about technological change in this industry in China (i.e. what sort of innovation is it and how it can be explained) was badly needed. It was also apparent, however, that the expectations the author of this thesis had about the firms' ability to enhance their technological capabilities and indeed to innovate were limited and possibly conditioned by the dominant view emerging from the literature[139]. This pointed in the direction of an abundance of solar module assemblers and PV product manufacturers (i.e. a strong presence in the low-tech. end of the value chain), whereas the high-tech content of the production, like Si cells or wafers, was largely imported from abroad. Local cheap and abundant labour was expected to be extensively used to reduce production costs and enhance competitiveness[140].

Some solar cell producers were also thought to be present in the country and joint ventures with firms in mature economies were expected to play an important part to ensure the cell's performance, quality and customisation, but also to guarantee the necessary know how and capital[141], all factors that constrained the growth of the local industry until the late 1990s (Dai and Shi, 1999).

Similarly, a strong government role was expected, both in creating market opportunities[142] and in controlling part of the industry through its own SOEs. Back in the 1960s, when national research in Si solar cells was initiated by the government[143], PV had been considered a strategic national industry, so some form of public involvement was expected.

Innovation was expected to take place but was thought to be about re-creating, adapting to local needs (i.e. for rural electrification in sunny and remote locations in the western part of the country – see Section 5.3.1) and diffusing a technology developed in mature economies, rather than about undertaking substantial modifications or even moving the technology forward.

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[139] See in particular what has been said about innovation in a developing country context (Sections 2.5.2 to 2.5.6) and about China's innovative potential (Section 2.2.3).

[140] This was a reasonable expectation given that the PV module assembly process, contrary to other production processes along the value chain, can be largely manual.

[141] As explained in detail in Chapter 4 and briefly recalled in this Chapter, as you move up the c-Si value chain the technological know-how and capital requirements become more demanding.

[142] The Government's extensive rural electrification programme launched in 1998 and presented in Section 5.3.1 was expected to have been an important leverage for the local industry.

[143] See the following discussion in Section 6.3.2.

Although an emerging conducive environment for innovation[144], together with the rapid rate of economic and social change underway in China and the recent market entrants in the domestic PV industry, seemed to suggest that there might have been more to the PV experience in China than cheap labour and small incremental technological adaptation, it was difficult to fully appreciate the rich picture that emerged instead from the analysis.

6.2 Results about the nature of innovation in the Chinese PV firms

This section starts with a brief profile of the 8 PV firms that responded to the questionnaire survey[145]. Sections 6.2.2 and 6.2.3 focus on their capabilities in processes and products and on how they perform with respect to competitors. It should be noted at this point that the firm-level data presented in this section does not attempt to tabulate a full range of firm-level innovative activity. Rather, it gives a set of examples of the kinds and levels of innovative activity that the firms were engaged in.

6.2.1 Basic profile of the firms in the sample, their technology choice and presence along the PV value chain

Table 16 provides a snapshot of the 8 firms selected to respond to the questionnaire survey[146]. The firms' names are identified with letters, for confidentiality reasons[147]. The table includes information about the firms' age (i.e. date of establishment), size, ownership and market orientation. It also contains information about their choice of technology (i.e. with which PV technology family they engage) and their presence along the manufacturing value chain. As explained in the analytical

[144] I.e. capacity for advanced science and engineering education, increased national R&D expenditure, see Section 5.2.2.

[145] Although the findings discussed below and in the rest of the Chapter are the results of both the questionnaire with the firms and the semi-structured interviews with the other stakeholders (as explained in Chapter 3), only the profile of the firms will be presented here while a brief presentation of the respondents of the semi-structured interviews can be found in Chapter 3 (Section 3.3.4). A detailed description of the methodology adopted to collect the data and of the fieldwork is also provided in Chapter 3.

[146] See Section 3.3.3 for details on how the sample has been selected and the questionnaire designed

[147] A list of the firms that have been interviewed is provided in the Appendix 2.

framework (see Section 3.2.2) an understanding of these two aspects is important for a broader appreciation of how advanced is what firms can do.

The choice of PV technology

As shown by the second column in Table 16, the sample included only firms involved in c-Si technology[148]. This confirmed what had already emerged during a preliminary search performed before undertaking the fieldwork in China (see Chapter 3 section 3.3.3): that the vast majority of the PV firms present in China in 2005 were involved in c-Si manufacturing.

Presence along the PV supply chain

As Table 16 shows, the sample included firms involved in c-Si wafer, cell, module and product manufacturing (see the third and the fourth columns in Table 16). As previously mentioned, feedstock producers, although they were intended to be part of the firms' population to be surveyed (see Section 3.3.3 and in particular Figure 12), could not be interviewed. This was due to the impossibility of getting access to the only two semiconductor producers who, in 2005, supplied the domestic PV industry with Si feedstock (in the form of rejected or substandard product from electronics grade sc-Si)[149].

Figure 34 visually presents with shaded areas the links in which the firms in the sample were positioned along the c-Si value chain.

[148] See discussion about the different PV technology families in Chapter 4

[149] As discussed in Chapter 5 (Section 5.3.3), at the beginning of 2005, 95% of the Silicon feedstock demanded by the domestic PV industry was imported from abroad. The domestic semiconductor industry provided the remaining 5% by supplying 50 tons (about 3MW) of electronic grade silicon per year (REDP, 2004)

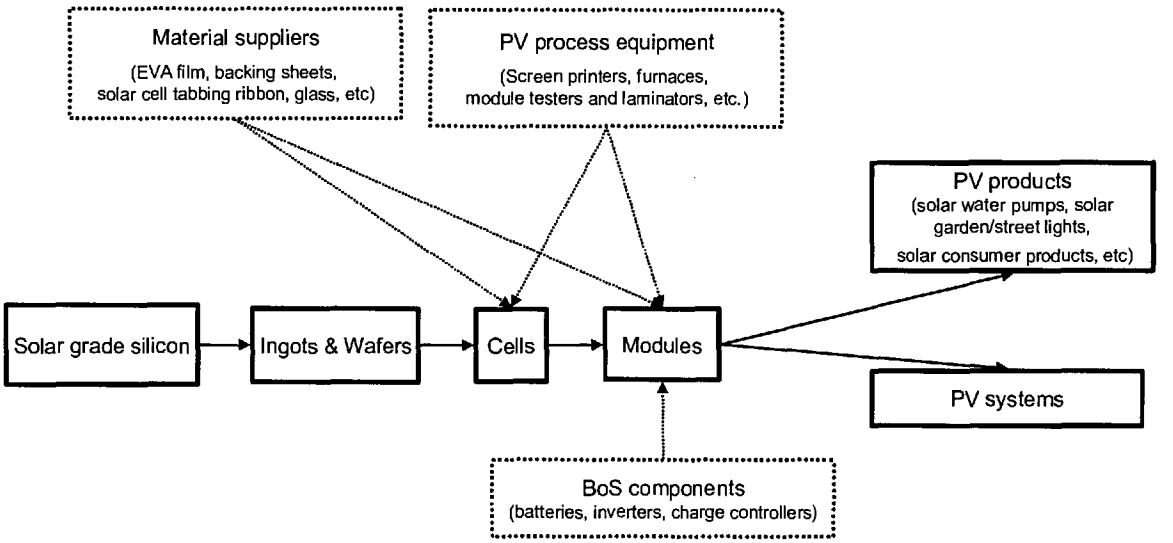
Table 16 Basic information about the firms in the sample (June 2005)

Firm	PV technology family	Presence in the manufacturing chain		Age	Size			Ownership	Market
		Main product line	*Other product lines*		*Production capacity[2] 1st half 2005(MW)*	*Production capacity 2nd half 2005(MW)*	*Personnel*		
A	c-Si[1]	Modules	PV products	1995	4	–	70	L[3] (Private)	D, E[5]
B	c-Si	Modules	Cells	2001	1	–	25	L (Private)	D, E
C	c-Si	Modules	Wafers, cells	1998	16	100	>600	L (shareholding)	D, E
D	c-Si	Modules	Wafers, cells	1979	4	50	400	L (stock firm)	D, E
E	c-Si	Wafers	–	1999	2	–	35	L (shareholding)	D, E
F	c-Si	Modules	Cells	2001	25	180	>1000	L (stock firm)	D, E
G	c-Si	Modules	Cells	1998	10	30	200	L (shareholding)	D, E
H	c-Si	Modules	–	2001	15	25	240	WOFE[4]	D, E

Note: [1] c-Si = crystalline Silicon. [2] Production capacity refers to the main product line. Since 5 of the 8 firms that were interviewed in May-July 2005 were in the middle of a production capacity's expansion plan, both the capacity in the first and in the second half of 2005 are indicated in the table. [3] L = locally-owned. [4] WOFE = wholly-owned foreign enterprise. [5] D = domestic. E = export

Source: Author's fieldwork

Figure 34 The Chinese PV firms presence along the c-Si value chain



Note: the shaded boxes indicate where the firms in the sample operate

Source: Author's elaboration

Although firms tended to have one main product line, usually module production, as shown in column three, which constituted the bulk of their sales, it was not uncommon for them to undertake manufacturing also in other business areas along the c-Si value chain (see column four, Table 16). It was for instance possible to find firms involved in module as well as cell production or producing modules and assembling them into PV consumer products (such as garden lights, watches, calculators, etc.). Usually firms that had more than one product line (for instance wafer or cell manufacturing, besides the main PV module line) tended not to sell these products but to use them to feed their own module production.

By choosing firms that participated in more than one manufacturing link along the c-Si value chain, this study was able to gain a fairly wide spread of firm types and sectors. Table 17 groups the firms in the sample according to the manufacturing links along the PV supply chain they operated in and indicates:

- The proportion they represented of all firms operating in China in the same manufacturing link in 2005 (when the fieldwork was undertaken).
- How significant they were with respect to the total production capacity available in China in 2005 in each manufacturing link.

Table 17 Proportion of population surveyed relative to total firms operating in that specific productive process and their significance in terms of production capacity

Productive process	Sample surveyed	Tot. no. of Chinese firms in productive process (2004/early 2005)	% of population surveyed relative to tot. no. of firms in that productive process	Tot. production capacity for productive process, MWp (2004/early 2005)	Significance of population surveyed in terms of production capacity (%)
Wafer	3	7	42.9	71.5	12.6
Cell	5	7	71.4	199	94.0
Module	7	22	31.8	255	76.9

Note: In mid 2005 there were 26 firms in China producing solar wafers, cells or modules. However, since companies might be present in more than one of the productive processes, the total number of companies in column 3 is higher than 26.

Sources: Author's fieldwork for production capacity pertaining to the 8 firms in the sample. REDP, 2004, Wang, 2006 for data pertaining to the firms not in the sample.

As illustrated by Table 17, when the firms selected to take part in the survey are grouped according to the productive processes they participated in, they represent a significant share of the total Chinese PV firm population, both in terms of total number of firms and production capacity. The only exceptions are the wafer producers in the sample, which constituted only 12.6% of the total capacity available in the country at the time of fieldwork. The location of the domestic wafer producers or the difficulties encountered in getting access to some of them prevented the author of this thesis from including a broader number of wafer producers in the selected sample.

The location

As illustrated by Figure 35 the firms in the sample were concentrated in two of the zones with the highest industrialisation rate in China: 1) the Tianjin-Beijing area, identified by the circle in the north-eastern part of the map; and 2) the Jiangsu-Zhejiang (Shanghai included) area, identified by the circle along the coast on the eastern side of the map.

Figure 35 Location of the firms visited and interviewed during fieldwork in China in mid 2005



Source: Author's fieldwork, May-July 2005

The firms' ages

The majority of the firms interviewed were established between the late 1990s and the early 2000s, while only one dated back to the late 1970s when PV manufacturing was first established in the country (see section 6.3.2 in this chapter).

The Firms' sizes

The size of each firm (columns 6, 7 and 8, Table 16) was assessed with reference to: the number of people employed and the production capacity (MW/year) the firms had in the first half of 2005 as well as that they expected to have by the end of 2005. When assessed in terms of the number of people employed, the sample was made of micro and small firms, with the largest firm employing around 1000 people and the smallest one just 25[150].

[150] According to the Centre for SME studies of the Indian Institute of Foreign Trade (IIFT) 'small' enterprises operating in the industrial sector in China are those having between 200 and 2000 employees (http://www.smeiift.com/sme/SME_Overseas.asp. Viewed in April 2009).

The firms in the sample resulted small also when the production capacity they had in the 1st half of 2005 was compared with the production capacity of the top 10 world module and cell manufacturers in 2004 (see Table 13 in Chapter 4).

However, when the plans for the expansion of the production capacity the firms had for the second half of 2005 were taken into account, then more than one PV firm in China was on the way to become a large world PV player[151].

Ownership

As illustrated by column 9 in Table 16, seven firms in the sample were locally-owned. Only one firm was a wholly-owned foreign enterprise (WOFE), but with an entirely Chinese management and labour force. Remarkably there were no joint ventures[152]. Of the domestic firms, three were shareholding enterprises absorbing both domestic state-owned and private capital; two were joint stock enterprises, while the remaining two were entirely privately owned[153].

Market orientation

Although firms produced for both the domestic and the international market (see last column, Table 16), the large majority of their output was exported. This is further illustrated by Table 18, which details both the share of the production that was devoted by each firm to export and the final destination of the goods. On average, 80% of the firms' production was exported abroad and very little remained for the internal market, which was increasingly resorting to imports. Europe (mainly Germany), followed by the USA, were the most popular markets of destination for the Chinese PV modules. Much less popular seemed to be the Japanese market, despite its geographic proximity and the far-reaching programmes promoted in the early 2000s by the Japanese government to boost installed PV capacity in the country (Ikki, 2004).

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[151] Indeed by 2007 two of the Chinese firms in the sample entered the top 10 PV world producers (Photon International, 2008).

[152] This applies not only to all firms in the sample but also to the vast majority of the PV firms that were producing in China in 2005 (see Chapter 5 for more details).

[153] *Wholly foreign-owned enterprises* are exclusively invested by foreign companies or individuals in China, in accordance with the laws of China. *Joint-stock company* refers to a company or corporation whose capital is divided into shares. Any legal entities or individuals may invest in the company in exchange for the proportional amount of shares. *Entirely private* firms are invested by a natural person and the company and all its properties are owned by the investor (http://www.chinadetail.com/Business/InvestmentChinaCompanyOwnership.php).

Table 18 The sample firm's main markets and their location

Firm	% of products exported	Main destination markets
A	80	Germany, USA, Ecuador
B	33	Germany (only small amount), countries around China
C	90	EU (mainly), USA, Africa
D	80	USA, Africa, EU
E	80	EU (Germany, France, Italy)
F	80	EU (mainly)
G	90	EU, USA, Japan, other countries in Asia
H	80-90	EU (France, Italy, Germany, Spain), USA, Canada, Mexico

Source: Author's fieldwork

Who was interviewed within the firms

The last information presented in this section pertains to the people who responded to the questionnaire within the firms.

Table 19 List of people interviewed within the firms

Firm	Position held by the person(s) interviewed
A	General manager and production manager
B	General manager
C	Project manager of overseas business department
D	General manager
E	General manager
F	Vice Chief engineer
G	CEO and Senior scientist of R&D centre
H	Senior buyer

Source: Author's fieldwork

As illustrated by Table 19, the majority of the interviewees were the general manager or the chief engineer of the firm. They were selected on the assumption that they could reasonably be expected to possess the best information about the firm's history and technology. As Table 19 shows, in two cases, where the general manager was not available, other senior figures were interviewed.

6.2.2 Capabilities in process and product manufacturing

In the analytical framework (Section 3.2.2) we discussed the importance of assessing how advanced the firm's processes and products are. We also explained that this can be empirically studied by: (a) distinguishing between different

complexity/maturity levels (i.e. basic, intermediate and advanced); and by (b) observing possible technological capability improvements over time. We suggested checking, for instance, for the firms' possible ability to diversify products over time or to increase product complexity.

In what follows we present the results obtained in exploring these aspects in the selected Chinese PV firms.

Capabilities for processes

Basic capabilities: routine operations on turnkey production line and minimum maintenance on the production line

The analysis of the results obtained from the questionnaire shows that all the firms interviewed were adopting commercial equipment, which usually came from more than one supplier, both abroad and, where possible, in China. In some cases, as discussed below, firms could even manufacture in house some of the equipment they needed.

Only in the case of one firm was the whole turnkey production line bought from a unique foreign supplier, who helped with the installation and maintenance.

All the firms were able to source from the most appropriate suppliers the equipment that was relevant for their production, i.e. they had the minimum technical capabilities and knowledge to choose what was more appropriate for their needs and did not need to rely solely on one supplier (maybe foreign) for the provision of turnkey equipment and for the assistance in the equipment's installation and maintenance. Table 20 provides some examples of the type of equipment acquired by some of the firms in the sample and their origin.

Table 20 Origin of some key equipment along the sample firms' production line

Firm	Type of equipment	Country of origin
B	Furnace	Made in-house
	Laminator	USA
C	Furnaces	USA
E	Furnace	UK
	Wire saw	Switzerland
	Other equipment	China
D	Wafer Etch equipment	made in-house
G	Main key equipment	China
F	Screen printers	Italy
	Coating and Passivation equipment	Germany
	Other equipment	China or made in-house

Source: Author's fieldwork

All the firms in the sample were able to undertake on their own (i.e. without external help) routine operations on the production line and were fully capable of conducting the necessary maintenance (both ordinary and extraordinary) to guarantee basic quality standards.

Intermediate capabilities: small modifications of production line installation and equipment and self-construction of small pieces of equipment

As detailed in the analytical framework (Section 3.2.2), several questions were aimed at understanding whether the firms were able to undertake small modifications. These might include: changes in how the production line is installed, small changes to some of the equipment along the production line or the ability to construct small pieces of equipment by themselves. As explained in Chapter 3 (Section 3.2.2), these capabilities can be used, with specific reference to PV, as proxies for adaptive or intermediate process capabilities based on search and experiment.

Modifications of the way in which the production line was installed did not play an important role in the firms' technological activities. Although, to suit different domestic conditions, two firms modified the standard installation suggested by the foreign supplier, the majority of the firms followed the instructions provided for the installation.

Far more important were changes in the single pieces of equipment. All the firms interviewed were in fact both able to undertake small modifications in the main production line's standard equipment and to construct small pieces of equipment to meet their specific production needs. These could include, for instance, adding to the

standard equipment a customised basket to catch the c-Si wafers as they were cut from the Si ingot, or manufacturing some spare parts or tools. These modifications were carried out either by the firms themselves or in close cooperation (and according to the firm's instructions) with the domestic suppliers or, in a few cases, with local universities with whom the firm had cooperative projects.

These modifications were undertaken either to improve production processes or, more often, to reduce production costs. During the survey it emerged that firms preferred to construct by themselves some of the spare parts to be used in the production line, because this was a much cheaper option than buying the same equipment from a local or indeed a foreign supplier (savings could be up to 50% and in some cases, depending on the type of equipment, 70%).

Advanced capabilities

a) Major modifications to productive processes and/or manufacturing of entirely new equipment to be used in the production line

Only five of the eight firms interviewed were able not only to make small modifications but also to substantially modify productive processes or to design entirely new equipment to be used for their own specific productive needs[154]. As for minor modifications, in some cases these changes were made entirely in-house by the firms, while in some others they asked their suppliers (where possible Chinese) to produce the required and customised equipment according to their own design and instructions.

In what follows, several examples of the major modifications or novelties undertaken by the firms on the productive process or on the equipment are briefly illustrated. Their relevance to PV cost reduction or process improvement is also explained.

1. *Improve cutting processes to reduce the thickness of the wafers*. One firm mentioned it aimed at achieving 180μm wafers (improving from the current 220μm) by improving its wafer slicing technology. As explained in Chapter 4 (Section 4.4.1), producing thinner wafers allows significant savings in the Si used in the productive process but presents a

[154] As explained in Chapter 3, these modifications are different from doing small piece of equipment or spare parts: they require significant technological effort, search for solutions and willingness to improve/move forward.

considerable technological challenge because reduction in wafer thickness should occur without increasing wafers breakage.

2. *Producing larger wafers and designing a bigger and suitable furnace to accommodate them.* As pointed out in Section 4.4.1, an increase in wafer or cell size allows to optimize the watts per kilogram of Si consumed. One firm was constructing its own customised furnace to accommodate the larger wafers it intended to produce. As in the case of the thickness of the wafers, also increasing the wafer's size is technologically challenging because there is a limit to how large a single cell can be built before current collection would start suffering, causing a drop in the cell's efficiencies (Kluftinger, Roller, & Gallagher 2005). Moreover temperature in the furnace is the primary factor that controls the strength of the Si wafer, and this must be taken into account when setting the furnace's temperature ramping conditions (http://www.memc.com/t-slip-breakage-furnace-slip.asp). Smaller diameter wafers can be ramped slightly faster, but larger wafers must be ramped more slowly to avoid physical deformation of the wafer as well as wafer breakage. This requires technological competence and experience.
3. *Special surface treatment to produce a cell's front surface of minute pyramids.* One of the firms that was interviewed had patented a cell with an inverted pyramid surface, which could guarantee superior light trapping performance. This is important to enhance cell's efficiency because: "the more sunlight that goes into a PV cell and the less that reflects back, the higher the cell's efficiency can be" (http://www.gatech.edu/newsroom/release.html?id=2708).

It is important to recall (see Section 3.2.2) that all these modifications to production processes or production equipment should be understood as 'major/advanced'. This is because they are the result of an autonomous technological effort to move forward in order to add value. These improvements can not be easily reproduced by some other firms (as in the case of small modifications to the production equipment, which are used by this study as evidence of intermediate capabilities), but they require advanced technical knowledge and problem solving skills that are firm-specific.

b) Adopting alternative c-Si production technologies and novel manufacturing methods based on emerging technology families (i.e. non c-Si)

Findings from the questionnaire suggest that one firm was considering entering Si feedstock production by purifying inexpensive, readily available metallurgical grade Silicon into solar grade Silicon (SGS) for the PV industry. This is a complex technological process that requires advanced technological capabilities. Moreover, ramping-up SGS production is a slow (between one to two years) and capital intensive activity (see Section 4.4.1.). This means that a firm willing to enter feedstock production should not only possess the necessary (advanced) technological capabilities but also be able to gather the necessary capital and plan investment and production capacity well in advance.

No evidence collected during the survey seems to suggest instead that there were firms thinking to adopt alternative and advanced c-Si production technologies such as, for instance, growing ribbons of mc-Si, which make an excellent use of Si and can offer a high potential for cost reduction (see Section 4.4.1). Although no firms among those interviewed adopted novel manufacturing methods based on emerging technology families like, for instance, organic PV, one firm was considering setting up in two years time a thin film R&D and manufacturing facility in China.

Capabilities for products

Basic capabilities: delivering standard PV products at a minimum quality requirement

All the firms in the sample could manufacture standard 'off the shelf' (see Section 3.2.2) c-Si products (i.e. wafers, cells and modules) with minimum quality requirements and to be used for off- and on-grid applications as well as for PV products such as garden lights, calculators, etc. This is evidence of the fact that they had assimilated basic product design and could satisfy the mainstream market demand.

Intermediate capabilities: small product modifications and international level of quality standards and procedures

All the eight firms interviewed stated they were able to make small modifications to their standard 'off the shelf' products. Modifications were usually undertaken to satisfy specific customers' requests or to improve the products' quality.

Examples of small modifications were numerous and varied across the firms, the type of product (i.e. wafer, cell or module) and the type of customer's request. Some examples included:

- Low-weight or double-glass modules for roof-top applications or large-area solar power plants.
- Modules for very humid weather conditions or for very extreme temperatures.
- Custom-sized solar modules.

These modifications require understanding of the scientific/technical principles necessary to make the technical changes and imply some modification in the way in which the products are produced (i.e. modifications in process capabilities).

Six of the firms in the sample obtained accreditations of product quality from international certification and regulatory bodies. Some of the certifications acquired included: IEC (International Electrotechnical Commission) solar simulation requirements for PV module qualification testing; TÜV (Technischer Überwachungs-Verein, in English: Technical Monitoring Association), to ascertain the safety and quality of the modules; CE (Conformité Européene), to declare conformity with the legal and technical directives of the European Union.

As detailed in Chapter 3, this study uses the acquisition of international certifications as evidence that firms have moved beyond the basic capabilities necessary to deliver products with minimum quality requirements and have acquired the necessary knowledge to improve product quality and keep up with the changing quality requirements of the global demand[155].

Advanced capabilities

a) Greatly modified and/or new products

Five firms stated they intended to produce greatly modified or new products between the second half of 2005 and 2006. These included: larger size wafers and solar

[155] Conversations had by the author with users of some the PV modules produced in China, seem to suggest that the effective quality of the modules (or indeed of other PV products made in China) might not be as high as the obtainment of international certification would instead lead to think. Since ascertaining the actual quality of the Chinese PV products is beyond the scope of this study, we use the obtainment of international certifications as evidence of the quality level achieved by the PV manufacturers in China.

cells; cells with higher efficiency and solar modules for non standard applications (e.g. for PV building integration) and markets (e.g. to be used in the automotive industry).

All these undertakings require advanced technical skills and knowledge. Enhancing the efficiency of a c-Si cell requires, for instance, increasingly sophisticated processing techniques because the higher the efficiency the more difficult it gets to achieve further improvements. Similarly, cutting thinner c-Si wafers from the ingot presents mechanical problems that should be understood and overcome in order not to break the wafer while trying to reduce its thickness. Finding non-standard applications for modules previously produced for conventional on-grid or off-grid markets implies improving not so much the technology but the applicative aspects of it and hence deepening knowledge and understanding of new markets.

Although these new products do require advanced product capabilities and the need to modify and manage more complex productive processes (i.e. they are evidence of the fact that a few firms in the sample had proceeded well above efficient imitation and skilful adaptations), they are not necessarily groundbreaking new products.

A small section of the questionnaire (see Appendix 1 at the end of this thesis) was aimed at understanding whether some of the firms intended to explore the possibility of producing completely new products, particularly whether they intended to:

1. Use new materials, like organics, III-V semiconductors, carbon nanotubes, etc.
2. Experiment with alternative module design (cells embedded in glass, concentrators, etc.).
3. Produce solar modules with complementary functions (for instance, for electricity production and solar thermal water heating).

Only one firm in the sample was thinking, and indeed very close to start producing, modules with an alternative design and with a material not used in its standard production: a module, based on a-Si, with a semitransparent finish, to be used in curtain walls or other vertical or sloped glazed surfaces.

b) Having patents or licensing own technology to third parties

Four firms, out of the eight in the sample, responded that they had patents or other protected intellectual property (i.e. trade marks, designs and copyrights) and in two cases they also licensed them. Two firms instead stated that, although they came up

with innovative product or process solutions they preferred not to apply for patents, fearing technological leakages, but to apply for a so called 'innovation award' granted by different Chinese governmental bodies at both the local and the national level. These certificates are domestically awarded to firms for significant quality or technological improvements and are used by the firms as an important selling point that enhances their reputation with domestic customers.

The improvement of technological capabilities over time

As explained in Chapter 3, in order to understand how advanced is what firms can do and to monitor possible advances in technological capability, this study observes the evolution of a number of indicators over time. These include: increase in product complexity, degree of product diversification, quality and technical improvements and expansion of production capacity. Two points in time were considered: when the firm started producing and when the survey was undertaken (May-July 2005).

Increasing product complexity

As explained in Chapter 3, increases in product complexity can be used as an indicator of firms' technological deepening over time (Romijn, 1999, Romijn, 2002).

Five firms reported they had been able to increase the complexity of their products through time. Examples vary across firms and include: the ability to produce cells with a higher efficiency and larger or thinner wafers over time.

As far as the efficiency of the cells is concerned, in 1999 the average efficiency of the cells produced in China was between 10 and 12% (Dai and Shi, 1999)[156]. At the time of the survey the average cells' efficiency was between 13% and 17% (depending on whether sc- or mc-Si was used).

In terms of Si wafer thickness, one of the firms interviewed declared that in the mid 1980s it used to produce 450μm thick wafers (this was also the national average at the time as confirmed by interviews had in China with different PV stakeholders). At the time of the survey, the same firm was producing 250μm-thick wafers and aiming for a mid term target of 180μm.

[156] Although during the interviews with the firms in the sample it was asked what was the efficiency of the cells they used to produce at the beginning of their activity, the interviewees could not remember the exact figure. They only stated that the efficiency was certainly much lower than the one they could achieve at the time of the interview. For this reason we adopt historic data obtained from secondary sources.

Degree of product diversification

Another important indicator, as discussed in Chapter 3, is the ability to diversify products over time and move along the PV Si value chain from less to more knowledge-intensive manufacturing links.

Table 21 shows the products manufactured by the firms in the sample at the time of the fieldwork (May-July 2005), together with those: (a) they manufactured when they started producing; and (b) they intended to invest in the future.

Table 21 Past, present and future products' plans of the Chinese PV firms along the c-Si value chain

Firm	Past	Present		Future
	Main product line	*Main product line*	*Other product lines*	*Plans for new product lines*
A	BoS and PV products	Modules	PV products	Wafers
B	Modules	Modules	Cells	Wafers, silver aluminium paste
C	Modules	Modules	Wafers & cells	PV systems
D	Wafers	Modules	Wafers & cells	Wafers
E	Wafers	Wafers	-	Cells
F	Cells & modules	Modules	Cells	Solar grade Silicon
G	Cells, modules & BoS	Modules	Cells	Cells
H	Modules	Modules	-	Modules

Source: Author's fieldwork

As shown by the table, at the beginning of their activity (see the second column of the table) four firms (A, B, C and H) were producing balance of system components (BoS)[157], PV products or solar modules only, i.e. they were taking part in those manufacturing steps of the PV supply chain with a relatively low technological content (see Section 4.3). Through time all but one of these firms were able to diversify their activities and to enter new and more technologically demanding manufacturing links, like cell and wafer production (see columns 3 and 4), where the role of the technology and the ability to master it are more important.

Two other firms (G and D) have been able either to abandon the more low-tech activities or to diversify their product range by entering new manufacturing steps along the PV supply chain.

[157] For an introduction to the BoS see Section 4.2.2.

As far as plans for future investment are concerned (see the last column in Table 21), five firms (A, B, D, F and G) intended either to consolidate their presence in the knowledge intensive links of the value chain or to move further upstream along the c-Si supply chain and to engage in even more high-tech processes, like the production of wafers or indeed solar grade Si, as mentioned previously. Only one firm (C), which was already present in wafer, cell and module production, intended to expand its activity to a more labour intensive sector, PV systems, with the intention of becoming the only fully vertically integrated PV firm in China.

Improvements in quality and technical performance

Six firms had international quality certifications at the time of the survey (see previous discussion) and had been able to improve the quality of their products over time.

This pertained to both the products' technical performance (i.e. ability to sell products with a longer life time or with better electric contacts) and to the ability of obtaining an increasing number of international certifications. During the semi-structured interviews with stakeholders involved with PV development and diffusion in the country, it emerged that only two of the firms in the sample were able to deliver products at an international quality standard only two years before the survey for this study was undertaken.

Further evidence of quality improvements over time came from a report published by the Chinese Centre for Renewable Energy Development in 2000. The report lamented the low technology level of the industry, not only in terms of cells' efficiency but also poor performance: "After 3–5 years of usage, yellowing, bubbling, de-lamination of contacts, and an efficiency decrease appeared in some modules. Thus, their actual service life is shorter than that of foreign products" (Centre for Renewable Energy Development and NREL, 2000, p. 22).

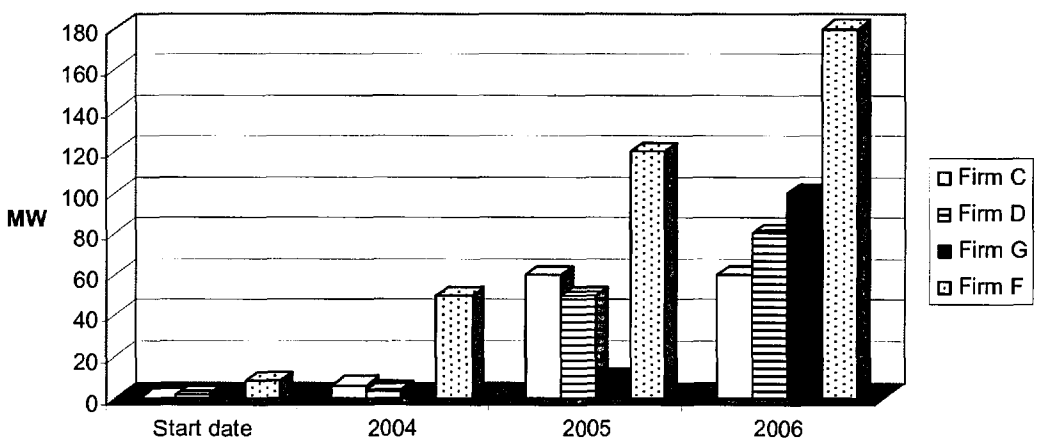
Expansion of production capacity

As explained in Chapter 3, the possibility of expanding the production capacity is an important indicator that indirectly affects the technological capabilities of PV firms. This is so because firms with limited production capacity may find it difficult to cut down production costs, to source materials at reasonable prices and to compete (see

Chapter 4). This could, in turn, affect the enhancement of their technological capabilities.

In terms of solar cell capacity, four cell producers (C, D, F and G), out of the five that were interviewed for this manufacturing link, had been able to increase their production capacity since the day on which they started producing. Figure 36 shows their progression over time and highlights what plans they had in 2005 for expansion capacity in the following year.

Figure 36 Cell production capacity (MW) of the firms in the sample: start date - 2006



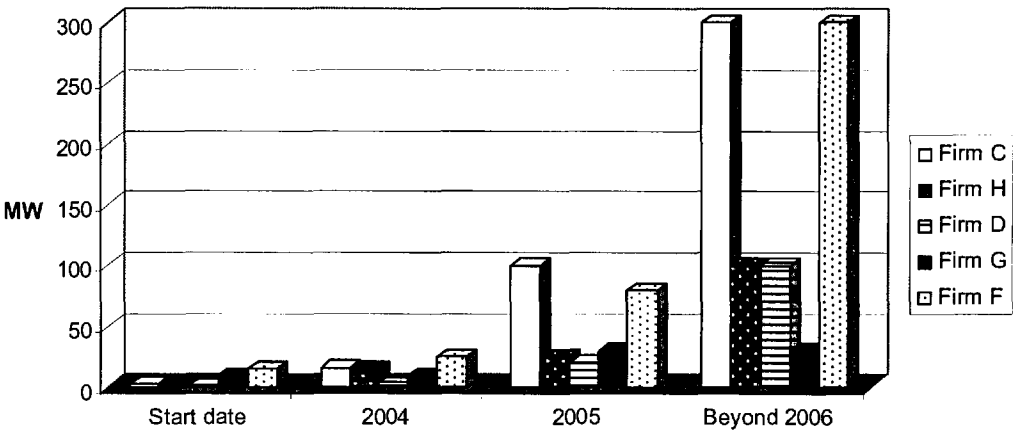
Source: Author's fieldwork

These cell manufacturers had been able to respond to the challenge of rapidly rising global solar electric demand (especially in Germany), by ramping up production capacity. In particular, two of them (firms C and F) managed to enter the group of the top ten world PV cell and module producers by 2007.

Only one cell producer (firm B), of the five interviewed, had not been able to increase its quite limited production capacity and declared during the interview that this was a major constraint to its future competitiveness and ultimately to its ability to deepen its technological capabilities.

In terms of production capacity for solar modules five firms – C, D, F, G and H - (out of the seven in the sample producing modules) increased their production capacity over time and intended to further expand it in the future. This is illustrated in Figure 37 below.

Figure 37 Module production capacity (MW) of the firms in the sample: start date – beyond 2006



Source: Author's fieldwork

6.2.3 Chinese firms versus competitors

As detailed in the analytical framework (Section 3.2.2) the complexity of what the PV firms in the sample can do with respect to international competitors is assessed with respect to two different dimensions:

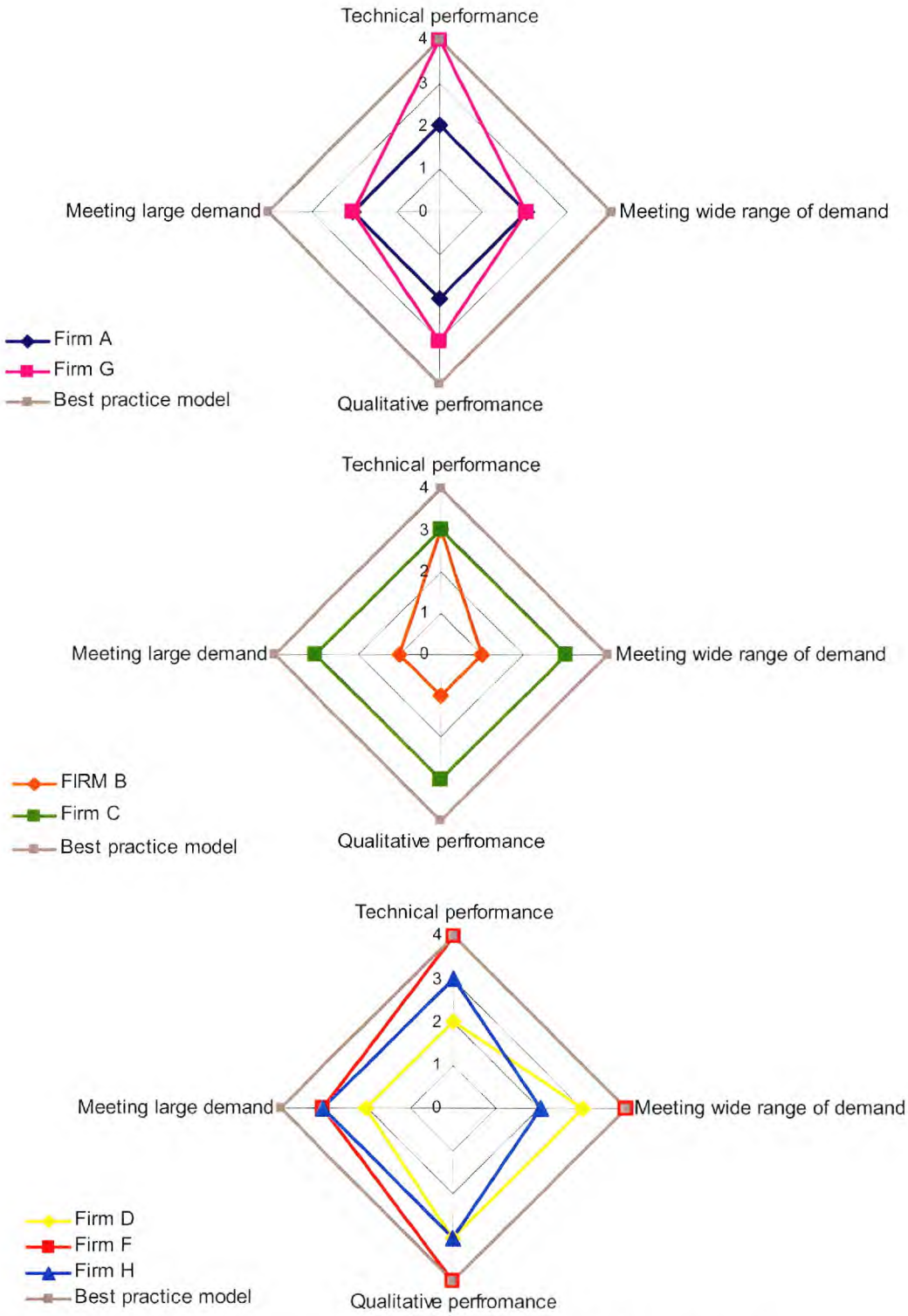
a) The ability to manufacture products that are commercial state of the art
b) The ability to take steps to push the technology frontier.

The indicators used to explore each of the two dimensions, how they have been measured and how the level of the firms' capabilities with respect to the 'best practice model' (i.e. the top world c-Si module producer in 2005) has been assessed have been presented in Chapter 3 (see Table 3 and Table 4). Here we draw on an existing study by Rush et al. (2007), to develop spider maps that graphically represent the extent to which the seven c-Si module producers in the sample can deliver products that are commercial state of the art[158] (

Figure 38). It should be recalled at this point (as already explained in Chapter 3, Section 3.2.2, point D) that only 7 out of the 8 firms in the sample are represented in the spider diagrams. Firm E, which is the only wafer producer in the sample, is exluded from the analysis because it was not possible to retrive some of the data relative to its production.

[158] For a definition of 'commercial state of the art' see Chapter 1, Section 1.4.

Figure 38 The ability of the PV firms in the sample of manufacturing products that are commercial state of the art



Source: Author's elaboration drawing on examples provided by Rush et al. (2007)

Three spider maps are generated where the level of capabilities of the different firms is represented against each of the four indicators we proposed to use in the analytical framework. The four indicators are: technical performance, meeting customer's demand with a wide range of products, qualitative performance and meeting demand for utility scale installation (i.e. meeting large demand).

Despite considerable differences among the firms,

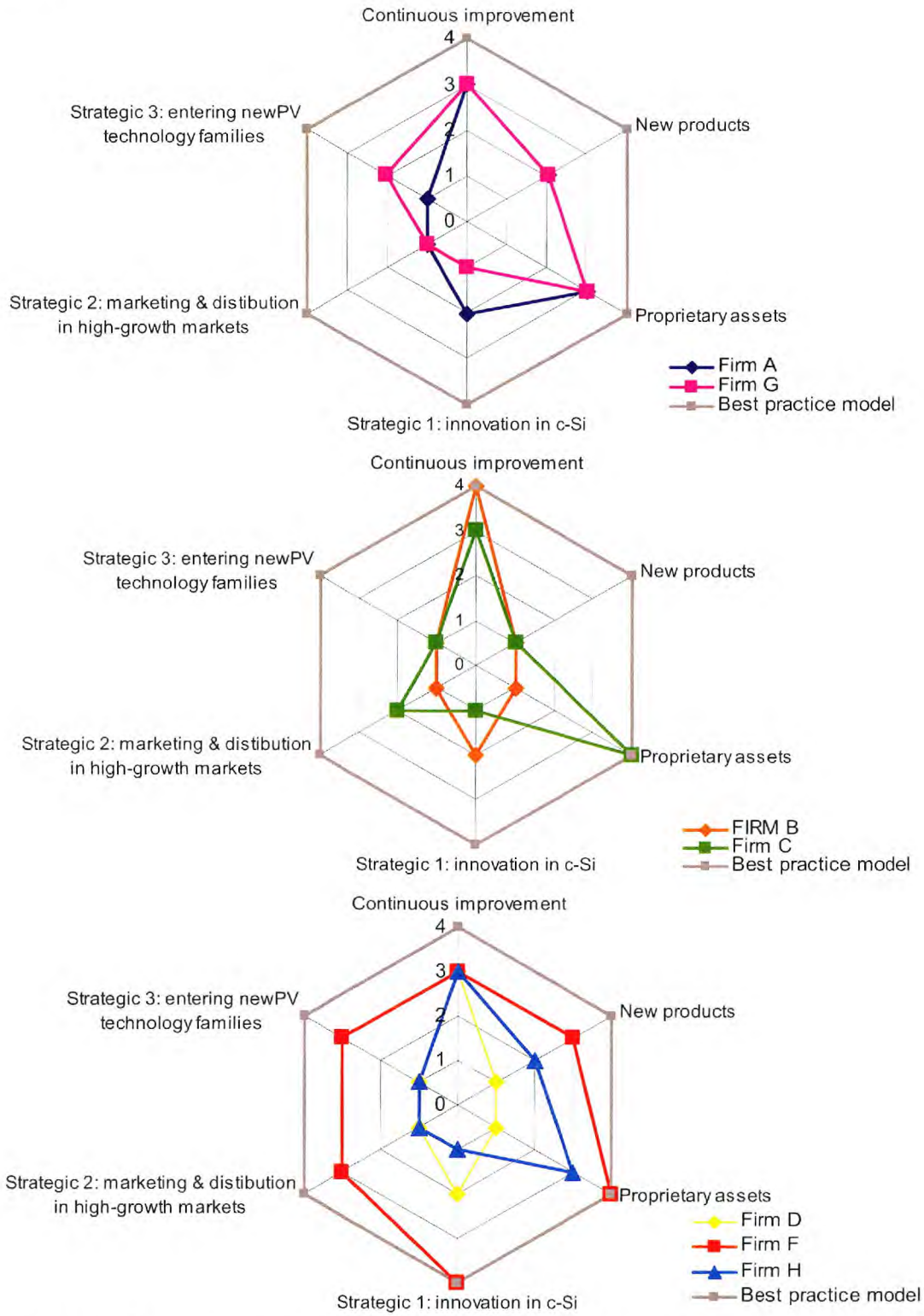
Figure 38 illustrates that all the seven firms had in 2005 a good level of technical performance with 2 firms producing c-Si modules with the same efficiency as the world's top module producer that was taken as the 'best practice model'. Moreover, 3 firms were able to produce modules with efficiencies that were 75% of the reference value[159]. Also in terms of qualitative performance, although differences across the firms remained, the firms in the sample were able to produce, or got quite close to producing, modules that were commercial state of the art.

Where the Chinese PV module producers seemed instead to be far from the best practice model was in their ability to produce a wide range of products and to achieve a production capacity large enough to meet demand for utility scale installation (i.e. to have a large production capacity that could allow them to satisfy not only small residential applications). As will be discussed in the following chapter, limited production capacity was indeed a constraint on the ability of some of the PV firms in the sample to innovate.

Figure 39 illustrates the possible steps taken by the seven c-Si module producers to push the technology frontier. As illustrated by the three spider maps in the figure, only one firm, firm F, scored high for all the six indicators we have suggested to use (see Section 3.2.2) and showed itself to have a strategic vision by wishing to enter in the near future high value-added links on the c-Si value chain (i.e. the production of c-Si feedstock) and by investing in additional marketing and distribution channels where the demand was booming (in particular in Japan).

[159] See Section 3.2.2 for detail on how the levels of capabilities have been assessed with respect of the four indicators.

Figure 39 The ability of the PV firms in the sample of taking steps to push the technology frontier



Source: Author's elaboration drawing on examples provided by Rush et al. (2007)

Although the other six c-Si module producers might well have scored high in one or two of the indicators we developed (for instance, the commitment to continuous improvement as measured by in-house R&D or having proprietary assets), they were far from the best practice model especially for what pertained to strategic decisions.

6.3 Results on the determinants of innovation in the Chinese PV firms

This second part of the chapter reports the results on how technological capabilities were accumulated by firms and what influenced their ability to innovate. As explained in the analytical framework (Section 3.2.3), two different approaches were adopted to deepen understanding:

1. That suggested by the TC literature, where the focus is on firm-level technological learning and what determines it from a static perspective.
2. That proposed by the IS literature, where the attention is on the system of which firms are part and on how its structure and performance conduces to innovation development and diffusion in the firms.

The findings presented below combine insights obtained from both the firm-level questionnaire and the interviews with the other stakeholders of the Chinese PV sector (see Sections 3.3.3 and 3.3.4).

6.3.1 Knowledge accumulation as a result of firm's learning and of the factors that affects it

This section is devoted to the results obtained by applying the insights from the TC literature as suggested by the analytical framework and schematically represented in Figure 9. The section is divided in two main parts: the first presents how the PV firms in the sample learn and the second reports the results about what influences this learning.

Learning

Evidence from the interviews suggests that new technical knowledge was acquired and assimilated by the firms in the sample by different means. In what follows they are presented.

In-house R&D

All the firms reported that they undertake in-house R&D and stated that this means of learning played a crucial role in their technological enhancement.

Table 22 In-house R&D: activities and personnel involved

Firm	In-house R&D	R&D expenditure (% of tot turnover)	Personnel in R&D (as % of tot. labour force or as n. of people)
A	✓	10-15%	10% (7 people)
B	✓	More than 50%	40% (10 people)
C	✓	10%	n.a.
D	✓	10%	6% (2 people but not full time)
E	✓	5%	6-7 people
F	✓	3-5%	15% (30 people)
G	✓	less than 10%	3% (30 people)
H	✓	n.a.	6% (12 people)

Source: Author's fieldwork

Table 22 above presents the resources devoted by the firms to in-house R&D. On average seven firms out of eight devoted between 5 and 10% of their total annual turnover to R&D activities. There was only one notable exception: firm B spent more than 50% of its turnover in R&D. This expenditure was used to modify existing processes and products and to design part of the production equipment, such as the previously mentioned furnace to accommodate large size Si wafers. It should be noted that this was a 'special case' in the Chinese PV industrial context. Firm B, as illustrated by Table 16, had in fact a very limited production capacity (to the extent to which the firm found it difficult to compete with the other domestic PV cell and module producers). However the long standing entrepreneur's experience in a national research institute devoted to c-Si PV made R&D the focal activity of the firm[160].

As shown by Table 22, on average, less than 15% of the firms' workforce was employed in R&D activities in 2005.

[160] The entrepreneur, who set up the firm in 2001, had worked for more than 20 years in one of the earliest established national research institutes that first undertook R&D on Si solar cells and then initiated production.

During the survey, firms were also asked what the reasons why they undertook in-house R&D were.

Table 23 Reasons for undertaking in-house R&D

Firm	Purpose of R&D
A	n.a.
B	Modifying existing products/design to suit different markets or/and satisfy specific customer's requests. Modifying existing production processes. Designing and developing new production processes
C	Modifying existing processes
D	Modifying existing production processes
E	Modifying existing products/process
F	Modifying existing products/process + designing new ones
G	Modifying existing products/process + designing new ones
H	Developing new market applications

Source: Author's fieldwork

The results, reported in Table 23, highlight two issues. First, as one would expect, companies tended to undertake R&D to modify existing manufacturing processes and products to reduce costs and to suit different market needs. This finding seems to be in line with Lall's claim that companies in developing countries are more inclined in using efficiently the existing technology imported from abroad rather than developing new products or processes in-house (Lall and Teubal, 1998). A rather more surprising result for a developing country dealing with a high-tech industry was the involvement in R&D activities to actually design and develop new production processes or new market applications. 50% of the firms had in fact either developed a new production process, for instance to increase the efficiency of the solar cells or to work with larger size wafers (see discussion in the previous part of the chapter), or were significantly modifying their products to exploit new market niches (possible applications to the automotive sector were one example).

Training

The majority of the companies, regardless of their production capacity volumes and level of technological competence, took courses or were trained by the supplier on how to operate specific pieces of equipment to be used on the production line.

Table 24 summarises all the training courses that were taken by the employees of the firms in the sample. If training given by the supplier of the equipment was a common way of learning for almost all the firms in the sample, firms with a smaller production capacity attended courses given by international organisations or national and local institutions.

Table 24 Training received by employees in the interviewed firms

Firm	National government	Local government	International organisations (e.g. UNDP, GEF, ADB)	Bilateral organisation (e.g. GTZ)	Private co. (i.e. supplier)
A	✓	✓	✓	×	✓
B	✓	×	✓	×	×
C	×	×	×	×	✓
D	×	✓	✓	×	✓
E	n.a	×	×	×	✓
F	×	×	×	×	✓
G	✓	✓	×	×	✓
H	✓	×	✓	×	✓

Source: Author's fieldwork

Several companies took part, for instance, in the NDRC/WB/GEF Renewable Energy Development Programme[161] aimed at encouraging technology improvement activities in the Chinese PV firms via direct grants and staff training. Since the second main goal of the Renewable Energy Development Programme is to sustain, via ad hoc financing, PV market development in China and to complement the Government's rural electrification programmes, the firms participating in the programme have also a better chance of gaining market shares in the domestic markets (ter Horst and Cheng, 2005).

Factors that affect learning[162]

Technology access

Technology, understood in this instance as the hardware, was accessed from both foreign and domestic suppliers. However, as discussed in the initial part of this

[161] NDRC/ GEF/ The World Bank China Renewable Energy Development Project (REDP) is an international cooperation project between the Chinese Government, the GEF and the World Bank. The programme was launched at the end of 2001 and it is expected to end in June 2008.

[162] The section presents the findings about those factors that are known from the technological capability literature to affect the learning process and that have been put forward by the analytical framework. The extent to which they are relevant for the learning process in the PV firms in China is instead described in Chapter 7.

chapter, several firms stated they preferred to develop parts of the equipment in-house (alone or with the help of domestic suppliers for the mechanic parts of the equipment) rather than buying it from foreign suppliers, because it was cheaper.

When technology was bought from foreign suppliers, this was done to acquire the best piece of equipment available to meet production needs rather than to access know-how via the use of foreign equipment by 'unpacking' it.

Endowment

a) Educational& professional background of the entrepreneur

As discussed in Chapter 3, the entrepreneur and the personnel employed by the firm can contribute to the firm's technological upgrade and innovation because they bring, through earlier education and experience, a certain stock of knowledge and skills into the firm (Romijn and Albaladejo, 2002).

Table 25 presents a snapshot of the professional and educational background of the entrepreneurs or the other senior figures who were interviewed during the survey in the firms (see Table 19). As illustrated by the table, six of the entrepreneurs had previous working or research experience in the PV sector. In some cases their involvement in the industry dated back to the 1970s when they were working for the early established state-owned PV firms (see section 6.3.2 in this chapter for the historic evolution of the PV industry). When these early PV firms went bankrupt between the late 1990s and the early 2000s, some of them decided to set up their own firms.

Three entrepreneurs gained experience abroad (see last column in Table 25), where they went first to acquire further education and then working experience in the PV sector.

As for their educational background, five entrepreneurs had a high educational level and some of them obtained their PhDs abroad.

Table 25 Entrepreneurs' professional and educational background

Firm	Previous experience in PV industry or R&D	Highest level of education completed	Education or working experience abroad
A	✓	n.a.	×
B	✓	PhD	✓ (USA)
C	NO	Master degree	×
D	✓	n.a.	×
E	NO	Master degree	×
F	✓	PhD	✓ (Australia)
G	✓	PhD	n.a.
H	✓	n.a.	✓ (Canada)

Note: due to time constraints during the interviews it was not always possible to ask entrepreneurs about their professional and educational background

Source: Author's fieldwork

b) Educational and professional background of the workforce

Table 26 presents a profile of the firms' workforce in terms of education and experience gained abroad.

There seems not to be a clear pattern of labour force skills across the firms. While some firms had a high percentage of skilled workers or university employees (for instance, firm C had only 4% of unskilled workers in its workforce) others had a much higher percentage of unskilled workers (see for instance firm H). This unclear picture seems not to be explainable simply by the incidence of labour intensive activities within the firms. A case in point is firm E, which was uniquely devoted to one of the most high-tech activities along the PV value chain (i.e. c-Si wafer manufacturing) but still employed 60% of unskilled workers.

Table 26 Educational and professional background of the workforce

Firm	Total No. of employers	Proportion of technicians (skilled labour force)	Proportion of engineers/university trained employees	People with working experience in foreign firms or with education gained abroad
A	70	36%	23%	✓
B	25	20%	12%	✓
C	644	55%	41%	✓
D	35	23%	17%	✓
E	100	35% technicians and engineers		×
F	>1000	n.a.	45%	✓
G	200	n.a.	40%	×
H	241	n.a.	9%	✓

Source: Author's fieldwork

Note: Technicians are here defined as that part of the labour force with a secondary school degree and skill training; university trained employees include both under-graduate and post graduate.

Other sources internal to a firm

Other sources internal to a firm that might affect learning are, as indicated by the technological capability literature and highlighted in the analytical framework: the firm's size, age and ownership. The results about these aspects have already been presented in the initial part of the chapter, where the profile of the firms has been provided. In Chapter 7 we will discuss the extent to which these factors have influenced the technological capability accumulation processes in the Chinese PV firms (i.e. are larger firms more able to enhance their capabilities? Is the age of the firm, and in particular the number of years that it has been producing for, important in determining innovative behaviour?).

Linkages

As suggested by the analytical framework, inputs supplied by various agents (like suppliers, customers, research institutes, etc.) can complement the firm's internal sources of capability discussed above. Results from the questionnaire, about the existence and types of interaction with external agents, show that intensive interactions occurred with suppliers (especially domestic), research institutes and to a lesser extent[163] with international organisations that offered training and market development programmes (see the early mentioned case of the REPD programme promoted by

[163] As previously pointed out, these programmes offered seem to attract mainly firms with smaller production capacity

NDRC/WB/GEF). Links with customers played instead only a marginal role mainly because the bulk of the market for the Chinese firms was located abroad and because they relied on distributors to commercialise their products to the final consumers (see Table 18).

Several of the firms interviewed stated that they commission from their domestic suppliers the manufacturing of production equipment or spare parts according to their own design. Feedbacks from these suppliers regarding any possible improvement to the initial blueprint provided an important source of learning for the PV producers. In turn, the subcontracting of parts and components provided important occasions for upgrading for the suppliers of PV production equipment.

Links between firms and research institutes were common, particularly in those firms in the sample with a limited production capacity. Firms tended to undertake collaborative research either with research institutes that possessed the necessary know-how and were located nearby, or with academic institutions where the entrepreneur or the chief engineer in charge of the R&D department undertook his university studies.

Remarkably, firms with larger production capacity preferred not to have collaborative research projects with universities except in the case of basic research.

Geographic proximity

While the PV firms in the sample were concentrated in two main geographic areas (the Tianjin-Beijing area and the Jiangsu-Zhejiang area, as illustrated by Figure 35) the evidence we collected seem to suggest that there were no proximity advantages (see Chapter 3, Section 3.2.3). Firms seemed to be located where they were mainly because those were the areas where the economic development was the highest and where firms could offer more attractive living conditions for their employers. Evidence we collected do not seem to suggest that firms' location was motivated by possible spillovers they could enjoy from being close to their suppliers, R&D partners or customers who, as explained, were mainly located abroad.

What seemed to be more relevant, instead of geographic clusters, were 'relational clusters': firms tended to liaise with those R&D institutions or suppliers with whom they have established trust. This was for instance the case of firm A that was located at the outskirts of Beijing and had collaborative R&D projects with the local

University of Technology as well as with Harbin University, where the senior figures of the firms were originally from and where they conducted their studies.

6.3.2 Structure and performance of the innovation system over time and its effect on innovation in firms

The following section presents the results about what affects innovation in firms that emerge from applying the systemic approach.

Findings about the system's structure (i.e. main agents and their interactions), the system's performance according to the seven functions suggested by the literature[164], the main drivers for innovation as well as the specific implications of the IS configuration and performance for firms' innovation, are presented in this section and organised over three main periods:

a) Late 1950s – 1978: the emergence of the PV system during the central planning economy and the 'first generation' of PV firms.

b) 1978 – late 1990s: the evolution of the PV system during the transition from central planning to market reform.

c) Late 1990s - 2005: the rapid take off of the Chinese PV industry and the 'second generation' of PV firms

As will be explained below, and as emerged during the interviews with both the Chinese PV firms and the other stakeholders in China, each of these three periods contain critical aspects to understand how the PV IS has evolved over time and has affected the PV firms innovative behaviour.

a) Late 1950s – 1978: the PV system's emergence during central planning and the 'first generation' of PV firms

PV system structure: components and interactions

The story of PV in China starts in 1958, when the government entrusted national research institutes (NRI) to conduct R&D for c-Si solar cells (Dai and Shi, 1999, Zhao, 2004). In the early 1970s the first PV pilot space and terrestrial

[164] See Chapter 2, Section 2.4.2, for the theoretical underpinning and Chapter 3, Section 3.2.3, to see how the 'system's structure and performance' have been operationalised.

applications[165] were launched. True manufacturing at a national (although limited) scale started only in the late 1970s, however, with the conversion of three state owned (SO) semiconductor plants in production lines for sc-Si cell production[166] (Cui et al., 1990).

The PV system in this formative period was characterised by a limited number of *functionally specialised actors*[167] (Liu and White, 2001). The NRI were exclusively in charge of undertaking R&D on c-Si, while the three converted Si cell producers were responsible for manufacturing/implementation only. The activities of both these actors were strictly controlled and guided by the central government and its bureaux (i.e. the different industrial ministries), which were also supplying the resources necessary to both firms and research institutes.

Until the late 1970s there was not a real PV domestic market and the limited domestic production was mainly used for pilot and strategic space and terrestrial applications (Cui et al., 1990). Other important actors along the PV supply chain, like for instance production equipment manufactures or PV service firms (i.e. installers, sellers, maintenance, etc.), were not present in China during this first phase of the PV IS.

Horizontal links or interactions between NRI and the state manufactures hardly existed. They were expected to deliver both their respective research and their productive outputs directly to the government bureaux which vertically administered them according to the central government's guidelines and priorities (Liu and Jiang, 2001).

Figure 40 provides a map of the PV innovation system under central planning and illustrates both the main actors and the (vertical) interactions among them[168].

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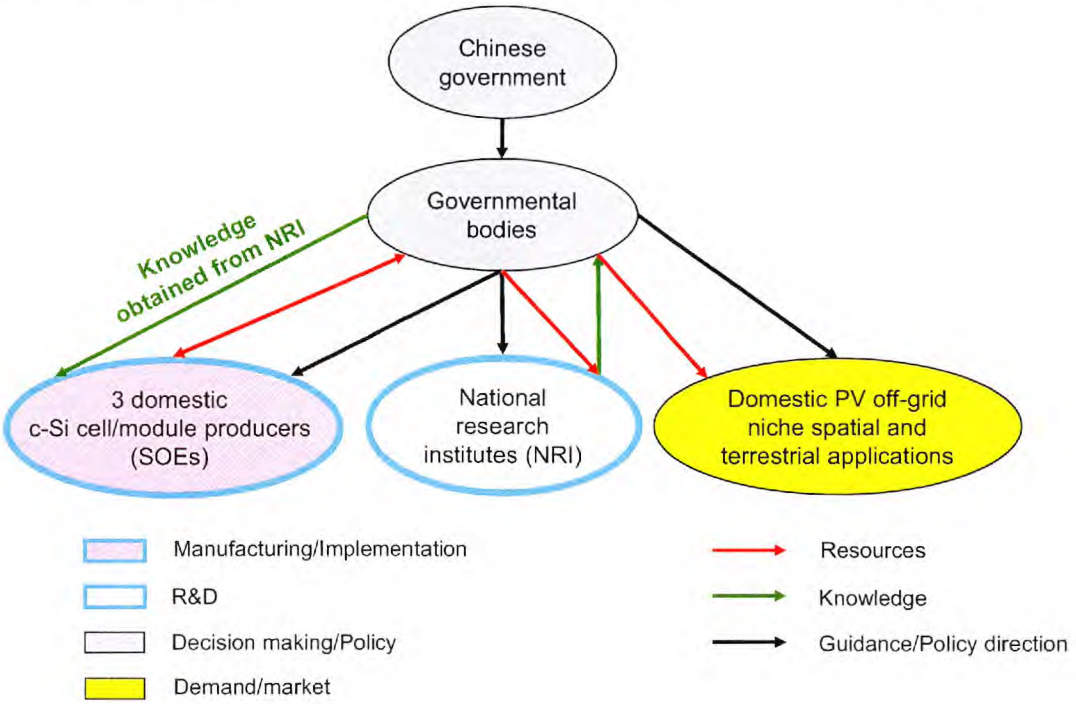
[165] For example, PV lamps for railway stations or PV powered beacon lights for telecommunications.

[166] It is worth remembering that the PV c-Si industry uses a process technology quite similar to that developed by the semiconductor industry. For more details see Chapter 4.

[167] See Section 5.2.1 for a national overview of the innovation system during the period of the planned economy.

[168] The Figure provides a snapshot of the system's structure towards the end of the planned economy period.

Figure 40 The Chinese PV innovation system under central planning: late 1950s – 1978



Source: Author's elaboration

The existence of organisations with a rigidly defined function (where innovation/S&T activities done by the NRI were strictly separated from the manufacturing activities of the firms) makes it difficult to map the PV IS under central planning according to the broadly-defined categories of actors (i.e. innovators, demand, policy support and facilitators) suggested by the analytical framework in Section 3.2.3 (see in particular Figure 10). In other words: neither firms nor NRI were truly 'innovators' because the range of activities they undertook was much more restricted than is usually assumed.

For this reason, instead of identifying firms and research institutes as 'innovators', we have preferred to use categories that describe their functions at the time: manufacturing/implementation for SO firms and R&D for NRI. We have however depicted these two actors in the Figure above with a thick blue line to allow the reader to follow their evolution in the following innovation maps (Figure 41 and Figure 42) where they are represented in blue and where their nature and activities get closer to the meaning of innovators (i.e. to create and share knowledge) we assigned to them in Chapter 3 (see Section 3.2.3).

PV system performance and innovation drivers

As pointed out, during this first phase, the performance of the PV system in China was very dependent upon the central government's decisions.

The Chinese government directly controlled several of the system's functions suggested by the literature (Bergek et al., 2008) and operationalised by the analytical framework as important for innovation to occur[169]. The government was the only body (together with its governmental bureaux) responsible for *mobilising the necessary resources*[170], both in terms of inputs to be given to the actors in the system (i.e. hardware equipment, financial resources for firms and research priorities for research institutes) and in terms of 'who should do what' (i.e. competences)[171]. The PV *market was artificially created* by the government, which decided on the types of PV applications and their quantities. In this respect the government was also strictly controlling the *direction of search*, which was pointing exclusively towards c-Si. *Technological legitimacy* derived directly from the government's strategic decisions and not from pressure or influence groups, as in the case of PV development in Germany (Jacobsson et al., 2004). No 'virtuous circles' could be created because there was no interdependence between the different system's components and functions.

The actors in the PV system other than the government were little more than mere executers and were supposed to accomplish only the specific task assigned to them: undertaking either production or research. There was no room for the *creation of positive externalities* (because there were no horizontal links) or, as discussed below, for *entrepreneurial experimentation.*

Two main innovation drivers can be distinguished in this period. At the beginning of the formation of the IS (late 1950s – early 1970s) the main reason to establish a national R&D on c-Si solar cells originated from the government's concern to ensure national security and self reliance.

From the mid 1970s, the innovation driver was the need to respond to the oil price shock that created global concerns about increasing energy prices. One of the Chinese government's responses was to kick off solar cell manufacturing (very limited

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[169] The seven functions are: knowledge development; influence in the direction of search; supply of resources; creation of positive externalities; facilitation of market formation; stimulus of entrepreneurial experimentation; legitimation of nascent technologies or industries.

[170] From here to the end of the Chapter where the evolution of the PV innovation system in China is presented, we identify the different functions that characterise the system's performance in Italics.

[171] Under the planned economy and through the early 1990s, all university graduates waited for work assignments in SO organizations. They did not have the opportunity to choose where to work, nor could they freely change jobs after they started (Liu and White, 2001).

in scale until the mid 1980s) by converting three pre-existing semiconductor plants into solar cell production lines.

Implications of the IS configuration and performance for firms' innovation

As anticipated, during this first formative phase of the PV innovation system in China, firms were very far from the innovator's role that is usually assigned to them (i.e. being responsible to develop and improve technology and to implement strategies to diffuse it on the market). Firms were only in charge of manufacturing and followed the instructions and targets given by the government's bureaux, on the basis of the science and technology inputs received from the NRI. Although a part of the NRI was affiliated to industrial ministries (like the Ministry of Metallurgical Industry) and focussed on more applied c-Si research and developmental tasks (Dai and Shi, 1999, Liu and Jiang, 2001, Liu and Lundin, 2006), they were very far from production sites and unaware of production needs, so their research did not have a truly applicative value and could not be fully used by firms.

By deciding on technological choices, providing all the necessary resources and by guaranteeing a secure market for the firms' products the system was reducing all the risks that are usually encountered by innovators. However, state PV cell/module manufacturers could not build on this advantage because they had little autonomy to experiment or to respond to the market needs.

Since horizontal links between the actors were not allowed[172], firms had no opportunities to liaise with the NRI, which were undertaking the activity that is usually more closely associated with innovation, i.e. R&D. As a consequence firms did not have views on what they needed in terms of R&D requirements.

Similarly, no inputs could be expected from customers or suppliers.

During the planned economy period, as a consequence of the system's specific structure and performance, firms were hence closer to technology users than creators. They were output-oriented and had no incentives to introduce, adopt or diffuse innovation pro-actively. The only possible innovation-related activity they could undertake was to accumulate knowledge on the shop floor, as a result of the by-product of using the hardware provided by the government.

[172] Horizontal links were only allowed among the different governmental bureaux. For more details see Liu and White (2001)

b) 1978 – late 1990s: the evolution of the PV system during the transition from central planning to market reform

As discussed in Chapter 5 (Section 5.2.2), the economic reforms implemented in China after 1978 have gradually dismantled the centrally planned economy. The role of the government has changed profoundly and an increasing number of actors have entered the economic scene. Moreover, in this period actors become more autonomous and functionally diversified than during the planned economy and the organizational boundaries around their activities have changed dramatically. These developments have greatly modified not only the national IS but also the PV sector.

PV system structure: components and interactions

a. Policy support

A drastic reduction in the direct state involvement in the country's S&T and industrial development[173] characterised this transition period. This translated into a substantial reduction in government funding, and resources in general, to both NRI and SOEs. Despite this, the government retained a certain influence on the PV sector. The *State Development and Planning Commission (SDPC) and the State Economic and Trade Commission (SETC)* provided both the industry and the domestic research institutes (i.e. the Chinese Academy of Sciences, universities and other R&D institutions) with broad policy guidelines on how to advance domestic PV technologies. The *Ministry of Science and Technology (MOST), the Ministry of Agriculture (MOA) and the National Electric Power Company* were instead the operative arms of the government and responsible to support both the PV industry via loans and subsidies and the research institutes via direct funding (Dai and Shi, 1999) [174].

b. Demand

The domestic market (no Chinese PV products were exported in this period) was no longer dominated by pilot spatial and terrestrial applications of a strategic nature but also by *commercial applications* like off-grid household-PV systems[175].

c. Innovators

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[173] See Chapter 5, Section 5.2.2

[174] MOST, for instance, managed a National Key R&D Program that included R&D fund for PV technology, during the period 1996-2000 (Dai and Shi, 1999).

[175] The internal market registered a rapid growth in the early 1990s with stand-alone household PV systems reaching 30% of the market share.

Three more *domestic firms* were added in this period to the three pre-existing ones. Two were SO enterprises manufacturing both sc- and mc-Si solar cells while the other was a joint venture (JV) with a USA firm for the production of a-Si cells. Despite the doubling of the number of firms participating in the PV industry, the production capacity in the country remained low: only 5 MW towards the second half of the 1990s but with a lower actual capacity due to serious bottlenecks in the production lines.

Foreign firms began to enter the domestic PV market in this period, both by providing domestic firms (initially via MOST) with the necessary production equipment for solar cell and module production[176] and by selling their final products in the domestic market.

While up to the first half of the 1990s the majority of the PV products sold in China were made in China, by 1998 50% of the market share was in the hands of foreigners who provided cheaper and better quality products (Dai and Shi, 1999)[177]. As we discuss below, this foreign presence in the local market had profound implications on the domestic firms' performance.

Also *domestic service firms*, in charge of the sales, maintenance and installation of the PV systems started to emerge in this period. Until 1992, there were less than 10 service firms, all affiliated with government sponsored R&D institutes. They used Chinese government subsidies and foreign technical aid to install PV systems in the country's remote rural areas (Dai and Shi, 1999). By early 1998, the service firms totalled 50 and several of them were private. Private service firms were, however, at disadvantage compared with SOEs service firms, which enjoyed larger market share, technological and financial advantage.

A total of *40 R&D institutions* existed in this period and concentrated on improving the efficiency of the existing c-Si solar cells and in exploring new types of solar cells (mainly a-Si).

d. Facilitators

International organisations, like the World Bank and the GEF, began to enter the PV system in this period with the aim of supporting the Government in the provision of loans for the installation of household PV systems in poor rural areas (Dai

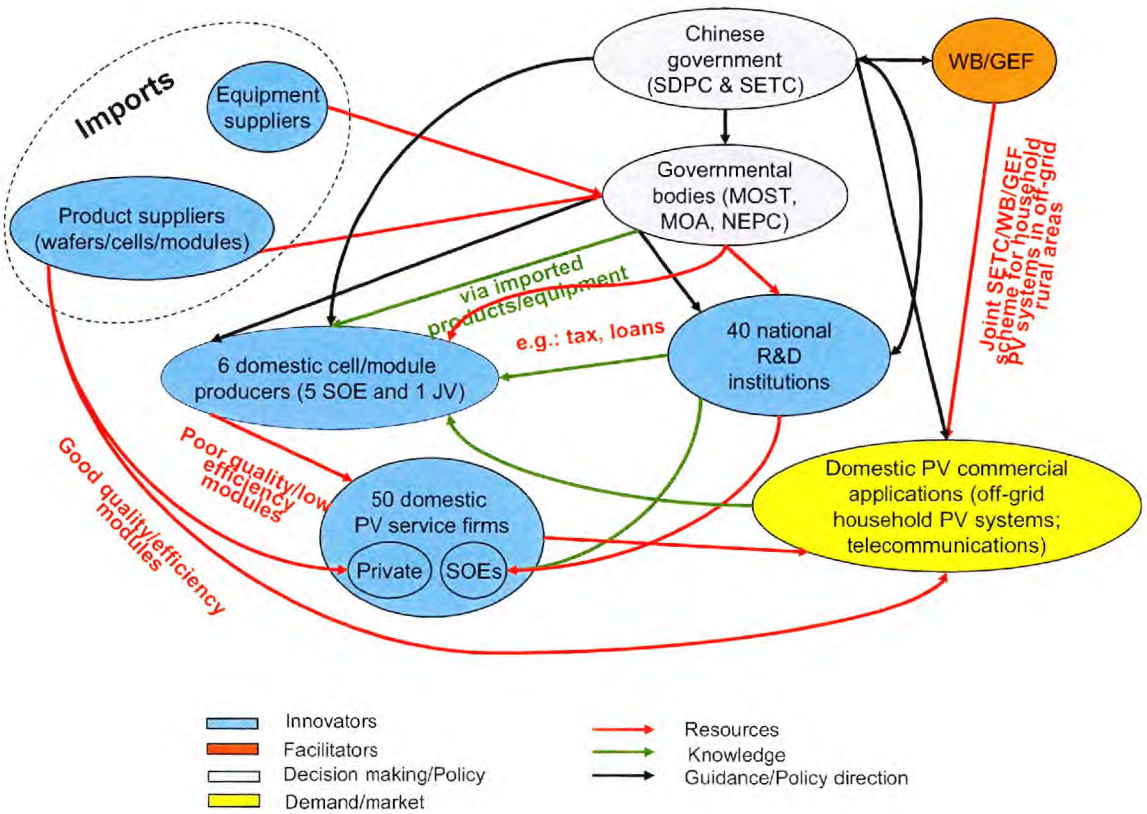
[176] From 1983 to 19887 China imported 7 PV cell production lines from abroad, mainly from the USA and Canada (Dai and Shi, 1999).

[177] This was particularly relevant for telecommunication and navigation applications where reliance and quality of performance are particularly important.

and Shi, 1999) and of initiating a process of capability building (for both PV manufactures and installers) that would have consolidated in the following period.

As a consequence of the decentralization of decision-making over both resource allocation and operational decisions, horizontal links between the different actors became not only possible but also encouraged. Both firms and research institutes were now exposed to market competition and supposed to look for their own production and research inputs.

Figure 41 The Chinese PV innovation system under the transition from central planning to market economy: 1978 – late 1990s



Source: Author's elaboration

Industry-science links became particularly important and stronger over time. NRIs and universities were allowed and encouraged to set up their own spin-offs so that they could commercialize their technology directly and obtain additional funds. One of the 6 cell producers that participated to the industry in this period was actually a national research institute that started to undertake entrepreneurial activities.

Resources could flow in this period, not only vertically from the government and its bureaux to the SO firms and the NRI, but also horizontally from foreign suppliers to domestic service firms and from these directly to the customers in off-grid rural markets.

Figure 41 provides a map of the PV system's main actors and interactions in the transition from a planned to a market-oriented economy.

PV system performance and innovation drivers

Contrary to the first phase of PV development in China, this 2nd period was characterised by a greater number of actors with a higher degree of autonomy and who could serve a wider number of functions.

Knowledge creation in the form of R&D (although under the broad priorities specified by the central government) was no longer a unique feature of the NRIs. Firms were given the mandate to invest in their own R&D activities and innovate based on their own strategic decisions (Liu and White, 2001). In this respect, firms got closer to the conventional role of innovator that is usually assigned to them. For this reason they are identified in Figure 41 with a blue circle. Further important sources of knowledge came from the import of foreign production equipment, which was used by the domestic firms to build their initial industrial knowledge. Moreover, feedback from the commercial domestic market and the comparison with the superior performance and quality of the foreign products (also sold on the domestic market) made firms more aware of their technical weaknesses and of the areas where knowledge accumulation was more urgent.

The government played an initial role in *facilitating market formation* by subsidising off-grid households PV systems. This *created new knowledge* on how to install and maintain solar modules and *guided several private firms in their search process* to enter installation and maintenance services.

Resources were no longer *provided* exclusively by the government and its bureaux but also by new actors, such as foreign PV producers or international organisations like the World Bank or the GEF.

In terms of *technological legitimacy* two opposite tendencies can be observed. On one side, the fact that PV was no longer considered a strategic sector, together with the government's reduced involvement in resource allocation, had weakened the

institutional status of both PV firms and research institutes. Moreover, the multi-institution management of the PV sector mentioned above created fragmentation in the policy direction and an improper use of limited resources. This further weakened PV legitimacy.

On the other side, the opening of the domestic market to commercial PV applications started to create public awareness of the benefits of the technology for off-grid household applications. This stimulated the entrance in the system of both foreign module producers and domestic service firms, which in turn strengthened the legitimacy of solar power.

Although the broad conditions for the establishment of a more self-sustained innovation system were laid (i.e. a larger number of less functionally specialised actors, the possibility of establishing horizontal links and expanded market opportunities), only limited self-reinforcing dynamics were initiated in this period. Among them was the entrance into the system of service firms attracted by the off-grid household market, initially supported by government subsidies.

Implications of the IS configuration and performance for firms' innovation

Three main events that occurred in the system in this period had a profound influence on firms' innovation/knowledge accumulation:

1) The withdrawal of the government from the PV sector, both in terms of resources provision and market creation.
2) The entry in the system of foreign products and production equipment.
3) The possibility for NRI to engage in commercial activities.

If on one side, as a consequence of the drastic reduction in the direct state involvement in the PV sector, firms had a larger autonomy and the entrepreneurs could, at least in principle, experiment with technologies and applications as well as search for their own most suitable resources and liaise with other actors in the system (like NRI, service firms, customers, etc), they were poorly equipped to use these factors as opportunities to accumulate knowledge and upgrade. The role assigned to them in the previous period, where they were detached from R&D activities and their performance was based on the government's output quota rather than economic measures (i.e. product's performance, quality, price, etc.), did not allow them to successfully

assimilate the technology they imported and to develop managerial and commercial strategies necessary to sell their (poor quality) products in a non protected market. Firms were caught in a vicious circle of import, lag behind, import again, then lag behind again.

The negative effects of this path dependency on the firms' innovative behaviour became even more visible with the entry in the innovation system of foreign producers who could sell on the domestic market cheaper and better quality products (Dai and Shi, 1999). Left without government support and with limited resources[178] (all of which resulted in reduced absorptive capacity), the firms could not stand up to foreign competition and went out of business. Of the six firms that made up PV industrial capacity until the late 1990s, only one was able to remain afloat without considerable restructuring and to participate to the rapid take off of the Chinese PV industry that begun in the early 2000s[179]. However, as we will argue in presenting the next phase of the PV IS, although firms did not survive to foreign competition, some of the individuals who took part in the manufacturing activities during this period were able to 'recycle' their knowledge by entering different (in some cases less knowledge intensive) links of the c-Si value chain.

The possibility for NRI to engage in commercial activities and to set up their own spin-offs meant that new traditionally non-manufacturing but knowledgeable actors could now undertake production. Moreover, their engagement in manufacturing activities was the first step upon which industry-research institute links could be initiated and strengthen in the following period.

To sum up, the system in this second period created the necessary pre-conditions for technological change in firms to occur (i.e. the participation in production of more knowledgeable actors, the possibility for the entrepreneurs to experiment, to take autonomous innovation decisions and to liaise with other actors in the system). However, firms could not use this as an opportunity to add value because they had a low absorptive capacity (which originated from the role the government had previously assigned to them) and because the right 'spark' was missing. This would be

[178] Dai and Shi (1999) note that shortage of money needed to import full production lines resulted in serious bottlenecks of production.

[179] A second firm, of the six early-established, is still producing but it has undergone massive managerial and productive restructuring.

provided in the subsequent period by a fast surge in global PV demand, which acted as the main driver to market entrance, specialisation, labour division, quality and performance improvements.

c) Late 1990s - 2005: the rapid take off of the Chinese PV industry and the 'second generation' of PV firms

Two main features characterise this third phase of the PV innovation system in China: the rapid growth in global demand for grid-connected PV and the entrance of new powerful Chinese manufacturers in the domestic market, where the former acts as a main innovation driver for the latter.

PV system structure: components and interactions

a. Policy support

On the institutional front, the *National Development Reform Commission - NDRC* (the former State Development and Planning Commission) remains, as in the previous period, in charge of policy promotion[180] and supports PV demand (and indeed other RET like wind and small hydro) by setting up rural electrification programs and by subsidizing the capital cost of the equipment in remote areas in Western China (Ma, 2004).

Provincial institutions, which share with NDRC the cost of capital grants for rural installations (Ma, 2004), also influence the sector. *Regional initiatives* such as the 100.000 roof programme proposed by the Shanghai municipality can offer further local demand support (Liu, 2005).

On the supply side, the grants given by the State Council and NDRC in support of technology-based SMEs (see Chapter 5) also affect the firms participating in the PV industry[181].

b. Innovators

As previously explained and as it emerged from the initial part of the empirical analysis (see Section 6.2.1), the *innovation system for PV in China is mainly focused around conventional c-Si technologies* (both sc-Si and mc-Si). At the time of the fieldwork there were *30 research institutes and universities* working in the development of the materials used in PV cells and in the accompanying manufacturing

[180] NDRC designs and implements national comprehensive development strategies in the form of 5-year development plans, which have a great influence in China's innovation policy.

[181] Two of the firms that have been interviewed benefited from these governmental grants.

process (Zhao, 2001). Although the main focus was on wafer-based solar cells (i.e. c-Si technology), several institutes and universities were also active in research for thin-film solar cells (Zhao, 2001, Yang et al., 2003). At the time of fieldwork, to the best of the author's knowledge, there was no R&D underway in high-efficiency solar cells under concentration and organic PV (i.e. the least mature of the PV technology families and the one that is still in the R&D phase - see Figure 19 in Chapter 3).

Domestic production is now present along the whole c-Si supply chain (see Chapter 5, section 5.3.3). Although module and cell producers are more numerous, manufactures are also starting to emerge in the upstream knowledge-intensive links of the c-Si value chain (i.e. feedstock and wafer production). Domestic manufacturers of PV process equipment are also gradually emerging, although key components of the production lines are sourced from mature economies, mainly Europe or the USA (see details at the beginning of this chapter).

A number of *domestic firms* have emerged since the late 1990s and are *responsible for PV system design and integration, component manufacturing, sales and after-sales service.* Some of them have also been involved in key government programs for rural electrification[182] (Ma, 2004).

c. Demand

As detailed in Section 5.3.1, the *domestic market is mainly represented by off-grid applications* supported by the government's rural electrification programmes. On-grid applications have instead only a marginal-demonstrative role[183].

The bulk of the demand is represented by the *export market* where about 80% of the domestic production is sold. This implies that the Chinese manufactures are crucially dependent on the policies promoted by foreign countries (mainly in Europe and the USA) and benefit from the high subsidies paid, for instance, by the German consumers. Therefore, both the export markets and their governments are considered by this study as important actors of the Chinese innovation system for PV and are shown in Figure 42.

d. Facilitators

There are also a number of *domestic and international facilitating institutions* whose role is to finance projects (i.e. to provide resources), to provide specialised

[182] See Table 24 for more details.

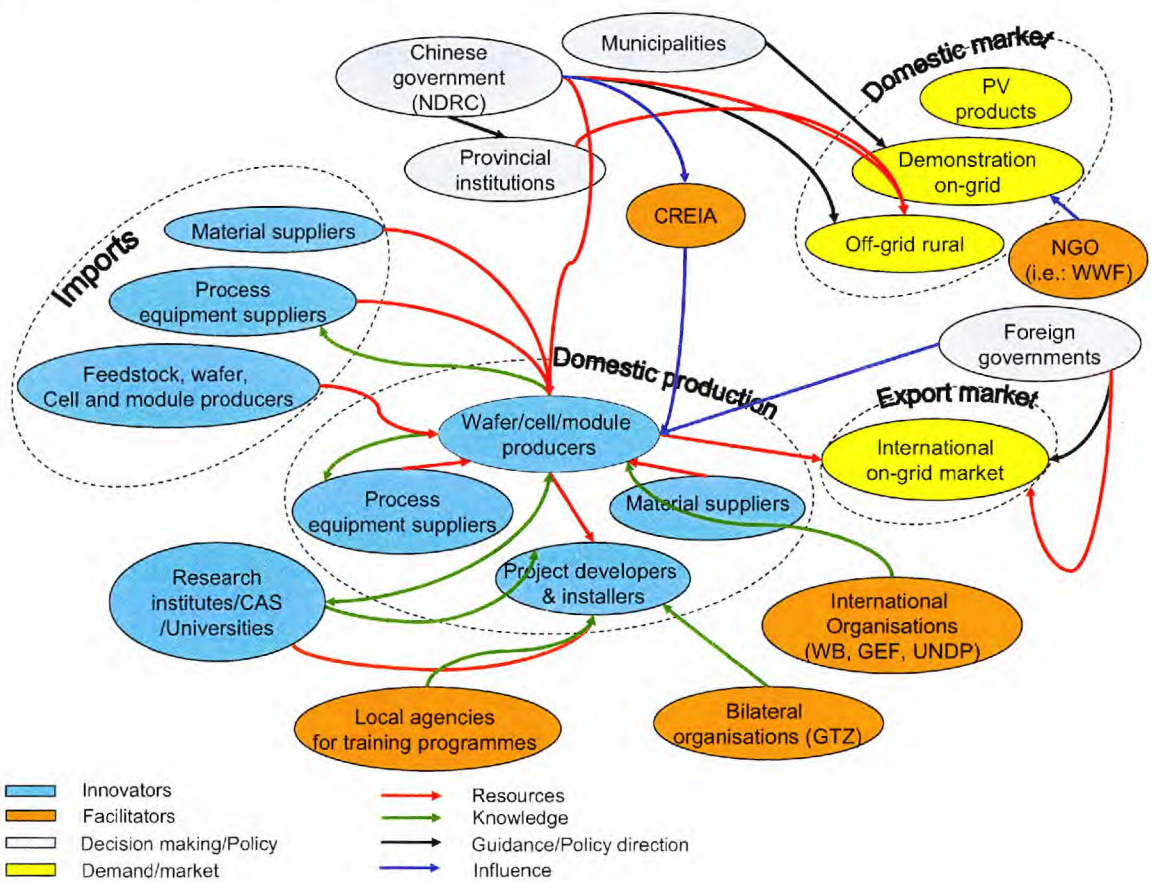
[183] This was so until April 2009 when the Chinese government announced its intention to support the on-grid domestic market (see previous footnote).

training to PV component manufacturers[184] or to act as consultants/technical experts for project installations (i.e. to provide knowledge). These include, among others, Beijing Jike Energy New Tech. Development Co., the Global Environmental Facility (GEF), the World Bank (WB), the United Nations Development Programme (UNDP) and IT Power (UK).

Several *local energy institutes together with international* (like the Deutsche Gesellschaft für Technische Zusammenarbeit - GTZ) *and local agencies* are active in developing and implementing additional training programs for local engineers and technicians.

Figure 42 presents an overview of the Chinese PV innovation system and of the systemic influences between the different actors as they appeared when fieldwork was undertaken.

Figure 42 The Chinese PV innovation system: 2005



Source: Author's elaboration

[184] As detailed in Table 24, several of the firms in the sample participated in the training programmes provided by these national and international facilitating institutions.

PV system performance and innovation drivers

In this third phase of PV development in China the system has begun to evolve into a more self sustained one and a number of actors external to the Chinese innovation system play an increasingly important role.

Knowledge is created and diffused within a number of institutions and thanks to the interactions between them. Universities and research institutes play an important role in undertaking basic research in cell's materials but also in maintaining a strict link with some of the PV firms with whom they share knowledge. Several of the entrepreneurs who were interviewed during fieldwork gained their education, or the first experience as young researchers, in local universities. These entrepreneurs still refer to their early established links to undertake basic research or to set up collaborative projects to address specific production problems[185].

In response to the growing domestic and international demand, a range of new actors, both upstream and downstream in the domestic PV supply chain, begin to enlarge the technological system, forming a more elaborate web of networks. Different types of markets emerge to satisfy the domestic producers' needs and to provide the necessary services to the final customers. A large number of production equipment firms, together with BoS producers and system installers also start to emerge. Similarly the number of firms involved in c-Si ingot and wafer production increases gradually. These new actors are strengthening the system by *supplying resources* and *creating knowledge.*

Industry networks tend to be strong especially between solar wafers and cell producers and their suppliers of Silicon (mainly international) on the one hand and their domestic suppliers of PV process equipment on the other. These relationships have proved to have a strategic importance in securing Silicon in the presence of a severe Silicon feedstock shortage (which occurred between 2004 and 2006 and is not yet completely over) and in obtaining customised PV process equipment at prices cheaper than those offered by foreign companies for standard PV process equipment.

In terms of *market creation,* although the Chinese government plays a part in supporting the domestic demand via its rural electrification programmes, the short duration of each programme (see Section 5.3.1) and the limited financial rewards

[185] This strict link between at least some of the entrepreneurs who have been interviewed and the universities where they gained their education and/or working experience is an example of what has been previously defined as 'relational clusters' (Section 6.3.1).

offered to the participating firms, do not provide a strong enough incentive for the domestic PV producers to invest in the domestic market. This is why the policies promoted by several governments in Europe and in the USA to increase the installed capacity from PV in their countries constitute a much more attractive alternative for the Chinese PV producers who, by exporting towards these countries, benefit from the EU and American incentive schemes.

6.4 Conclusions

In a nutshell, the results obtained by the study show a local industry that has entered the international market with its c-Si module production and is accumulating competencies all along the c-Si value chain, i.e. in both the low and high tech segments. Although knowledge has been accumulated in the PV technology family that is closest to commercial and technological maturity (i.e. c-Si), the Chinese firms can be competitive beyond cheap labour and have learnt to be more efficient and to reduce production costs through technological capability improvements and the acquisition of other non technological assets (like strategic view, enhanced business culture, better management). Differences between the firms in terms of how advanced their technological capabilities are, how competitive they are or how far they are from the technology frontier remain considerable and will be discussed in detail in Chapter 7. Overall, however, the domestic industry has been able to rapidly add value by improving the quality and the performance of its products and processes as well as by developing unique firm specific competencies. This has happened thanks to a learning process that has put emphasis on in-house R&D for quality improvements and for the development of enhanced or new production processes and products. It has also happened thanks to early investments in the sector and to a domestic innovation system that has grown over time creating the conditions for a rapid take off of the PV industry in the early 2000s. International surges in solar PV demand, together with promotional schemes to support PV installed capacity in several mature economies (like Germany or the USA), have provided the Chinese firms with the right opportunities and motivation to add technological and qualitative value.

7 THEORETICAL IMPLICATIONS OF THE EMPIRICAL FINDINGS

Picture 9 On how empirical findings on the type of clay and the firing temperature led to the discovery of porcelain and to a revolution in pottery (and to a more enjoyable cup of tea!)



Source: Pictures taken by the author at the Shanghai Museum during fieldwork in China, May-July 2005

7.1 Introduction

In this chapter, we examine critically the results we presented in the previous Chapter and discuss them in the light of the TC and IS literatures that underpin this study[186].

The chapter starts (section 7.2) with a brief summary of what we know and what is less understood about firm-level innovation in developing economies and RET emergence and development from an innovation system point of view. The summary, which draws on the literature that was critically and in more detail reviewed in Chapter 2, is useful to recall key ideas that have been debated in the early pages of this thesis and that will be re-discussed in this chapter in the light of the results presented in Chapter 6.

Sections 7.3 and 7.4 respectively pull out the main theoretical insights the study has obtained about the nature and the determinants of innovation in the Chinese PV firms and relate them to the existing TC and IS theories.

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[186] Chapter 2 offers a detailed review of the literature

7.2 What we know and what is less understood about firm-level innovation in developing countries and RET systemic development: a summary

There has been considerable progress in recent years in what we know about the processes that lie behind both technology change in firms in developing economies and RET emergence and development.

While we know that technical change and innovation do take place in developing countries and outside large, globally famous, high-tech corporations, they should be understood in a rather different way, which encompasses not only the 'new to the world type of innovation' but also, and in particular, the continuous and incremental effort devoted by firms to adopt, assimilate and to improve known technologies.

We also know that technological change is both a firm and a systemic matter, i.e. is the result of both the individual effort of the firm and the broader innovation system in which the firm is embedded.

If firms want to move up the value chain they need to accumulate knowledge (i.e. 'technological capabilities'), which results from purposive learning. Learning does not encompass only the formal in-house R&D that is usually associated with innovation in firms in mature economies but also other informal activities (like, for instance and among others, incremental learning by doing, reverse engineering or training) that are nonetheless important for firms, in particular in developing countries.

Learning in firms can be enhanced by a number of factors. A skilled labour force and an entrepreneur with a previous relevant working experience and educational background could for instance be crucial to unleash learning. Similarly, links (also favoured by geographical proximity) between the firm and its network of suppliers and customers could boost learning and allow for technological change to take place.

In their knowledge accumulation process, firms in developing countries have tended to proceed from technology acquisition via technology transfer from mature economies, to adaptation and eventually to substantial improvements and possibly own generation (i.e. innovation). This progression from an initial low skill base and from simple to more complex, technology intensive tasks, requires not only getting better at how a firm produces (process innovation) and in what it produces (product innovation), but also at developing those capabilities that are unique to the firm and difficult to replicate (i.e. going proprietary). In the development of a technology base that is

proprietary to the firms, product innovation via the development of independent design capacity plays a particular important role. Design provides in fact to firms in developing countries "the potential to innovate in products without pushing out the technology frontier" (Forbes and Wield, 2006, p. 21).

As said above, we also know that firms do not innovate in isolation but as part of a broader 'innovation system' in which they are embedded. When the emergence and diffusion of a specific technology, like PV, is studied from an innovation system perspective, we know from the literature that it is important to identify who is part of the system and how this performs with respect to a number of processes (i.e. 'functions') that are known to be important for technological innovation to occur. Drawing on the experience of RET development in a number of mature economies, like Germany, the Netherlands, Sweden and the UK, we also know that the process through which RETs emerge and diffuse on the market could be facilitated or indeed obstructed by a number of factors (Jacobsson et al., 2004, Foxon et al., 2005). These might include, among others, poor market articulation, lack of legitimacy of the new RET in the eye of the different actors, or failures in guiding actors towards different competing technologies and market applications.

The identification of these inducing and blocking factors for each technological IS that we seek to study is essential to improve the functioning of the system and to ultimately foster innovation for RET.

Despite all this knowledge about technological change and all the specific insights we possess about firm-level dynamics in developing countries and RET emergence and diffusion, there are still open issues that need to be understood. What remains unclear is the extent to which the firms' incremental innovation processes observed by the TC literature in engineering-based industrial sectors in developing countries also holds true for emerging RET like PV. These technologies are in fact characterised by a greater systemic embeddedness and knowledge intensity which could present lower opportunities for incremental innovation from a low skill base and indeed might constitute higher barriers of entry for firms in developing countries. Moreover a static understanding of the firm-level factors (i.e. entrepreneurial background/education, firm's size, age and links with suppliers or customers) that favour learning might not be sufficient to appreciate more complex and systemically

embedded dynamics. While each of the elements that, from a TC perspective, could be conducive to learning is potentially important, the relations between them and the broader institutional and organisational set-up within which firms are embedded are particularly important.

On the side of an innovation system approach, the strength of the concept lies in its holistic perspective encompassing the analysis of actors, networks and institutions that influence the innovation processes. What we know less about are the micro-level system dynamics and particularly the extent to which the broad system and its components affect a firm's innovative behaviour.

When we apply this innovation system perspective to study RET in a developing country context we know even less. We do not know if the dynamics that have been observed for certain RET in mature economies (like for instance PV in Germany. See Jacobsson et al., 2004)[187] hold true also for emerging economies. In these countries where fragmentation, instability, etc. are usually referred by the literature to be common features, a system, or key elements of it, may not even exist or processes (i.e. the functions) that could be expected to be relevant for innovation to occur in mature economies may simply not hold true for developing countries.

It is upon this knowledge, which we derived from both the TC and the IS literatures, and its limits that this study departed by exploring the nature and the determinants of the innovation effort underway in the PV firms in China

7.3 Key issues on the nature and path of technological change in the Chinese PV firms

This section draws out, from the results obtained by the study, three key insights that characterise the nature of the technological effort underway in the Chinese PV firms: the development of capabilities that go well beyond a minimum knowledge base; a knowledge accumulation path that has not followed stages conventionally observed in firms in developing countries and the need to understand technological capabilities in the PV firms in China as a sub-set of a larger bundle of competences.

[187] See also the detailed discussion in Section 2.4.7.

7.3.1 Beyond a minimum knowledge base: intermediate, advanced and proprietary capabilities

A first important theoretical insight that derives from the results presented in Chapter 6 is that the PV firms in China have accumulated not only the minimum knowledge base (i.e. the basic TC that have been defined in Chapter 3) essential to use the technology, to reproduce it efficiently with minimum changes and adaptations (to suit for instance specific local requirements) but also those *skills necessary to change the technology*, i.e. to undertake significant modifications to processes and/or products or even to develop distinctive technological or strategic solutions that permit the firms to stay ahead of competitors. Although, as discussed below, the firms in the sample differ in their ability to 'change the technology' and indeed to be competitive, they have all been able to improve over time the depth and the breath of their technological effort.

In terms of the depth of their technological effort, all the firms have been able to *improve their productive processes and to deliver products with a better performance and quality* over time[188]. Moreover all the firms sell their products with their own brand and organise their own distribution both domestically and abroad, capturing all the value added associated with production, branding and distribution.

In terms of the breadth of the technological effort, all the firms[189] *have moved (or indeed intend to move in the near future) from less to more knowledge intensive links of the c-Si value chain.* This move has implied not only a greater technological effort to learn more complex productive processes, but also the ability to articulate a strategic vision of where the firm intended to go in the future and where it expected global demand to go. Moving upstream and being able to master more than one productive process responded to the need to reduce costs[190] but also to build up specific competences that fewer firms in China possess. In other words, firms responded to the need to compete not only on the basis of the cheapest possible product but on the basis of technological assets that are more difficult to gain and to reproduce and that can guarantee higher profits. While for some of the firms 'going proprietary' has meant

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[188] We recall here that these improvements result from a purposive technological effort that requires firms to develop ad hoc technological solutions to technological problems encountered (see Section 3.2.2).

[189] This applies to all the firms in the sample apart from two that are respectively and uniquely devoted to module and c-Si wafer production.

[190] Recall the importance of moving towards vertical integration and scaling up in this technology. See chapter 4

patenting their process or product innovations, for others it has implied reaching a high and difficult to match degree of vertical integration or manufacturing speciality solar devices for niche applications, like for example the automotive sector.

Although, as explained below, remarkable differences remain between firms, these *technological improvements are giving firms a competitive edge that goes well beyond an efficient running of routine operations and are taking them closer to the international competitors in terms of quality and performance*[191].

Despite the progresses made by the Chinese PV firms in the depth and the breath of their *technological effort*, however, this *is taking place only in the most technologically and commercially mature PV technology family*: c-Si. Although, as discussed in Chapter 4, there might be scope for firms to continue to operate in this mature technology for several years to come, important technological breakthroughs could come at any time. In this respect the PV firms in China show a shallow technological effort with a limited forward vision, which may cast doubt on their ability to continue to add value and to compete in the mid term.

Noteworthy differences exist in the firms' ability to 'change the technology' and to add value by moving closer to international competitors[192]. We take three of the firms interviewed as examples of the differences in their technological effort. Figure 43 illustrates the differences in the capabilities accumulated by these three firms. Besides the division in basic, intermediate and advanced capabilities adopted in the previous part of the chapter to describe how advanced is what the Chinese PV firms can do in processes and products (see how the analytical framework has been developed in Section 3.2.2), we have added here two extra degrees of complexity: proprietary and strategic capabilities. Proprietary capabilities account for any possible proprietary steps taken by the firms from patents and beyond (for instance the move of one of the firms in the sample towards vertical integration is included in this category). Strategic capabilities encompass instead those possible strategic decisions a firm might take to move the technology frontier forward and that we have used to assess firms' capabilities with respect to international competitors (see the final part of Section 3.2.2).

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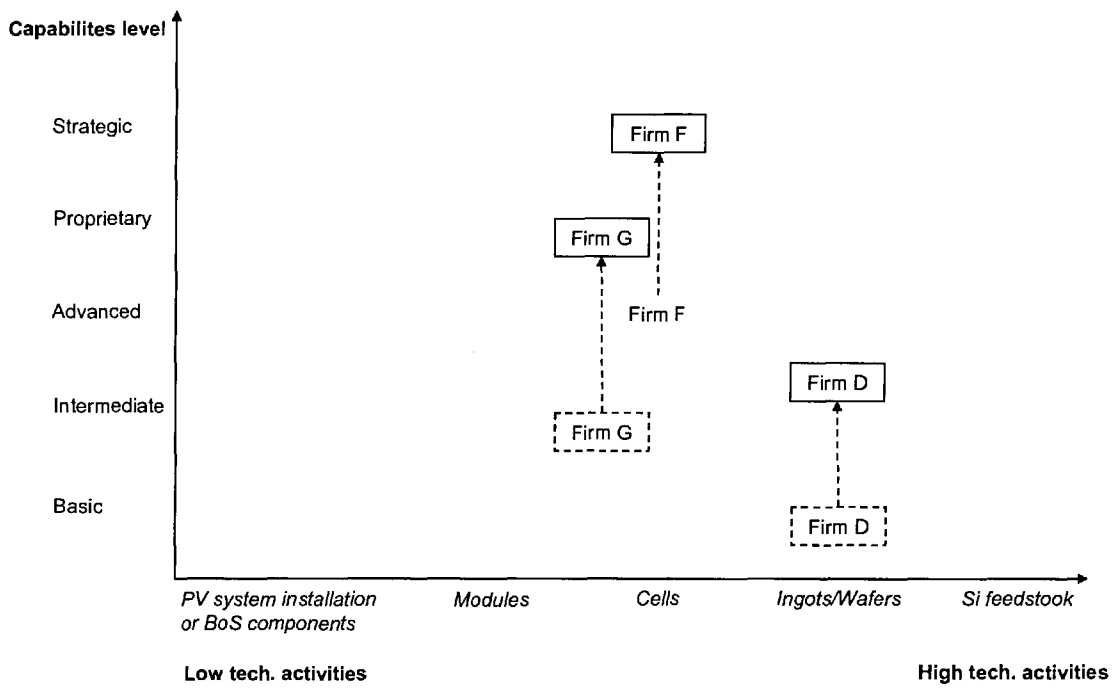
[191] As illustrated in Chapter 6, all the firms interviewed possess international quality certifications (which was not the case in the late 1990s) and deliver cells or modules with efficiency and life time quite close to that of international players.

[192] Possible reasons behind these differences are discussed both in Sections 7.3.2 and 7.3.3, as well as in Section 7.4.

We believe the addition of two more complexity levels better reflect the level of maturity of the TC that the Chinese PV firms have accumulated in both absolute (with respect to the firms' themselves) and relative terms (with respect to competitors).

Firm D started to produce c-Si wafers and cells (and to assemble them in modules) in the late 1970s. It has managed to significantly improve its process and products by enhancing, for instance, its wafer slicing techniques and delivering thinner wafers over time (and indeed it aims to achieve even thinner wafers). Moreover, it has remained afloat without radical management changes even with the entrance of foreign PV products and producers into the domestic market in the mid 1990s (see Chapter 6) and with the rise of powerful new domestic competitors in the late 1990s-early 2000s. Nevertheless, the firm has not developed proprietary capabilities that are distinctive to the firm. Although the firm exports its production, its strength is in the domestic market where its market share depends on the reputation it has gained after such a prolonged presence there. In its ability to 'change the technology', firm D positions itself in between what we have defined as intermediate and advanced technological capabilities, but it does not possess distinctive or proprietary capabilities other than reputation.

Figure 43 Capabilities differences across the firms



Source: Author's elaboration

Firm G is a spin-off from a Shanghai science and technology university. The firm, which produces c-Si cells and modules, has greatly improved its processes and products over time and has entered proprietary innovation by patenting its products. Despite being strongly export oriented, however, it remains far from international competitors (and indeed leading domestic PV firms) in terms of strategic vision and the capability of scaling up production (see

Figure 38 and Figure 39). As discussed in Chapter 4, this latter aspect could hinder not only a firm's capability to compete but indeed to devote necessary resources to further innovation.

Firm F, which produces both PV cells and modules, started producing in 2001 and was 'born global', showing a very rapid international growth, selling proprietary products under its own international brand. The firm possesses its own globally-leading manufacturing process operations, which allow it to be ahead of national competitors and to compete with international players on an equal basis. Moreover, the firm possesses a strategic vision (see Figure 39) and is involved in taking the c-Si technology frontier ahead by designing and developing new ranges of products and by producing record efficiency commercial c-Si solar cells (and aiming at further increasing these efficiencies).

These examples highlight how international competitiveness and the commitment to continuous value added depends not only on advanced technological capabilities (possessed for instance also by firm G) but also on other strategic assets such as vision, management and marketing. These aspects are all discussed in Section 7.3.3.

These insights support the already strong body of evidence emerging from the TC literature that innovation takes place also in developing countries (at least in rapidly industrialising countries like China) and that TC are indeed accumulated by firms in these countries and not only by leading foreign multinationals (Forbes and Wield, 2002, Bell and Pavitt, 1995, Romijn, 1997, Lall, 1992).

We observe, however, a *technological deepening that is more profound than the TC literature suggests for firms, in particular SMEs, in developing countries* (Intarakumnerd et al., 2002, Arocena and Sutz, 2000, Romijn, 2002). The Chinese PV

firms are in fact not only interested in using a technology developed and produced elsewhere (as a predominant presence in module assembly and PV installation would possibly have suggested) but also in developing domestic capacity to add further technological value and to generate own technological solutions.

Contrary to what is observed in the existing literature, the domestic PV market plays an extremely limited role in diffusing the technology developed by the firms. The test for the firms' technical and qualitative performance happens in the global market.

Although the firms' entry point in the international PV market has been non-technological (the firms exported in 2005 only the final assembled c-Si modules where the technological content is relatively modest – see Figure 21), our findings *do not support the view that they can only produce the low knowledge intensive components of the c-Si value chain nor that they compete exclusively on the basis of cheap labour and heavy discount.* Although we do not deny that discounting might be an important leverage in the firms' commercial strategy, from an innovation point of view we note a distinct *separation between what firms sell and what they can do.* In other words: there is a considerable difference between production capacity and technological capabilities.

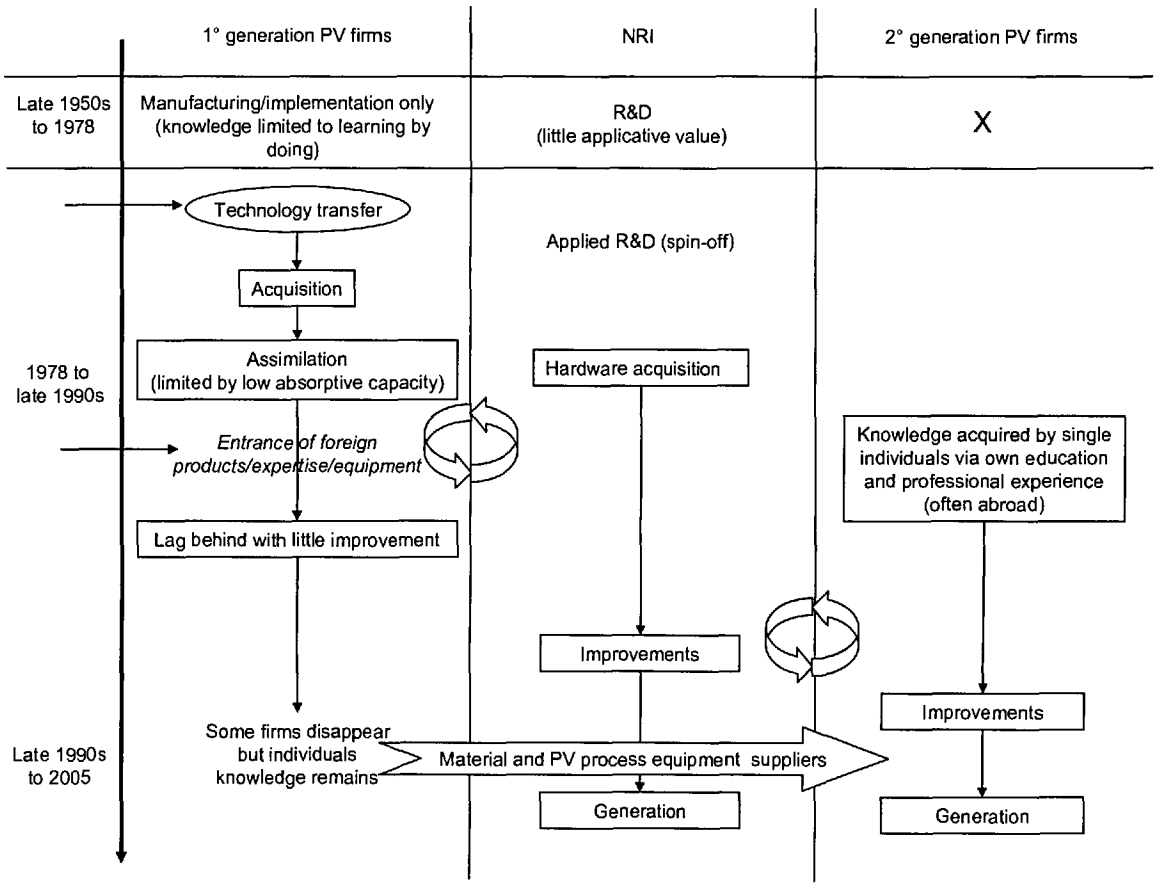
This separation is at the core of the Chinese PV firms' competitiveness.

7.3.2 From a reversed accumulation model to 'born global'

A second important theoretical insight that emerges from our findings concerns the knowledge accumulation path followed by the firms in the sample. Two important features are: 1) there is a considerable difference between the innovation path followed by the firms that started to produce in the 1970s (i.e. the first generation of PV firms), when PV manufacturing was first established in the country, and those that started to produce in the late 1990s – early 2000s (i.e. the second generation of PV firms); and 2) in understanding the technological innovation path of the Chinese PV industry it is analytically useful to observe the trajectory followed not only by firms but also by another non-firm actor: the national research institutes (NRI). As we explained in Chapter 4 and further explored in Chapter 6 with specific reference to PV (see Section 6.3.2), in the formative phase of the Chinese IS manufacturing and R&D activities were strictly separated and the activity that is usually more closely associated with innovation (i.e. R&D) was not conducted by firms but by the NRI. We hence believe that observing the paths followed by both firms and NRI could provide better insights in the Chinese PV knowledge accumulation path.

As discussed in Section 2.5.6 and briefly recalled at the beginning of this chapter (see Section 7.2), the literature suggests that catching up firms follow a reverse innovation path that goes from acquisition, to assimilation and adaptation, to improvement and eventually to own generation.

Figure 44 The Chinese PV firms' accumulation path



Source: Author's elaboration

Figure 44 shows that the firms that started to produce PV modules and cells in the 1970s (hereafter called first generation PV firms) seem to have followed a path similar to that suggested by the literature. Firms started to import production lines from abroad in the early 1980s, after having spent years in manufacturing c-Si cells and modules under government direction and without the possibility of undertaking any innovation-related activity (i.e. R&D or networking with other actors in the system). Accessing foreign technology and using it to learn basic production operating techniques provided firms with the first building block of technological capabilities.

An initial assimilation started but this was of a limited scale for two reasons: a) firms lacked the necessary sound technological background to produce cells and

modules of good quality and performance; and b) firms did not have the necessary non-technical competence (i.e. organisational and managerial capabilities) to search autonomously for the necessary financial, human and capital equipment resources previously provided by the government. With the entrance in the domestic market of superior foreign c-Si cells and modules, the majority of the domestic firms could not face competition and went out of business.

So the first generation PV firms' technological innovation path stopped at (poor) assimilation. The knowledge accumulated by the single individuals who used to work for these firms did not disappear completely, however. Some of the former general managers or chief engineers 'recycled' their knowledge by entering less knowledge intensive links in the c-Si value chain (i.e. production equipment for c-Si cells and modules) and constituted the basis upon which new firms that entered the market in the late 1990s-early 2000s (i.e. the second generation PV firms) could develop.

In the meanwhile, NRI, which had been totally devoted to R&D activities until the late 1970s, were starting to undertake productive activities. Their technological accumulation path begun with their own scientific education and R&D activities. For them, the import of equipment was more a tool to have the necessary hardware to produce than a means to learn and to obtain technological knowledge.

The technological accumulation path followed by second generation PV firms is closer to that followed by NRI than to first generation PV firms. What is striking about at least some of the firms that entered the domestic market in the late 1990s-early 2000s, is that they have been able to add value quickly and to enter the world PV market as global players. These firms have skipped the two initial phases of acquisition and assimilation and have entered the innovation path directly from improvement and generation. This stage-skipping behaviour is, however, only apparent because knowledge acquisition and assimilation happened at the individual level. As an example, the CEO of firm F took years of education and working experience to develop the capabilities that allowed his firm to quickly become one of the top 10 world PV cell and module manufacturers. He was able to start from a leading position because he had already completed all the preliminary knowledge accumulation process at an individual level.

What our findings seem to suggest is that a traditional technological accumulation path, as the one suggested by the TC literature, was indeed followed by

the Chinese PV firms until the late 1990s. This was so because at the time PV cell manufacturing was treated not as a knowledge-intensive industry but as an engineering-based industry, where knowledge could be acquired via technology imports and where ideological and strategic concerns had the priority on technological requirements. Evidence of this could be found in both the strict separation between innovation related activities, like R&D, and manufacturing and in the fact that firms were not supposed to look for their productive resources or to develop non-technical capabilities and market strategies.

Moreover, a true PV market hardly existed until the late 1990s so there was no market pull that could stimulate PV firms to improve their knowledge. When the global PV market started to take off in the late 1990s those individuals who already had accumulated the necessary knowledge via their own education or by participating in R&D activities, for instance in NRI, were in a good position to emerge.

These insights *confirms that the technological accumulation process is indeed gradual, but initial knowledge (i.e. learning how to do things) in this sector is not acquired by firms via technology transfers, as suggested by the literature, but derives from the knowledge that the individuals (i.e. the entrepreneur and the technical employers) already possess.* This partly explains why the firms that started to produce in the early 2000s have been able to skip the lengthy two stages of acquisition and accumulation and to move fast towards improvements and own generation. In this respect second generation PV firms seems to behave more like firms in technologically leading countries than like technology followers in developing countries, as the literature suggested.

The path that firms follow in accumulating their technological knowledge may well be related more to the knowledge intensive nature of the technology in which they embark than to the nature of the economic development of the country within which the firm operates. In other words: *the accumulation path followed by firms* that started to produce c-Si cells in China since early 2000s *does not seem related to the level of the economic development of that country*, as the reverse innovation model put forward by the literature suggests. A 'reverse model' of catching up, which starts with the import of hardware from mature economies to acquire the initial technical knowledge base, makes it possible to enter those links of the c-Si value chain where the technological content is lower, like, for instance module assembly.

7.3.3 Technological capability as a sub-set of a larger bundle of competences

In assessing how advanced is what the PV firms in China can do, we adopted a technological focus. Studying firms' technological capabilities made sense both because this was the approach suggested by the TC literature that underpins this study and also because technological innovation constitutes one of the main avenues through which the PV industry worldwide could drive solar electricity to cost competitiveness (see Section 4.4).

While undertaking the interviews in China, however, it soon appeared clear that the firms that possess more advanced TC are not necessarily also the most competitive or indeed those that are better positioned to generate technological change. In other words: to successfully move up the c-Si PV value chain and to increase competitiveness, a good mastery of the technology is not sufficient. Organisational and managerial capabilities, as well as vision and strategy, are at least as important for success in this technology.

A few examples taken from the interviewed firms serve to illustrate this point. Firm B possesses intermediate to advanced TC[193], but has an extremely limited production capacity and it struggles to gain market shares in both the domestic and the international market. As discussed in Chapter 4, scale is becoming an increasingly important factor for the PV industry and firms that are not able to increase their production capacity are bound to be cut off from competition. Scaling up does not require 'how to do' technological skills but rather those non-technical capabilities necessary to mobilise additional resources and to raise cash via capital increases (Kluftinger et al., 2005).

Firm C has possibly not achieved the same technological deepening as firm B[194] but it possesses strong organisation and managerial capabilities that have allowed it to become not only the first and only vertical integrated PV firm in China[195], but also to rapidly scale up production and to gain market shares in the international markets[196].

What our analysis shows is that in the Chinese PV firms, *technological capabilities are a necessary (and indeed essential) requirement to produce*, especially

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[193] The firm has not only developed the necessary technological capabilities to enter more knowledge intensive links of the Silicon value chain (i.e. from module assembly to wafer production) and to improve its processes and products over time, but can also construct customised pieces of equipment to be used on its production line.

[194] It is interesting to note that firm C required the technological assistance of the general manager of firm B when it started to establish its production facilities in the late 1990s.

[195] The firm is present on the c-Si value chain from Si wafer production to PV system installation

[196] The firm in 2007 was among the top ten world c-Si module producers.

in the knowledge intensive links of the value chain, *but they are not sufficient to add value and to compete.* Technological capabilities are an important sub set of a larger array of organisational and managerial competences necessary to the firms to move forward. It is only when a strong technical knowledge is combined with a strong management and a forward looking vision that a firm becomes successful. This is for instance the case of firm F, where a combination of advanced technical and non-technical capabilities allowed the firm to become, in less than seven years, the fourth world c-Si cell and module producer (Jäger-Waldau, 2007a).

As we discussed at length in Chapter 2 (Section 2.5.1) the TC approach originated in the early 1980s to explain firm-level dynamics in 'technology followers'. Its main focus has been on the creation of a minimum knowledge base necessary to select, install and deploy existing engineering-based technologies created elsewhere (Caniëls and Romijn, 2003). Organisational and managerial capabilities are not among the concerns of the TC literature because they are implicitly considered to belong to a more advanced level of knowledge (i.e. non-technical capabilities could come only after a firm knows how to do things).

Although we do not deny that knowing 'how to do things' is a sine qua non requirement for firms that operate in c-Si PV, we claim that the development of organisational and managerial capabilities is also essential and needs to be understood to draw a comprehensive picture of firms' innovative behaviour in this technology.

Although a detailed coverage of the role of non-technical aspects in the innovative behaviour of the PV firms in China is beyond the scope of this study, we suggest that a deeper analysis in this respect should be encouraged in further research. New insights might come from looking at key contributions that come from recent theories of firm behaviour in economically advanced countries, where organisational learning and core competences are given a greater emphasis (see among others, Dodgson, 1993, Dosi et al., 2000).

7.3.4 Revisiting understanding of innovation in developing countries

The level of technological capabilities accumulated by the Chinese PV firms and the path they have followed to accumulate them are indeed different from those observed in other more traditional and engineering based technologies. This challenges our understanding of technological change and innovation in developing countries. In a global context, where knowledge intensive technologies are becoming more important

and widespread (this refers not only to technologies like c-Si PV, but also, and among others, to pharmaceuticals, biotechnologies or nanotechnologies), does it still make sense to use an analytical perspective that considers the technological effort of firms in developing countries to be a 'special kind of innovation', in which acquisition of foreign technology followed by assimilation and improvement are the dominant pattern of the innovation process? Moreover, does it still make sense to claim that "[...] entrepreneurship should be understood [*in these countries*] within the context of latecomer catch up, behind the frontier innovation, and technology acquisition from abroad" (Hobday and de Barros Perini, 2005, p. 2).

We believe that adopting this point of view a priori conditions our analysis because we tend to pay attention only to certain aspects like incremental innovation from a low knowledge base and less to others like the transition process from this stage to build strategic capabilities to approach or even take forward the technology frontier (Dutrénit, 2007).

The recognition that there is limited understanding of what innovation means in developing countries and how it is challenged by emerging knowledge intensive technologies, would also allow us to improve our conceptual frameworks and consequently, to suggest policy recommendation that could better reflect new challenges and requirements of firms in these countries.

7.4 Key issues on the micro approach to industrial innovativeness

This second part of the chapter considers key insights relating to what influences the Chinese PV manufacturers' ability to innovate. This section discusses the micro-level learning mechanisms (i.e. we pull out the theory insights we obtained by applying the approach suggested by the TC literature), while Section 7.5 covers the systemic determinants of firms innovative behaviour.

7.4.1 R&D as the main mechanism for learning in the PV manufacturing firms

In-house R&D has emerged as the most important mechanism through which the Chinese PV manufacturers learn.

There are two purposes of this R&D effort for all the firms: 1) to improve productive processes in order to reduce production costs and enhance competitiveness; and to 2) strengthen the knowledge base necessary to enter more knowledge intensive links in the c-Si value chain.

The outcome of the R&D activities might not be new to the world but is certainly new to the firms. Firms need R&D to sort out specific technological problems they encounter in production (for example, how to enhance cutting techniques to obtain thinner wafers without breaking them) and to improve. These are improvements that can hardly be learnt from the technology leaders' experience and that hence require firm-specific purposive innovative effort.

While the overall focus of the R&D effort is the same for all the firms interviewed (i.e. to enhance competitiveness by reducing the production cost while improving at same time the quality and the performance of the final product), the depth of the R&D effort is different in firms with small production capacity and in firms with large market shares. Firms with limited production capacity tend to use their R&D departments to develop in-house those parts of the production equipment that could be bought more expensively outside. This is because they are already so constrained in resources that they cannot afford to push the frontier any further.

Since these firms compete with the big (domestic and international) players in the international markets, however, they have to place themselves in the market segments that allow high profitability margins and ensure they keep this position. This also explains why firms with small production capacity need to move upstream and to acquire proprietary assets with the strategic role of their R&D departments. Since these firms are constrained in both financial and human resources, they tend to complement their in house R&D with other types of learning like the training courses offered by the production equipment suppliers or by international organisations active in China for the promotion of RET (i.e. the GEF or/and the World Bank).

For firms that have already acquired large market shares, especially in international markets, in-house R&D is about gaining strategic positions in these markets with significantly enhanced processes and new products.

As we discussed in Chapter 2, firms' R&D activities are associated in the literature with the acquisition of advanced technological capabilities. This is because, in building the minimum knowledge base necessary to kick off the catching up processes,

formal R&D is often substituted in firms in developing countries by other more informal learning mechanisms like reverse engineering, debugging or training. When firms in developing countries undertake in-house R&D this is done to quickly learn from the leader's experience, to customise products or processes to a particular user's need or indeed to come up with a new design. Design, it has been argued, can provide the potential for firms in developing countries to move substantially up the value chain of global manufacturing while following the technology frontier set by technology leaders as efficiently as possible (Forbes and Wield, 2000, p. 1097). So, it is suggested, context (i.e. the development context) does matter when explaining the profile of R&D activities, which are opened to firms in developing countries (Forbes and Wield, 2000).

What our study seems to suggest is that the types of R&D activities that the PV firms in China tend to undertake seem to be determined not so much by their catching up and behind the frontier nature, but rather by: a) the level of technological capabilities that the individual firm already possesses; b) the knowledge intensity of the link in the value chain at which the firm operates; and c) the competitive, more than the developing, context.

For all the PV firms the context matters, but this is not necessarily the one where firms are located but rather the context where they have the largest market share and that determines the performance and quality conditions. Our evidence shows that PV firms have substantially improved the performance and quality of their products since they started to export. These outcomes have been the result of the effort of the in-house R&D departments.

When it comes to undertake R&D activities, it is argued (Hobday, 1995, Dutrénit, 2007, p. 137-138) that the context within which firms in developing countries operate constrains them in three main respects: a) disarticulation and distance from the main sources of innovation and R&D centres; b) distance from the most advanced markets, which make it difficult to benefit from the user-producer links for innovation; and c) they confront imbalances in the national systems of innovation where they operate and find difficulties in accessing scientific knowledge at the frontier so as to be able to move the technology frontier by themselves.

The firms that operate in the c-Si value chain in China are more and more globalised, so the above factors are less relevant for them, especially b).

We argue that, when it comes to firm R&D, the context matters but it is the international context within which firms operate more than the developing context they are based in.

7.4.2 Scientific education and intra-firm linkages are the main drivers of a Chinese PV firm's learning

A sound technological knowledge gained both via education (i.e. university degree in physics, material science, electrical engineering) and working experience in the sector by the founder/manager(s) are the prime drivers behind the in-house R&D in the Chinese PV firms.

PV is a knowledge based industry, which depends on formal research to advance the technology frontier (see Chapter 4). This particularly applies to the links of the value chain, like wafer or cell production, that have higher know-how requirements (see Chapter 4, Section 4.3). Moreover, a specific technical knowledge is necessary to modify production processes, since innovating in PV means reducing the cost of the technology while maintaining useful cell efficiencies.

More than half of the PV manufacturers that were interviewed either grew out of research institutes and universities or were led by people with a sound scientific and technical background who had built up their expertise over many years of research in such organisations. It is this strong R&D background that has allowed the deepening of the technological capabilities and explains why half of the firms that have been interviewed hold patents.

Intra-industry links are another important driver for learning for both the Chinese wafer, cell and module producers and their suppliers, particularly domestic. Since: "Even the best-resourced organisation cannot do everything with respect to technology [...] part of the strategic challenge lies in choosing which technology activities to conduct in house and which to outsource to partners" (Rush et al., 2007, p. 227). Outsourcing to domestic suppliers part of the production equipment to be used by the firms in the sample to meet specific production and qualitative requirements have not only allowed producers in lower end of the c-Si value chain to emerge but has also provided them with an extraordinary opportunity for learning.

7.4.3 Partnership with research institutes and international organisations provides competitive advantage to Chinese PV firms with limited production capacity

For firms with limited production capacity, other factors seemed relevant to unleash learning and to accumulate knowledge.

In the sample, the firm's size seems to have a negative impact on innovativeness and competitiveness. Firms with a limited production capacity are not necessarily poorly technologically equipped (or have accumulated less knowledge), but they may be less able to compete. This means that they have less resources to devote to their further technological upgrading, but also tend to have fewer links with suppliers and, as a result, fewer inputs into their innovative activities. As a consequence, these firms end up being less innovative (which includes the ability to diffuse what you can do on the market) even if they are technologically competent.

The firms try to compensate for this limited production capacity by strengthening links with a number of partners. Interactions between these firms and research institutes or universities play an important role in stimulating the firms' knowledge and the ability to solve fundamental problems related to the production (for example, how to improve cell's efficiency via better cell surface texturing, etc.).

Also links with international organisations tend to be important to provide additional knowledge via ad hoc capability building programmes. Moreover affiliation with international organisations that operate domestically can also provide additional domestic market opportunities[197].

7.4.4 Innovating in PV in China challenges traditional modes of firm-level learning

Learning in PV (c-Si) has a strong 'knowledge' component, where ad hoc education/experience is a necessary condition to enter the industry. Firms, especially in developing countries, that want to enter this industry face barriers higher than for engineering-based technologies where entry from a low skill base is possible (Mytelka, 2004). Foreign technology, in the form of imported equipment, has a negligible learning impact per se and needs to be accompanied by individual effort to acquire knowledge and stimulate learning.

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[197] See discussion done in Section 6.3.1 under the 'training' heading.

Technology imports have been a vehicle of knowledge used by first generation Chinese PV firms. This failed as an innovation strategy however, because it was not backed by a sound scientific and knowledge base and by in-house R&D. Technology import seems to work as a strategy to acquire knowledge for those engineering based technologies like automotives, textile, etc. (Mytelka, 2004). C-Si PV, and in particular certain links on the value chain where the Chinese firms are moving into, needs special knowledge, which is not acquirable via imports.

These findings imply that although the manufacturing of PV components has a role to play in the low carbon industrialisation strategies of developing countries (see Section 1.1.), not all nations will possibly be in the position to benefit from it, because the traditional entry point from a low skill base is hardly possible.

Moreover, the findings we obtained by applying the micro-level approach suggested by the TC literature provide us with a quite static view of the learning process in the Chinese PV firms. This is to say that we know 'how' the PV firms in the sample learn but we do not know 'why' firms decide to learn in the first instance and how the system in which firms are embedded concur to their learning effort.

Focussing only on the static firm-level learning mechanisms would lead us to suggest policies that are broadly related to firm learning alone. We would suggest, for instance, more education to be promoted in the country or more university-industry links and more international programmes. This would give us only a partial insight into the technology accumulation process that occurs in firms, however.

By adopting a system level perspective we miss somehow the firm's perspective (which we will hence suggest to include in a framework where the TC and the IS approaches are integrated, see Section 7.6) but we obtain a richer picture of other processes that are relevant for innovation by firms and indeed for their learning: most of all, we have a view on 'who' provides these inputs or 'how' they are provided.

7.5 Key issues on the systemic approach to innovation in PV firms

This Section draws out the main insights we obtained by studying the PV firms' innovation determinants from a systemic perspective.

We begin the discussion with two questions: is in-house R&D firmly anchored in the sciences and enhanced by intra-firm linkages enough to explain the rapid growth

of the Chinese PV industry since the early 2000s (see Chapter 5) and its ability to go well beyond a minimum knowledge base? Can the systemic analysis provide some additional insights?

We will argue that acquiring the necessary knowledge (both technical and non-technical) is only a necessary but not a sufficient condition for the industry to emerge, to add value and compete. Knowledge needs to be 'activated' by market demand, resource availability and by supporting policies. Although this is broadly intuitive, what is new is that these 'activating mechanisms' do not need to be local for innovation in PV to occur in a certain local context. On the contrary, local system dynamics can intertwine with global technological dynamics for the local system to create innovation.

7.5.1 Learning needs to be 'activated' by viable markets and resources: on what systemic functions/process are vital for firms to innovate

Drawing from the systemic analysis we presented in Chapter 6, we notice that certain processes of the seven that are usually identified by the TIS literature for a technological systems to emerge and diffuse are particularly relevant for the PV firms. These are:

- Knowledge, which should be both technical and managerial
- Resource availability
- Market creation

'Knowledge development' was the very first constituent of the Chinese PV innovation system. Even if the initial knowledge developed under the central government priorities and guidance was not conducive to innovation (i.e. manufacturing and R&D activities were strictly separated and horizontal links between the – few – actors were not allowed) and even if the early PV firms did not succeed in moving into the high growth period of the Chinese PV industry (from the early 2000s onwards), it provided an initial opportunity for the individuals to learn and to respond quickly to the new domestic demand in the late 1990s-early 2000s. Individuals that participated in what we have defined as the first generation PV firms, used their learning to enter less knowledge intensive sectors of the c-Si value chain and to satisfy the demand for PV production equipment coming from new entrants.

These knowledge-related factors are important to appreciate that what matters to better understand innovation in PV manufacturing firms is not necessarily 'how long a

firm has been producing for' but 'how experienced the single individuals are'. This is not to say that PV firms, as such, do not need to learn. But individual learning rooted in science education seems likely to be far more important in knowledge intensive industries.

The Chinese government played a key role in creating initial knowledge, but withdrew gradually from a sector that was no longer perceived as strategic. With the opening up of the domestic PV innovation system from the early 1980s, knowledge inputs have been provided by other actors (like foreign PV equipment manufacturers) that either did enter the national system or that were external to it, like foreign universities or R&D institutions. So the knowledge creation function evolved from 'totally nationally provided' to being more and more global.

This knowledge role confirms the findings of the TC analysis but enriches them by providing insights in the sources of knowledge provision (not only links with suppliers but also education acquired abroad and entrance in the system of a number of new actors that contributed in disseminating knowledge). Moreover, the IS approach helps us to understand that knowledge accumulated by an individual firm per se is not enough; it needs to be activated by market and resources availability. In other words, the functions 'market creation' and 'supply of resources' act as triggering mechanisms for the accumulated knowledge. This was intuitively apparent also from the insights we obtained from the TC approach, where we emphasised the role played by inter-industry links to enhance learning.

PV firms from the late 1970s – late 1990s struggled to stay afloat because they did not have enough scientific and non-technical knowledge, but also because they did not know what they needed in terms of R&D and equipment. So even when the system expanded by providing new market opportunities and resources, as well by giving the firms the freedom to decide on their innovation related activities, firms could not benefit and the 'market' and 'resources' switches could not provide the right sparks to ignite knowledge, which was quite restricted.

If we compare these first insights obtained from the IS analysis with the TC analysis, we can say that we have a less thorough view of micro-level dynamics (i.e. with the systemic analysis we are not able to assess the importance of the firm's learning mechanisms, such as R&D or the importance of a diversified number of

interactions for firms with limited production capacity), but a broader view of the system.

While these insights (that knowledge and early investments in the technology are necessary first steps that need to be activated by resources and market opportunities), are hardly new, what is interesting from the IS analysis is that it explains by whom these inputs are provided and this, as we will argue, has significant theoretical and political implications.

7.5.2 Functions do not need to be satisfied locally: on the importance of defining the system boundaries

In observing the 'market creation' and 'supply of resources' functions, as well as the policies that have been promoted to support them (in particular market creation), we notice that they are not necessarily provided from within the Chinese NIS. The function 'market creation' is provided, for instance, both domestically, through the rural electrification programmes promoted by the Chinese government, and internationally by the on-grid installations that are driving the global PV market and that are supported by conducive policies in mature economies. Similarly, although the domestic innovation system has grown over time and can now provide domestically resources, such as PV production equipment or materials, that until the late 1990s were acquirable only abroad, foreign suppliers still play a predominant role in the broad system to which the Chinese PV manufacturers belong. More subtly, other functions like for instance 'legitimation' are, to a certain extent, also provided abroad. The Chinese PV manufacturers are in fact benefiting from the legitimation process that has taken place in countries like Germany and that has resulted in policies to support the domestic German market, to which the Chinese PV firms largely export.

By applying the TIS perspective to the Chinese PV innovation system, as suggested by the literature, we observed that several of the functions necessary to the firms to achieve innovation are not provided locally (at least not entirely). So why did the domestic PV manufactures that entered the Chinese market in the early 2000s decide to do so if the processes/functions necessary for their development and innovative effort were provided abroad? Because there were favourable local conditions that induced them to do so and that intertwined with the international

dynamics. Among the domestic drivers, the policies promoted by the government to attract back home Chinese scholars or entrepreneurs who were gaining their education or professional experience abroad played a significant role in attracting back home some of the people who now run the PV firms in China. Moreover, cultural factors, expectations of the growth of the domestic market, the existence of a science and PV specific knowledge base – resulting from previous national/individual investments – together with other favourable macro policies, such as the 'SMEs fund' (see Section 5.2.2) and the export policies, contributed to driving powerful new players in the domestic market.

These insights show that an emerging and PV conducive macro environment intertwined with stronger drivers, such as market creation, coming from abroad. This could have important implications for the application of a technological IS to a local context. If we adopt a 'technology perspective' and want to understand more about the development and diffusion of that specific technology, looking only at inducing and blocking mechanisms in a specific national context (as it is done in the existent literature, see for instance Jacobsson et al. 2004, Jacobsson and Bergek, 2004, Negro et al., 2007, Negro et al. 2008,) can lead to misleading conclusions about the 'goodness' of that system in achieving innovation and the policy prescriptions we are able to give.

7.5.3 What is good to unleash technological innovation at a broad innovation system level is not necessarily good for the firms

In the TIS literature it is argued that in guiding the direction of search of the different actors in the system it is important to stimulate technological variety (Jacobsson and Johnson, 2000). It is suggested that this can be done by providing financial and market incentives that can guide firms or indeed research institutes to enter the system because they see important opportunities for further growth or indeed rewards in the sector.

The Chinese system has not been good at creating technological variety - quite the contrary. The Chinese government initially guided the actors' search into only one technology, c-Si. The system has specialised in this technology and a division of labour has emerged, driven by the demand from several powerful c-Si cell and module producers that entered the market in the late 1990s-early 2000s. So although we recognise that a lack of technological variety could compromise the future of the Chinese PV innovation system (i.e. what will happen to the c-Si centred Chinese

innovation system if c-Si is substituted by other technology families that are rapidly approaching technological and commercial viability?), our findings do not support the view that a lack of technological variety (so a weak domestic 'guidance for search' function) has prevented firms from entering the market. Quite the contrary, it has created specialisation and a division of labour which are among the competitive assets upon which new powerful PV manufacturers can count to cut costs further and to compete in international markets.

The message we want to put across here is that the extent to which the system is conducive to innovation really depends on the goals of the different actors.

7.5.4 Local system failures do not imply no local innovation: on how we assess a system's performance

It is not necessarily the case that, if there are local system failures there is no local innovation. There are two main reasons for this:

1. A weakness of the domestic system in meeting one of the functions that are relevant for PV manufacturing can be compensated abroad (see previous section).
2. Moreover, certain system failures can be bad for innovation diffusion in the local market but not necessarily for the generation and the development of knowledge in the same country context.

The existing TIS approaches use 'diffusion rates' as the yardstick of a system's success in achieving innovation. This happens even though the point of departure is to understand 'system emergence and diffusion'. Jacobsson and Bergek (2004), for instance, use diffusion level of wind turbines, solar cells and solar collectors in Germany, the Netherlands and Sweden to shed light on differences in the performance and evolution of the three systems over time (for instance, how could we explain that at the end of the system's formative period, "[...] the Netherlands and Sweden were ahead in wind turbines and solar collectors respectively [...] but lost their advantage subsequently"? Jacobsson and Bergek, 2004).

If we use 'diffusion rates' in assessing the 'effectiveness' of the Chinese PV innovation system in achieving high rates of installed PV capacity (see Figure 29), we conclude that the system has indeed not been successful. We would then investigate why and find out that there is a poor local PV legitimation, that the government prefers

to support other RET that are nearer to commercial maturity (i.e. wind and biomass) and that it promotes PV only for some specific rural applications that are socially necessary but not profitable for firms. We would then suggest strengthening the legitimation and the market creation functions.

We cannot avoid noticing that the Chinese PV manufacturing industry is not only booming (i.e. it has been able to greatly expand its production capacity in a short span of time), however, but also that it has moved forward from an innovation and competitive point of view. We can then legitimately ask, how was it possible for a system that displayed failures (and these include, besides poor legitimacy and market failures, also poor resource provision, understood as part of the equipment which is largely imported from abroad) to be so successful in creating a rapidly growing and dynamic industry?

Possible local system failures (e.g. the function 'market creation' is poorly served in the country x) *do not necessarily result in scarce innovation* (i.e. firms in the country x have been successful in taking the PV technology forward although the local demand has been modest; this is because the demand has emerged elsewhere). A lot depends on what criteria are used to assess the 'effectiveness' of the system's performance (which, we argue, should include both development and diffusion) and on whether some of the processes that are crucial for the firms could be satisfied elsewhere.

We argue here that local system failures do not necessarily prevent innovation in that specific local context. Much depends on how global the system is and on how much local producers can benefit from global and indeed local opportunities (e.g. the Chinese firms have benefited from favourable export polices which have helped the boom in the industry).

7.5.5 Conclusions on the insights obtained from the IS approach and how these compares to those from the TC approach

All these issues question the validity of a functional approach as a useful analytical tool for policy makers, especially in developing countries. It is claimed that: "functional analysis can be a useful analytical tool for policy makers in that it helps these to systematically map 'what is achieved' in a specific IS in terms of seven key processes important in the evolution of an IS. System-specific weaknesses in an emerging IS can then be defined in functional terms and these can be used as focusing

devices for policy makers in their search for identifying the key policy issues" (Jacobsson and Bergek, 2006).

Our analysis shows that indeed a system analysis is useful, also in rapidly industrialising countries like China, to identify the main process that are relevant for firms and who could best provide them with what they need. In this respect the IS analysis provides, with respect to the TC analysis, richer insights into how firms innovate and why.

Problems arise when we use a TIS functional approach and apply it at the national level: problems with how the boundaries of the system are defined and to the benefit of whom or what we seek to give policy recommendations (i.e. what are our policy objectives? What do we want to have more of? PV manufacturing firms? PV installed capacity? Competing PV technology families?). These are all important policy objectives to define, because what is advisable to reach a policy objective is not necessarily also good for another goal (as earlier examples illustrated).

In relation to the boundaries of the system, we have shown that studying an innovation system in a certain national context to understand more about the emergence and the diffusion of a certain technology can lead to ambiguous results because, as the Chinese PV case illustrates, domestic elements of the system can be affected by international dynamics that occur in other technological systems. As a result our policy recommendations could be distorted. In the case of the Chinese PV system, should the Chinese government, after having realised that its market creation policies in support of rural electrification have failed to attract the booming domestic industry into the domestic market, decide to open up the on-grid market with costly incentive policies while the local industry is booming because it is driven by markets and policies promoted by other countries? Would it not be better for the Chinese government to focus on more urgent development needs or to decide to support other RET that are closer to commercial maturity?

The point here is that *suggesting policy measures on the basis of a TIS analysis applied at the national level does not necessarily provide the best insights and focusing devices for policy makers.*

We argue that what is relevant is the view point we adopt and the objective of the policy we seek to promote. If we adopt a TIS approach, then we should take into account the TIS which is relevant to the technology and not to the country. This is because we have seen that the PV IS in China is affected by a great number of

components, institutions (with policies) and networks that are not local. We would then have a TIS that contains both national and international elements. What is relevant is that this not only pertains to the actors, but also to the links between them and to the institutions. Institutions in one country can affect the development and diffusion of the technology in anther country. This has profound implications for our capability to recommend policies.

7.6 An integrated TC and IS approach?

The results obtained by the study showed that the innovation behaviour of the PV firms in China was not merely due to the individual capability effort/learning of the firms. By superimposing a system analysis it became clear that a key role was also played by other elements of the system of which firms are part (for example, the international PV demand or the policies promoted by some governments in mature economies – most notably Germany - to increase PV installed capacity).

Thus by using insights from both approaches (i.e. the TC and the IS literatures) it has been possible to provide a more complete explanation of the PV firms' innovation behaviour than would have been possible from using only one of the two approaches.

It is legitimate to ask, therefore, whether an integration between the two approaches would be feasible.

Although exploring ways for a full integration lies beyond the scope of this study, we can identify some conceptual issues a combined framework should address.

A combined framework that seeks explanations into firm's innovation should:

- *Adopt an actor oriented focus*, where the firm is the point of departure of the analysis and its learning and how this is affected by the broader innovation environment are at the centre of the analysis. Different from to a broader TIS approach that has technology as the main concern, the actor oriented focus we propose would allow a better understanding of one of the actors of the innovation system: the firms, of what influences their innovation behaviour and, in turn, how they contribute to the direction and the outcome of the innovation process for the specific technology under analysis.

The contribution already provided by Markard and Truffer (2008) could offer useful conceptual hooks for a better specification of an actor oriented focus and pointers towards a combined TC and IS framework.

- Have a *better specified definition of the system's boundaries,* where not only the national elements and dynamics that influence innovation in firms operating in the technology under study are taken into account, but where the whole (i.e. national and international) IS of which firms are part is considered.
- Be *ideally applicable to different kinds of innovation* (e.g. organisational, financial, marketing and technological innovation. See the definition of innovation provided in Section 1.4) *and technologies* (e.g. engineering-based and knowledge-intensive).

Our study has shown that the latter point could represent a major challenge for a combined TC and IS framework. The TC approach was in fact originally developed to analyse the creation of a minimum knowledge base necessary to firms to select, install and deploy existing engineering-based technologies created elsewhere

Our study has already provided evidence of the limits of the TC approach in understanding firm-level learning in a knowledge intensive technology like solar PV. Moreover, we have shown how the non inclusion in the approach of non-technological capabilities (for example managerial or organisational capabilities) is a limit in understanding the innovative behaviour of firms, especially of those firms that operate in the PV sector.

Consequently, it seems likely that an attempt to develop a fully integrated combined framework that could be used to study all types of technologies and innovation would encounter significant analytical challenges.

7.7 Conclusions

In this chapter we pulled out the main insights the study has obtained about the nature and the determinants of the technological effort underway in the Chinese PV firms and critically discussed them in the light of the TC and IS literatures that underpin this study.

We found out that the Chinese PV firms, despite differences among them, are moving fast from being imitators and users of imported technology (i.e. only assembling modules by importing foreign cells and competing on cheap labour) to building up absorptive capacity to sustain genuine innovation. This technological deepening is more profound than the TC literature suggests for firms, in particular SMEs, in developing countries. Moreover, our findings suggest that the traditional technological accumulation models based on acquisition, assimilation and eventually improvement, observed by the TC literature for engineering-based technologies might well be no longer appropriate for high-tech industries like PV. In the manufacturing of PV components, our findings show that an initial knowledge base anchored in scientific education is a necessary condition to kick off production, especially in those links of the PV value chain (like wafer and cell manufacturing) that are more knowledge intensive and that allow participating firms to gain higher profits. This knowledge intensive nature of PV (in particular of certain productive links) narrows the opportunities, described in the literature, of firms' entry in the industry from a low skill base and makes the role of technology imports as the key mode of learning only marginal.

The study also found that acquiring the necessary technological knowledge, as suggested by the unique application of the TC approach to the study, is only a necessary but not a sufficient condition for the PV industry to emerge, to add value and compete. Knowledge needs to be 'activated' by market demand, resource availability and by supporting policies. These results have been suggested by the application of the IS approach to the study. Although these insights are broadly intuitive, what is new about them is that these 'activating mechanisms' do not need to be local (as suggested by the application of the TIS literature to different national contexts) for innovation in PV to occur in a certain local context. On the contrary, local system dynamics can intertwine with global technological dynamics for the local system to create innovation. These findings call for an improved definition of the system's borders and an improved understanding of the criteria we use to assess the 'goodness' of the system in achieving innovation.

8 IMPLICATIONS FOR POLICY

Picture 10 "All truths are easy to understand once they are discovered; the point is to discover them", *Galileo Galilei*



Source: picture taken by the author during fieldwork in China, May-July 2005

8.1 Introduction

The insights discussed in the previous chapter suggest several implications for policy. These have relevance for the further development of the Chinese PV industry and its ability to innovate further, for the technological and market prospects of PV in China as well as for other developing countries willing to enter PV manufacturing. We discuss these policy implications in turn.

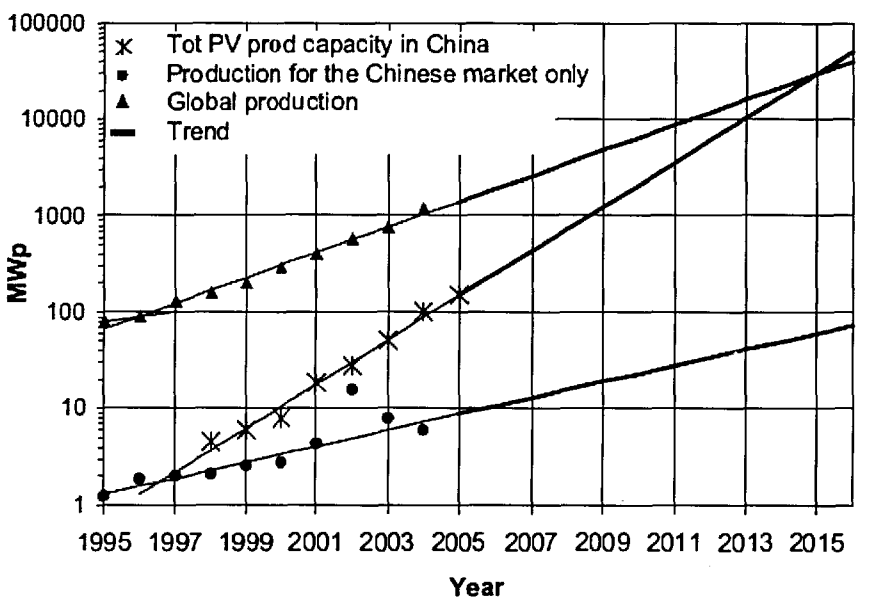
8.2 Policy recommendations for China: what way forward for the Chinese PV industry and for PV technology?

The findings of the study show that the Chinese PV firm's ability to innovate has been based on the accumulation of individual knowledge and relevant experience, coupled with an intense firm-level R&D effort enabled by both domestic and international factors. Can the PV industry continue to move forward and possibly innovate? If yes, under what conditions?

China is rapidly becoming the world largest c-Si module producer. Indeed, if the 2005 trends in the domestic and global production capacity were to continue for the next 10 years, China's PV production would be set to saturate the global market by 2015 (see Figure 45) . In other words, at current rates of growth, Chinese supply alone will soon exceed global demand. This is a potentially risky situation, given the over-reliance of the Chinese industry on overseas export markets, especially in Germany and Spain (see discussion in Chapters 5 and 6). What will happen to the Chinese industry if the subsidies that currently support the export markets die out? Will the industry still be able to add value and innovate, without a market that provides rents and inputs to innovation?

Recent trends seem hardly sustainable in the absence of new global solar electricity markets and in particular of the taking off of the domestic market.

Figure 45 Illustrative extrapolation of the consolidated PV production capacity trend in China over the last 10 years



Source: Marigo, 2007

The promotion of sound and *long-term measures for the development of the domestic on-grid PV market* would possibly provide the local industry with an alternative to the over-reliance on overseas markets. This would particularly benefit those firms that currently have a limited production capacity and that struggle to compete with bigger domestic and international players.

Moreover, a major determinant in the future of the industry concerns the promising new PV technologies that are currently starting to be commercialized or are in their infancy. This will be a possible threat for the c-Si industry but also a challenge for the Chinese government, which, as we have seen, is currently doing little to support technological variety. If the c-Si industry has benefited so far from technological specialisation because it has increased the division of labour and ensured provision of services and components in the lower end of the c-Si value chain, putting all the eggs in the c-Si basket might be a dangerous strategy. c-Si technology is certainly in high demand at the moment, but it is also very close to technological maturity. It follows that further cost reduction opportunities and efficiency improvements are quite limited. Better prospects for a global larger scale PV adoption will possibly be provided in the mid-term by other technologies (i.e. some thin film, PV under concentration or novel PV), on which China is currently only marginally focussing its national R&D effort. Technological learning takes time and China might lose its current competitiveness should technologies that are now in the demonstration phase really take off. In this case countries where R&D in novel PV technologies is underway will possibly be advantaged. For a national PV strategy point of view, the *promotion of PV technological variety in the early stages of R&D* would allow further technological learning away from the nearly mature c-Si technology family and the heavy reliance on continuing international market pull.

8.3 Implications for other developing countries willing to enter the same high-tech industry

The findings of this study have several technological and strategic implications for developing/rapidly industrialising countries wishing to enter the PV sector.

As discussed, several links in the c-Si value chain are more knowledge intensive than others and require a specific technological and science-based background. This applies in particular to Silicon feedstock, ingot casting and indeed wafer and cell production. Moreover, the knowledge intensive nature of the industry also implies a long time for learning. This refers to the time needed both by the individuals to acquire the necessary technical education and relevant working experience and by the system to develop. As a consequence, developing

countries that want to enter PV manufacturing should make an early start. This is risky, however, because an early decision to embark into the technology that now has the largest market share (i.e. c-Si) could lead to picking a losing technology. We know that other PV technology families have possibly better prospects in terms of cost reductions and performance. Similarly, late entry into the emerging PV market could result in 'lock out' if firms in other countries develop faster. This is indeed what has already happened: China has nearly saturated the market and has locked out other countries wishing to enter the same PV technology family, especially in module production. Even by producing super-large volumes, other firms will possibly not be able to compete, simply because there is currently an oversupply of c-SI modules. Moreover, there is little room for innovation in design, as design does not play an important role in module manufacturing

Should then developing countries completely abandon the idea of entering the PV sector? No, the idea is to use possible knowledge and expertise that already exists in these countries, not so much for PV cell or module production but for ancillary/complementary services. Building integrated PV is bound to become more and more important in the years to come, so for a developing country departing from any possible already existing expertise in building might make more sense than embarking in lengthy PV components learning. This way they would not be cut off from a growing industrial sector but make the most of the already existing expertise to complement the strengths of other countries.

9 CONCLUSIONS

Picture 11 Dancing the Tango at the Temple of Heaven (Tiantan) in Beijing



Source: picture taken by the author during fieldwork in China, May-July 2005

9.1 Introduction

This thesis was inspired by the limited attention given to firms in developing countries as autonomous generators or innovators of technology. This gap in our knowledge is particularly evident in emerging energy technologies, like solar PV, which have been increasingly affecting the volume, composition and direction of world trade (UNCTAD, 1993) and which could offer developing countries opportunities to follow more sustainable low carbon development pathways.

In Chapter 1 (see Section 1.2) we suggested that considering firms in developing countries as 'users' or 'borrowers/imitators' of technologies developed in mature countries has two drawbacks: it not only limits our understanding of how technological change for low-carbon energy technologies takes place in these countries but also focuses our analytical attention only on certain aspects pertaining to the 'user' side of technological development. These are, for instance, the acquisition of a minimum knowledge base via technology imports or the promotion of policies to enable entrepreneurs or governments in developing countries to develop strategies to catch up with mature economies and learn from 'behind the technology frontier'. This study offers a different perspective and aims at contributing to redress this gap in the

literature by studying the innovation effort underway in a rapidly industrialising country, China, to develop domestic technological capacity for the manufacture of solar PV components.

This final chapter begins by summarising the key findings about the nature of the innovative effort in the Chinese PV firms and the enabling factors and environment. It goes on to identify the contribution the thesis has made to the two literatures that underpin this study, the TC and the IS literatures, and more broadly to our knowledge about innovation for RET and firm-level learning in developing countries.

The Chapter ends with a discussion of the limits of the study in particular for a broader understanding of innovation for low-carbon energy technologies in developing countries other than China and with suggestions for further research.

9.2 Key findings of the study

We began by asking two questions:

a. How advanced is what PV firms in China can do?
b. What factors affect their knowledge accumulation process, how have they changed over time and how might they drive the firms' innovation effort further?

We found out (see Section 6.2.2 for the presentation of this specific result and Section 7.3.1 for its discussion in the light of the existent theory) that during the period under study the PV industry in China had progressed well beyond basic operational capabilities (i.e. those that can allow firms to run plants at a minimum efficiency level and to deliver standard products with minimum quality requirements) and was quickly moving away from being a mere borrower of imported PV components.

Despite significant differences across the firms, in terms of technological competence and degree of competitiveness in the international market (see Sections 6.2.3 and 7.3.1), there is a tendency towards the handling of more complex processes (like, for instance, advanced wafer cutting processes, enhanced solar etching and module coating techniques) and more complex/better quality products over time (for example, thinner or larger wafers; higher efficiency cells). Firms have been rapidly moving upstream (i.e. from module to cell or wafer manufacturing) where the technological know-how is higher and where more complex and deeper technological

capabilities are necessary. Moreover, some firms have developed proprietary capabilities and are competing with international PV module and cell producers on the basis of product performance and quality and not uniquely on heavy discounts based on cheap labour.

Despite the significance of these findings, the Chinese PV firms have accumulated and deepened their technological capabilities mainly in the PV technology family that is closest to market and commercial maturity: c-Si (Sections 6.2.1 and 7.3.1). In this respect the Chinese firms display a shallow technological involvement and are far from taking the lead in those PV technology families that are now in their infancy but that show good prospects of substituting c-Si technology in the mid to long term.

How it has been possible for the Chinese firms to move from being 'borrowers' to 'generators'? At the micro level (see Sections 6.3.1, 7.3.2 and 7.4), the analysis has shown that a first necessary enabling condition has been a sound knowledge base firmly anchored in the sciences (i.e. it is difficult to undertake c-Si cell or wafer production if you do not have specific technical knowledge and lack a scientific background). This has fuelled in-house R&D, which has served as the main learning mechanism for firms.

At the systemic level (Sections 6.3.2 and 7.5) markets and resource availability have acted as triggering mechanisms for this pre-existing knowledge base. Market opportunities, in particular abroad, have stimulated more firms to enter the Chinese PV system but also to improve the performance and the quality of their processes and products.

These findings have allowed us to improve our understanding of what is meant by innovation in developing countries and what determines it. Our academic knowledge so far has been based on the study of traditional engineering based technologies where technological upgrading was possible from a low skill base and where imports of technology from abroad were the main way through which firms could learn and establish a minimum knowledge base upon which to develop incremental changes and adaptations.

Our findings suggest these traditional accumulation paths are challenged by new knowledge intensive technologies, like PV, where a pre-existing technical and scientific background is essential and where market entry from a low skill base becomes extremely difficult.

Moreover, the findings also show that technological capabilities per se are no longer enough to enable firms to undertake technological change, move forward, catch up and compete. New technologies and the ways in which they are embedded in innovation systems require the development of other non-technological capabilities that pertain to organisational and managerial knowledge. These are necessary to elaborate a vision of the firm's technological and business path and to compete in the international markets. This means that the analytical tools scholars have used so far to study firm-level learning in developing countries are no longer sufficient and need to be extended to encompass the learning requirements of knowledge intensive technologies.

On the systemic analysis front, the study has shown that national dynamics intertwine with the international context of the specific technology under analysis (e.g. although PV industrial development is local, it has been driven by the global PV demand and indeed by the policies promoted in several mature economies to support it). This result questions the use of an innovation system approach that tries to understand local technical change by focusing exclusively on national specificities. Moreover, the study also shows that applying a technological IS approach to a local context could lead to misleading conclusions about both the 'effectiveness' of that system in achieving innovation and the policy prescriptions we are able to give.

9.3 The contribution of the thesis

This thesis makes significant novel contributions to knowledge of three kinds: methodological contributions by developing an analytical framework relevant for analysing PV innovation in China; empirical contributions by collecting and analysing contemporary and primary data on the state of the Chinese PV manufacturing industry; and theoretical contributions to the technological capability and innovation system literatures, and their inter-relation.

9.3.1 Methodological contribution

To understand how advanced is what the PV firms in China can do and what influences their innovativeness, this study has developed an *analytical framework* that:

1. Is *PV technology specific*. Existing frameworks that study firm level innovation and learning have been developed for and applied to engineering-based types of industries (see for instance the case of farm equipment – Romijn 1997 – or of

steel production – Figueiredo, 2002). This is the first time, to the best of the author's knowledge, that an analytical framework has been specifically developed to study firm's TC in a high-tech industry and more specifically in the PV industry.

2. Is *more comprehensive with respect to the existing frameworks* (Lall, 1992, Romijn, 1997, Ariffin, 2000, Figueiredo, 2002) that investigate firm-level TC in developing countries. This is because, beside the usual study of a firm's ability to increase the value added of its products and processes, this thesis also encompasses the firm's positioning in the PV manufacturing value chain and in a broader PV technology family and competitive context.
3. It *combines and contrasts two well-defined approaches* – one with a technological capability and intra-firm learning focus and the other with a wider systemic perspective where the broader innovation system of which firms are part is also taken into account. Since until now the two approaches have been adopted separately to address similar broad issues (i.e. insights into the forces that drive competitiveness and economic growth), the effort of this study in combining them is *a first attempt to establish a full integration of the two analytical levels.*

9.3.2 Empirical contribution

On the empirical front, the main contribution lies in the *application of this analytical framework to the PV industry in China*, a sector which has not been studied before from an innovation view point. Moreover, this study represents the first *application of the innovation systems approach to PV manufacturing and technology in China.* This has provided valuable information upon which other PV centred innovation systems could be compared and contrasted (Marigo et al., 2007).

Contemporary and primary data on the state of the Chinese PV manufacturing industry have been gathered, organised and presented for the first time (Marigo, 2007). These data constitute a unique body of empirical evidence on the sector which was not available before and which is extremely rarely obtained by researchers who are not Chinese

Furthermore, since the study adopts a time-based approach, it has *mapped for the first time the main actors and interactions of the Chinese PV innovation system over time.* This allows us not only to understand the PV system's evolution and

dynamics in fostering innovation over time but also provides useful information for those scholars interested in better understanding the timing, phases and sequences of technological change in the industrial development of PV.

9.3.3 Theoretical contribution

The thesis makes the following contribution to the existing theory and more specifically to the technological capability and innovation system literatures that underpin this study:

1. It adds *to the debate about what we mean by innovation in developing countries and 'how' and 'why' firms in these economies accumulate technological capabilities.* Moreover, the study also supports and enhances the insights obtained by other researchers in the field of firm-level innovation in developing countries. By dividing TC, as suggested by the existing literature, according to the level of difficulty and the functions they have to accomplish (i.e production and processes), this study has shown that such a division is appropriate and relevant also to study the nature of the TC accumulated by firms in knowledge intensive sectors like PV. In this respect, the thesis also *supports those scholars that have used or intend to use the TC literature as a framework for investigating knowledge intensive sectors.*
2. It also *adds to the debate on how RET emerge and diffuse in the market* by providing specific insights derived from the study of the PV innovation system in China. The study has shown that an innovation system approach can be used both to map the different elements of the PV innovation system of which the firms are part and to study the enabling factors and dynamics of their innovation behaviour. This approach has also allowed to show that the system as a whole, in which elements and dynamics both internal and external to the Chinese innovation system are included, has been important for the emergence and the development of the PV industry in China. These findings indicate that the *use of an innovation system approach to study innovation in firms involved in RET also in developing countries is both possible and relevant.*
3. It provides evidence on how a static firm-level analysis provides only a partial picture of how firms (with a particular reference to Chinese PV firms) innovate and compete.

4. It also provides evidence on: a) how a broad systemic analysis leaves unexplored important micro level dynamics like firms' learning and suggests that an actor-oriented systemic analysis might compensate for these shortcomings; and b) why the application of a technology-centred innovation system (TIS) to a specific country-context gives partial, and possibly distorted, insights into how technologies, in particular RET, emerge and diffuse in the market.
5. By combining and comparing two different and partially complementary bodies of literature (i.e. the TC and the IS literatures), the *factors that affect technical change in PV manufacturers have been studied on two levels of analysis: micro and systemic.* These two levels complement and strengthen each other and give a deeper understanding and knowledge about the factors related to technological development and diffusion in firms involved in PV component production. In so doing the study also provides an *initial basis upon which an integration between the two literatures can be established.*
6. It provides *enhanced policy guidelines* for developing countries wishing to undertake PV component production and more broadly, RET manufacturing. These derive from the combined insights obtained by applying both the TC and the IS analytical approaches.

9.4 Limitations and suggestions for further research

9.4.1 Limitations and methodological reflections on the thesis

In investigating the extent to which developing countries are becoming autonomous agents in the development of RET technologies, this study has focussed on a specific country, China, and a specific RE technology: solar PV. We recognise, of course, that there will be limits to the extent to which one can generalise from these country- and technology-specific insights to the experiences of other rapidly industrialising countries, like India or Brazil. First, China is a very special case due to its history, size, market opportunities, 'business attitude' and indeed profile of economic development. We suggest that it might be difficult to replicate in other rapidly developing countries the specific country conditions that have allowed the rapid

take off of the Chinese PV industry (i.e. early R&D investments in the sector, focus on one technology family that has favoured specialisation and division of labour; favourable policies for the return of top class scholars/entrepreneurs who had gained education and working experience abroad, together with funds for the support of SMEs operating in low carbon energy technologies).

Moreover, PV is quite specific in terms of technology families and different degrees of complexity along the supply chain. It follows that the results obtained by this study for this specific technology could not necessarily be extended to other RET, in China or elsewhere.

Despite these limitations, however, we believe some general lessons for other developing countries can tentatively be derived. An important insight is that learning, especially in knowledge intensive technologies, takes time for the individuals, the firms and indeed the whole system; this should be taken into account in undertaking technological decisions and in suggesting policy recommendations.

A further important generalisable result is that an approach like that used by this study, in which firm-level factors have been observed together with systemic dynamics, is able to deliver deeper and more satisfactory results about firms' innovative behaviour in developing countries than that suggested by conventional approaches based only on quantitative indicators. The latter on their own can in fact give only a shallow view of the innovation potential of firms - or indeed of a country.

Had more time and resources been available, it would have been valuable to extend the sample even further, to include the other firm that started producing in the mid 1970s and that was still in business at the time of fieldwork, as well as one or two other Chinese c-Si cells and modules producers that started their manufacturing activities in late 2004-early 2005. This might have confirmed or added new insights into the nature and drivers of technological change in the Chinese PV component producers.

Moreover, it would have been valuable to interview some of the customers, for instance in Europe, that use the Chinese PV modules. This might have allowed a deeper understanding of the nature of the technological effort underway in China by keeping into account also the view of the final end users of the PV modules, or indeed of other PV products produced in China.

With more time and resources at our disposal it would have been interesting to explore how the domestic PV industry finances its business activities. Although this issue has remained somehow in the background in this study, there is no doubt that a better understanding of financing mechanisms would allow deeper insights into what influences innovation in the Chinese PV manufacturers.

9.4.2 Suggestions for further research

The aim of this section is to identify some key issues that could be fruitfully investigated by further research.

First, there are some theoretical issues raised in the thesis that would benefit from further research. Two such issues are: how and to what extent to integrate the TC and the IS approaches more closely; and how to establish linkages between the TIS and the NIS approaches. In adopting the TC and IS literatures as the basis for exploring the nature and the determinants of the innovation effort underway in the Chinese PV firms and in combining the insights from them, we have established a first important link between the two literatures. There is, however, scope for further research on how micro-level dynamics could be better represented and integrated in a broader innovation system approach.

On the need to establish a link between the TIS and the NIS approaches, our study clearly showed that using an NIS perspective to better understand technological change has profound limits. This is because firms and newly emerging technologies like PV are more and more affected by dynamics and system components that do not belong to the national context. A significant case in point is the driving effect of PV policies promoted in mature economies on the development and rapid take off of the Chinese PV industry. Similarly, we have shown that taking the innovation system that surrounds a certain technology and analysing it in a specific national context, can lead to misleading results because the TIS encompasses elements and dynamics that go well beyond national borders. These findings call for a better definition of the innovation system's boundaries and application areas, in circumstances where it is evident that technological variables are affected by both national and more global dynamics.

In addition to these theoretical research issues, several empirical areas could be the focus of useful future research. An analysis, like that undertaken by this study, of the innovation effort underway in the PV sector in other rapidly developing countries

(India, for instance, where a PV component industry already exists) could provide further useful comparative information. In this way it would be possible to assess better the extent to which the insights obtained for the PV industry in China might be generalised and whether the systemic dynamics observed in this study are valid also in other developing country contexts.

Finally, a second important empirical area of further investigation concerns the role played by non-technological capabilities in enhancing the PV firms' ability to add value and compete. We have shown how organisational and managerial capabilities, together with technological capabilities, upon which this study has focussed, have been crucial to the ability of the PV firms in China to move forward and compete. We hence suggest that further research should be encouraged in this area. Looking at key contributions that come from recent theories of the behaviour of firm in economically advanced countries, where organisational learning and core competences are given a greater emphasis (Dodgson, 1993, Dosi et al., 2000) could possibly add new insights to what we already know about firm-level learning in developing countries.

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Appendix 1: the firm-level questionnaire survey

Technological capabilities acquisition and competitiveness in Chinese PV wafer, cell and module manufacturers

Questionnaire

The Department of Environmental Science and Technology at Imperial College London (UK), is carrying out a survey to find out how Chinese PV manufacturers innovate and what is driving them in this process.

Your participation would be greatly appreciated and your answers would be crucial for the success of the research. This questionnaire will take 1 hour to complete.

ALL INFORMATION THAT YOU PROVIDE WILL BE CONFIDENTIAL. Only information aggregated across firms will be used.

A report detailing the results will be sent to you once the analysis is completed.

Thank you for your participation in this study

Date of interview				
名称	中文			
	英文			
地址	中文			
	英文			
邮政编码				
电话				
电传				
电子信箱				

Date of interview

	En	Cn
Name of respondent and his/her position in the company		
Respondent's e-mail		

SECTION A: GENERAL INFORMATION ABOUT THE COMPANY'S ACTIVITY

1. 公司在哪一年成立的？In what year was this plant established?

2. 现在核心业务是什么？刚开始的业务是什么? What is your core business now (i.e.: the business which had the largest sales in 2004) and what was it when you started your business? *(please tick all that apply)*

	现在	*开始时*
Solar cell materials (a-Si, p-Si,m-Si, CIGS, others)	☐	☐
Device processing (wafer cutting, metal contacts, anti-reflection coating, encapsulation, etc.)	☐	☐
Module production (electric circuitry, circuit protection systems, front glass, temperature control, structural materials, module shapes and sizes, etc.)	☐	☐
PV products (flat plate, building unit replacement, street illumination, car parks, etc.)	☐	☐
Balance of system (inverters, charge controllers, batteries, etc)	☐	☐

3. 现在您们还有其他的业务吗？开始时，您们还有其他的业务吗？Do you have other significant activities? Did you have other significant activities when you started your business? *(please tick all that apply)*

	现在	*开始时*
晶体硅片 Solar cell materials	☐	☐
太阳(能)电池 processing	☐	☐
电池组件 production	☐	☐
PV products	☐	☐
Balance of system	☐	☐

4. 关于将来投资方面，您们能指出下面的业务的重要性? Could you please specify what is the importance you attach to these activities in terms of future investment? *(please rank up the activities listed below from 1 to 5. With 1 as the most important and 5 as fifth most important)*

Solar cell materials	☐
Device processing	☐
Module production	☐
PV products	☐
Balance of system	☐

5. 什么是您们公司的所有权? What is the ownership structure of your company? *(please tick one)*

State owned enterprise		☐
Collective-owned enterprise		☐
Individually owned (i.e.: private)		☐
		☐
Sino-foreign joint venture	% local	_____
	% foreign	_____

a. 如果您们有国外和所者，您们的关系是哪一年建立的？If you have a foreign partner (JV), in which year was the relationship established?

b. 您们的国外和所者是哪个国家的？What is the nationality of your principal foreign partner?

SECTION B: PROCESSES

1. 您们有多少生产线？How many production lines (working in parallel) do you have?

2. 您们采用商品化的生产线吗？Are you adopting commercial (turnkey) production lines?

是 ☐ 否 ☐

a. 如果是，请您指明生产国？If yes, could you please specify the nationality of the supplier(s)?

3. 现在什么是您们生产线的输入和输出？您们开始您们的业务时，它们是什么？What are the input and the output of your production line(s) and what were they when you started your business?

现在

	Description	*输入*	*输出*
	E.g. 2" Wafer production; cell processing	*E.g. Wafers, metals for contacts, reagents, etc.*	*E.g. devices, i.e. cells*
第一个生产线 Line 1			
第二个生产线			
第三个生产线			

开始时

	Description	*Input*	*Output*
第一个生产线			
第二个生产线			

第三个生产线

主要的生产线

4. 您们主要生产线的分布/排布是怎样的？What is the layout of your main production line? *(Please tick all the machinery and equipment you have in your main production line now as well as when you started this business)*

FOR WAFER PRODUCERS ONLY

Equipment list	*Today*	*At start*
Crucible Spray System, Kiln	☐	☐
Wet Station	☐	☐
Furnace	☐	☐
Band Saw or Wire Saw	☐	☐
Wire Saw	☐	☐
Wet Station	☐	☐
Resistivity Probe	☐	☐
Other *(please specify)*		

FOR CELL PRODUCERS ONLY

Equipment list	*Today*	*At start*
Resistivity Probe	☐	☐
Etch Station	☐	☐
Dopant Sprayer & Belt Furnace	☐	☐
Plasma Etch Station	☐	☐
HF Etch Station	☐	☐
PECVD Furnace	☐	☐
Screen Printers, IR Dryers/Furnace	☐	☐
Cell Tester	☐	☐
Other *(please specify)*		

FOR MODULE PRODUCERS ONLY

Equipment list	*Today*	*At start*

Glass Wash Station	☐	☐
Cell Tester	☐	☐
Tabber/Stringer	☐	☐
Bussing Station	☐	☐
Layup Station	☐	☐
Laminator	☐	☐
Final Assembly Station	☐	☐
Module Tester	☐	☐
Other *(please specify)*		

5. 谁安装的主要生产线和管理初级的运行状态？Who installed the main production line and supervised the start-up phase? *(please tick one)*

The supplier	☐
Your company with the help of the supplier	☐
Your company alone	☐
Others *(please specify)*	☐

6. 您（或者您们公司的其他人）曾经参加过这个生产线的技术和/或操作培训课程吗？Have you (or somebody in your company) ever taken a technical and/or operational training course to operate the production line?

7 谁正在管理在生产线上的设备的常规的和大的维护？Who is taking care of the ordinary and the extraordinary maintenance of the equipment in the production line? *(please tick one)*

The supplier	☐
Your company with the help of the supplier	☐
Your company alone	☐
Other *(please specify)*	☐

9 您对您的生产线的安装方法做过任何修改吗？如果是，请介绍一下。Have you introduced any modification in the way your production line is installed? If yes please elaborate

是 □ 否 □

10 您对您生产线上的标准设备做过小的改动/变吗？(比如自己加工一些小配件).如果是，请您介绍一下。Have you introduced any minor modification in your main production line's standard equipment? (E.g. home made spare parts or small components). If yes, please elaborate

是 □ 否 □

11 您曾经设计和/或制造您的生产线上的整个新的机器或设备？Have you ever designed and/or manufactured entirely new machines or equipment to be used in your production line?

是 □ 否 □

a) 如果是，请指出其机器或设备 If yes, please specify which equipment

b) 如果是，您是一开始就制造您自己的设备还是您首先借鉴标准生产线后再对它做些修改？ If yes, did you manufacture your own machine right at the beginning or did you first adopted the standard production line and modify it later on?

At the beginning ☐ Later on ☐

c) 您是自己设计和制造这些设备还是在其他人的帮助下制造的? Did you design and manufacture these machines alone or did you get technical assistance from someone outside your business?

自己 ☐ 其他人的帮助 ☐

d) 如果有其他人的帮助，请介绍一下 If you used technical assistance, please specify

e) 您自己制造的机器符合环境和安全标准吗？ Do the machines that you manufactured yourself respect environmental and safety standards?

是 ☐ 否 ☐

12 这一些改变 (如果有) 是受益于其他方面的技术/知识 (比如光电技术, 等) Have the changes (if any) that you introduced in the installation of the production line and the new home-made machines you constructed benefited from know-how coming from other sectors (i.e. optoelectronics, etc)

是 ☐ 否 ☐

13 您有一个实验室 (或测试间) 来发展基于新材料(比如有机材料)的新产品吗? Do you have a lab (or a small pilot line) devoted to the development of new products based on advanced materials (i.e.: organic materials)?

是 ☐ 否 ☐

14 如果是，请您介绍实验室是则怎样组织和谁在里面工作? If this is the case, could you briefly explain how the lab is organised and who is working in it?

SECTION C: 产品

1. 现在您的产品是什么？开始时， 您的产品是什么？(清在下面的栏目上打勾) What are your products? What were they when you started your business? (please tick all that apply)

Description	*Today*	*At start*
Monocrystalline Si solar cells / modules	☐	☐
Polycrystalline Si solar cells / modules	☐	☐
Polycrystalline transparent Si solar cells / modules	☐	☐
EFG cells	☐	☐
Polycrystalline ribbon Si solar cells	☐	☐
Apex (polycrystaline Si) solar cells	☐	☐
Monocrystaline dendritic web Si solar cells	☐	☐
Amorphous silicon / modules	☐	☐
Cadmium Telluride (CdTe) / modules	☐	☐
Copper-Indium-Diselenide (CIS) / modules	☐	☐
Hybrid silicon (HIT) solar cell / modules	☐	☐
Other *(please specify)*		

2. 您能介绍一下您们现在的年产量是多少？开始时，您们的年产量是多少? Could you please specify how many products you produce now annually and how many did you produce when you started your business?

Description	*Quantity/year today*	*Quantity/year at start*
Monocrystalline Si solar cells / modules	_____	_____
Polycrystalline Si solar cells / modules	_____	_____

Polycrystalline transparent Si solar cells / modules	_____	_____
EFG cells	_____	_____
Polycrystalline ribbon Si solar cells	_____	_____
Apex (polycrystaline Si) solar cells	_____	_____
Monocrystaline dendritic web Si solar cells	_____	_____
Amorphous silicon / modules	_____	_____
Cadmium Telluride (CdTe) / modules	_____	_____
Copper-Indium-Diselenide (CIS) / modules	_____	_____
Hybrid silicon (HIT) solar cell / modules	_____	_____
Other *(please specify)*		

3. 什么是您们产品的主要指标 (清在下面适合处打勾)? What are the main specs of your products (please fill in if appropriate)?

	Product1_____		Product2_____	
	Today	At start	Today	At start
Min efficiency	_____	_____	_____	_____
Max efficiency	_____	_____	_____	_____
Min power out	_____	_____	_____	_____
Max power out	_____	_____	_____	_____
Min size	_____	_____	_____	_____
Max size	_____	_____	_____	_____
Min Operating Temperature	_____	_____	_____	_____
Max Operating Temperature	_____	_____	_____	_____
Lifetime	_____	_____	_____	_____
Guarantee	_____	_____	_____	_____

4. 您们的生产效 lü 是多少? (= 100% - 废料输入 – 不合格输出)? 刚开始时,生产效 lü 是多少? What is the average yield of your process (= 100% - wasted input – output not meeting specs) and what was it when you started your business?

	Today	*At start*
Average yield		

5. 您们产品的总的生产成本是多少？刚开始时， 是多少？What is the overall manufacturing cost of your product? What was it when you started your business? *(please fill in only where appropriate to your product. Please specify the year in which you started your business)*

Product	*Cost*	*Today*	*At start (year_____)*
Material	RMB/cm^2 of wafer or RMB/kg of ingot		
Cells	RMB/Wp		
Modules	RMB/Wp		

6. 现在您们的劳力成本占总成本的比例是多少？刚开始时，是多少呢？What fraction of the overall cost is due to labour now and what was it when you started?

Product	*Today*	*At start*
Labour cost (as % of overall manufacturing cost)		

7. 请告诉我们被其他标准认证的产品。Please tell us about the products that have been certified by different standard setting bodies

	Description	*Certification*	*Country/Area*
Product 1			
Product 2			
Product 3			

8. 您们产品的最终用途是什么？What is the final application of your products (direct or indirect)? *(Please tick all that apply)*

Grid connected residential systems	☐
Solar villages	☐
Office buildings	☐
Pumps	☐
Solar power stations	☐

Lighting equipment	☐
Traffic signs	☐
Radio relay stations	☐
Telecommunication systems	☐
Off-grid villages	☐
Others *(please specify)*	☐

9. 您们能根据客户的要求对产品做小的修改吗？(比如，您能提供适合潮湿环境下的模型吗，或极端温度下的模型？Can you make minor modifications to your products to address specific requests from customers? (*For example: can you provide modules for very humid weather conditions? Or for very extreme temperatures?)*

是 ☐ 否 ☐

a. 如果是，请您介绍一下。 If yes, please specify

b. 如果时，什么时候您们开始根据客户的要求来做产品的呢？If yes, when did you start to customise your products?

10. 您们正在生产或打算生产全新的产品吗？(比如，多功能的产品) 如果是，请您介一下。Are you producing or thinking to produce completely new products (For example: products that can have more than one function?). If yes please specify

是 ☐ 否 ☐

11. 您们打算用新材料(如有机材料)制造产品吗？Are you thinking to engage in products using new materials (i.e. Organics materials)?

是 ☐ 否 ☐

12. 您们要给您们的产品付专利费吗？Are you paying royalties to manufacture some of your products?

是 ☐ 否 ☐

SECTION D: 研发 R&D

1 您们公司自己做一些研究和发明工作吗？Does your company engage in in-house R&D activities?

是 ☐ 否 ☐

2 在总收入里，有多少比例用于您们自己的研发工作？How much do you spend in in-house R&D activities in terms of percentage on your total turnover?

3. 有多少人员工作在研发岗位？How many people are involved in R&D activities?

4. 您们研发工作的特性是什么？What is the nature of your R&D activity? *(please tick all that apply)*

Modifying existing products/design to suit different markets or/and satisfy specific customer's requests	☐
Modifying existing production processes	☐
Designing new products	☐
Developing new products	☐
Designing new production processes	☐
Developing new production processes	☐
Others *(please specify)*	

5. 您们有任何知识产权吗？(如，专利，工业设计和商标？) Do you have any protected intellectual properties (i.e.: patents, industrial designs and trade marks)?

是 ☐ 否 ☐

6. 您们有知识产权的证书吗？Are you licensing any of your protected intellectual properties?

是 ☐ 否 ☐

7. 如果您们没有开展研发工作，那是什么原因？If you do NOT undertake any R&D activity, why is it the case? *(please tick all that apply)*

Nature of products does not require local R&D	☐
Shortage of skilled technical personnel	☐
Shortage of engineers with relevant expertise	☐
Shortage of financial resources	☐
Firm was established only recently and R&D activities are not yet underway	☐
Others *(please specify)*	

SECTION E: MANPOWER SKILLS

1. 您们有多少工作人员？开始时，有多少？How many employees do you have? How many did you have when you started?

	Today	*At start*

Number of employees

2. 开始时，您雇用了多少下列人员？现在呢？When you started this business, which of the following categories of people did you employ? And which do you employ at present?

	As % of employees	
	Now	*At start*
No. of technicians		
No. of engineers, scientists or university-trained designers		
No. of economists or university trained business administrators		
Other *(please specify)*		

3. 您雇用的人员接受了下列那些培训？Have any of your employees received training from one of the following entities? *(please tick all that apply)*

National government	☐
Local government	☐
International donor agencies (i.e.: UNDP, GEF, ADB, etc.)	☐
Bilateral organisations (i.e. GTZ, etc)	☐
Private company (i.e. your supplier)	☐
Other *(please specify)*	

4. 您雇用过由外企工作经验的人员吗？Have you ever employed people with working experience in a foreign company?

是 ☐ 否 ☐

SECTION F: EXPORT AND PRICES

1. 从销售来说，您们产品的主要卖方在哪里？开始时，又在哪里？ 请在下列情况给出比例。Measured by sales, where are the buyers of the products in your main business line located? Where were they located when you started? *Please give the % between the following locations*

	Today	*At start*
在您们工厂所在地区 Within the same district as your plant		
不在您们工厂所在地区，但在同一城市 Outside the same district as your plant but within the same city		
其它中国城市 Within your country but outside the city where your plant is located		
海外 Overseas		

2. 如果您们销售到海外，具体国家是: If you sell products overseas, where do you export them to?

3. 您们批量销售价格是多少？What is your best (large volume) wholesale price of your products?

	Best wholesale price
Product 1	
Product 2	
Product 3	
Product 4	

4. 您们的产品从 2000 年后有改动吗？如果有，是多少？Has the price you can charge for your most important product changed since 2000? If it has, by how much? *(please tick one box for each market)*

Market	*Price has increased*		*Price unchanged*	*Price has decreased*	
	< 10%	> 10%		< 10%	> 10%
中国市场 Chinese market	☐	☐	☐	☐	☐
其他市场 Other markets	☐	☐	☐	☐	☐

5. 什么因素促使 2000 年后的价格的改变？What has caused the change (if any) to prices since 2000? *(please elaborate)*

SECTION G: COMPETITION

1. 在 2004 年，您们公司国内市场的比利是多少？ In 2004, what percentage of the total sales in the domestic market is supplied by your firm?

2. 在中国或其他国家的竞争对手对您们影响大吗？刚开始呢？ Is the rivalry with competitors located within China or in other countries significant today? Was this rivalry significant when you started your business? *(Please say YES or NO for each point in time)*

	Significant today	*Significant when you started*
Competitors within China		
Competitors from Japan		
Competitors from India		
Competitors form other countries in Asia		
Competitors from Germany		
Competitors from other EU countries		
Competitors from North America		
Competitors form other countries		

3 竞争对手在下列那方面影响您们的产品和服务？ How do your most significant rivals compete against your most important product or service today? *(Please tick one box for each of the options provided)*

	Very significant	*Significant*	*Significant to some extent*	*Not significant*
Lower prices	☐	☐	☐	☐
Higher quality	☐	☐	☐	☐
Faster delivery	☐	☐	☐	☐
On-time delivery	☐	☐	☐	☐
Innovative design	☐	☐	☐	☐
Product variety	☐	☐	☐	☐

Flexible production volume	☐	☐	☐	☐
Bringing out new products	☐	☐	☐	☐
Customisation	☐	☐	☐	☐
Services linked with products	☐	☐	☐	☐
Respected brand-name	☐	☐	☐	☐
Product/service warranty	☐	☐	☐	☐
Promotion of social/labour/environmental standards	☐	☐	☐	☐
Sells direct to end-users	☐	☐	☐	☐
Other *(please specify)*				

4 要成立一家能生产和销售的公司，要花多少钱？How much money would a new firm have to spend in order to build a production plant and set up a marketing and distribution operation which competes with your own?

SECTION H: INPUTS TO TECHNOLOGICAL DEVELOPMENT

Relations with customers

1. 谁销售您们的产品？开始时呢？Who do you sell your products to? Who did you sell them when you started?

	Today	*At start*
Distributors/agents/importers/exporters		
Directly to end-users		
Retailers		
Others *(please specify)*		

2. 您们主要的服务对象是谁？Which customer segment do you mainly serve?

On grid (please specify if it is: utility, corporations, government, residential)	☐
Off grid (please specify if it is: industrial, residential, government, Bilateral aid funded)	☐

3. 下列那些因素影响您们的客户？How important are the following factors to your most important customers (based on share of turnover).

	Critical (will win an order)	*Very important*	*Important to some extent*	*Not important*
lowest price	☐	☐	☐	☐
High quality	☐	☐	☐	☐
fast delivery	☐	☐	☐	☐
On-time delivery	☐	☐	☐	☐
Innovative designs	☐	☐	☐	☐
Product variety/range of products	☐	☐	☐	☐
Flexible production volume	☐	☐	☐	☐
Bringing out new products	☐	☐	☐	☐
Customisation	☐	☐	☐	☐
Services linked with products	☐	☐	☐	☐
Associated with a brand name	☐	☐	☐	☐
Product/service warranty	☐	☐	☐	☐
Meeting social/labour/environmental standards	☐	☐	☐	☐
Sell directly to end-users	☐	☐	☐	☐

Relations with suppliers

1 原材料从那里购买？刚开始呢？From whom do you buy your raw materials from? From whom did buy when you started?

	Today	*At start*

2 从销售来说，您们的供货商在哪里？刚开始呢？Measured by sales, where are yours plant suppliers located? Where were they located when you started? *Please give the % between the following locations*

	Today	*At start*
Within the same district as your plant		
Outside the same district as your plant but within the same city		
Within your country but outside the city where your plant is located		
Overseas		

Relations with Universities and research institutes

1. 您们的研发计划与大学合作吗？Do you have collaborative R&D projects together with universities

是 ☐ 否 ☐

a) 如果是，请您介绍一下。If yes, could you please elaborate?

SECTION J: GOVERNMENT SUPPORT FOR INNOVATION AND RENEWABLES

1. 您们公司在 1998-2004 期间有其他方面的资金来支持您们的创新工作吗？Did your company receive any public support (financial or other assistance and advice) for innovation-related activities in the period 1998-2004? *(Note: financial includes: loans, grants, subsidies, funds).*

是 ☐ 否 ☐

2. 其经费来源于下列那方面？What were the sources of this public support for innovation-related activities? *(please tick all that apply)*

	Financial support	*Other types of support*
Local or regional government	☐	☐
Central government	☐	☐
Other (*please specify. Examples: International organisations such as UNDP, GEF, ADB, etc. or bilateral programmes*)	☐	☐

3. 在 1998-2004 其月间，您们公司因为创新工作有没有税收上的优惠？Did your company receive any tax incentives related to innovation activities during the period 1998-2004?

是 ☐ 否 ☐

4. 您们工司参于或接受下列可再生能源计划？Did your company participated in or received assistance from any of the following types of renewable energy-related programmes? *(please tick all that apply)*

Brightness rural electrification program	☐
National Rural Electrification Programme (Song Dian Dao Xiang = 'Sending electricity to townships')	☐
REDP (World Bank/GEF renewable energy development project)	☐
Other *(please specify)*	

SECTION K: OBSTACLE AND VIEW FOR THE FUTURE

1 在过去 12 个月里，什么是您们产品市场增长的最大阻力？What has been the largest impediment to growth in your main market region (the one which contributes to your turnover most, see question 1 in section F) over the past 12 months?

2 什么是您们客户群增长/降低的关键因素？What has been the critical factor that has driven the growth/decline of your principal customer segment (i.e. on grid, off-grid) over the past 12 months?

3 请玄五个重要的因素，这些因素限制您们工厂在国内和国际社市场的增长。Please choose 5 most important factors that potentially constrain your plant's ability to grow in the domestic and international market *(Please rank up to 5 factors, with "1" as the most important and "5" as fifth important)*

Getting enough wafers for cells/modules production	☐
Cost or quality of electricity	☐
High labour cost of skilled personnel, including technicians	☐
Quality of available skilled personnel, including technicians	☐
National government's regulations on licensing, certification and qualification	☐
Local government's regulations on licensing, certification and qualification	☐
International quality standards	☐
National government's taxes	☐
Local or non-national government taxes	☐
Difficulties in establishing distribution outlets	☐
Lack of after-sales service providers	☐
Financial constraints when expanding the production capacity	☐
Others *(please specify)*	

4 您期望在下面 12 个月里，您们产品市场增长/降低比利是多少？What rate of growth/decline (in electricity output terms) do you expect in your market region over the next 12 months?

5 在下面 12 个月里，您期望哪一个客户群增长最快？Which customer segment do you expect to grow faster in your market region in the next 12 months?

SUPPLEMENTARY QUESTIONS

NOTE: the two following sections contain information that will be interesting to retrieve but that are not vital to achieve the research objectives

SECTION J: ENTREPRENEURIAL HISTORY

1. In which year did you start working in the PV industry (not necessarily in this company)?

2. How many years have you held this position?

3. Before working in this company, what did you do?

work in another Chinese company producing the same products and having the same core business	☐
work in a foreign company producing the same products and having the same core business	☐
Work in a university or science laboratory investigating related issues	☐
Work in the semiconductor/optoelectronics industry	☐
Work in a completely different business	☐

4. What is the highest level of education you completed?

Postgraduate education at home (MSc and/or PhD)	☐
Postgraduate education abroad	☐
Undergraduate education at home	☐
Undergraduate education abroad	☐
High-school education	☐
Secondary education	☐
Primary school education	☐
No education	☐

5. If you completed part of your education abroad, in which country?

SECTION K: LOCATION

1. Is your plant located in an industrial park/export processing zone?

   Yes ☐ No ☐

2. Please list in order of importance (1 to 5) up to 5 factors that:
   a) positively influenced the choice of your plant's location when it was first established
   b) would be an advantage for locating a new plant in this location today

	Today	*At start*
Local market size		
Proximity to other firms in the same line of business		
Low rents or costs of buying property		
Proximity to local universities and research institutes		
Quality of local transport infrastructure		
Quality of local telecoms infrastructure		
Supply of skilled labour		
Supply of unskilled workers		
Availability of government services		
Possibility of expanding new products		
Quality of locally provided financial services		
Proximity to suppliers		
Proximity to clients		
Proximity to distribution channels		
Quality of local housing, schools, and social networks		
Levels of local pollution and other environmental problems		
Fewer regulatory requirements and taxes based on government's assignments		
Other (please specify)		

Appendix 2 List of firms interviewed during the survey

Firm's name	*Location*	*Person(s) interviewed*
CSI Solar Technologies Inc.	Suzhou	Mr. Brian Lu, General Manager
Hope Industry and Trade Co., Ltd.	Beijing	Mr. Wang Haibo, Production Manager Mr. Yan Jinggang, General Manager
Ningbo Solar Electric Power Co., Ltd	Ningbo	Mr Zhou Jianhong, President
Suntech Power Co., Ltd.	Wuxi	Dr Shi Zhengrong, CEO Dr Ji Jingjia, Senior Scientist, R&D Centre
Tianwei Yingli New Energy Resources Co. Ltd.	Baoding	Mrs Ma Yan, Project Manager of Overseas Business Department
Topsolar Green Energy Co., Ltd	Shanghai	Mr Sun Tietun, Vice Chief Engineer
Zhejiang Sino-Italian hotovoltaic Co. Ltd.	Ningbo	Mr Tangjun, General Manager
Zhonglian Solar Technology Co., Ltd.	Beijing	Dr. An Zhonglin, Director

Appendix 3 Contact list created before undertaking fieldwork

Category	Area of competence	Name of institution contacted
Academic	Innovation and management (also with special reference to PV)	Beijing University (Beijing)
		Research Centre for Innovation and Development, Zhejiang University (Hangzhou)
		Tsinghua University (Beijing)
	Solar energy technology, industry and economics	Xi'an Jiaotong University (Xi'an)
		Beijing Solar Energy Research Institute (Beijing)
		Solar Energy Institute of Shanghai Jiaotong University (Shanghai)
		Department of Physics, Zhejiang University (Hangzhou)
		China National PV Technology Development Centre (Hangzhou)
	Air pollution and urban environment	SAES – Shanghai Academy of Environmental Science (Shanghai)
Industry[1]*/Market*	PV industry, PV systems, market and applications	Beijing Jikedian Renewable Energy Development Centre
		Beijing Jike Energy New Tech. Development Co.
		Bejing Corona Science & Technology Co. Ltd
		Institute of Electrical Engineering, Chinese Academy of Sciences
International Cooperation and NGO	Capability building and bilateral commercial opportunities	REDP - Renewable Energy Development Program, GEF/WB/China National Development and Reform Commission
		CCRE - Capacity Building for the Rapid Commercialisation of Renewable Energy in China, UNDP/GEF/ China National Development and Reform Commission
		GTZ – German Development Cooperation (Beijing)
		Sino-Italian Cooperation Program for Environmental Protection
		IT Power (UK based but with offices in Beijing)
	PV market development	WWF China
Policy/business	Bridge between regulatory authorities, research institutes and industry	CREIA (China RE Industry Association)

[1] The 8 firms who took part in the survey are not included in this contact list.

	professionals	
	Technological and policy support to the government's RE initiatives	CRED (Centre for RE Development, subordinated to the Energy Research Institution of the State Development Planning Commission)

Appendix 4 Questions for the semi-structured interviews

National R&D trends

- How many research institutes/universities conduct research on PV in China?
- What is their main research focus? Mainly conventional c-Si technology or also other PV technology families like thin film, high efficiency cells under concentration, organic PV?
- Who are the main national bodies in charge of financing R&D for PV?
- A part from the government, are there other sources of funding for PV R&D (i.e.: VC, international/bilateral organisations, etc.)?

Market creation and prospects

- What do you think are the main market barriers to PV development and utilisation in China?
- What do you reckon will be the drivers for future PV development in China?
- Are there specific mid-long term targets set by the Chinese government for PV installed capacity?
- What are the prospects for future PV market applications in China: off-grid vs on-grid?

Innovation drivers (Role of policy vs market and technology)

- What is the role of government policy in creating incentives for innovation? In what way does policy drive innovation (Research direction? Timing? Collaboration?).
- What are the main organisations involved in promoting policies for PV in China (both at the national and local levels)?
- Are there on the pipeline specific programmes to promote PV?
- Which is the role (if any) of local governments, including provincial, municipal, and county governments, in developing PV (both as far as the installed capacity and PV industry development are concerned).

- What do you think will be the impact of the new China's RET law in stimulating PV?
- Does a long term policy framework influence innovation?
- What is the role of market forces in influencing innovation?