Development and Diffusion of Building-Integrated Photovoltaics: Analysing Innovation Dynamics in Multi-Sectoral Technologies

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Doctor of Philosophy

The University of Edinburgh

2015

Abstract

The ongoing transformation of the energy system along a more sustainable trajectory requires advancements in a range of technological fields, as well as active involvement of different societal groups. Integration of photovoltaic (PV) systems in the built environment in particular is expected to play a crucial long-term role in the deployment of renewable energy technologies in urban areas, demanding the successful cooperation of planners, architects, engineers, scientists and users. The realisation of that technological change will require innovation at both an individual (within firms and organisations) and a collective (sector) level, giving rise to systemic approaches for its characterisation and analysis of its drivers.

This study investigates the processes that either accelerate or hinder the development and diffusion of Building-Integrated PV (BIPV) applications into the market. Affected by developments in both the renewable energy and construction industries, the BIPV innovation system is a multi-sectoral case that has been explored only partially up to now. Acknowledging the fact that drivers of innovation span the globalised BIPV supply chain, this research adopts both an international and a national spatial perspective focusing on the UK.

The analysis is based on a novel analytical framework which was developed in order to capture innovation dynamics at different levels, including technological advancements within firms, competition and synergy with other emerging and established innovation systems and pressures from the wider socio-economic configuration. This hybrid functional framework was conceived by combining elements from three academic strands: Technological Innovation Systems, the Multi-Level Perspective and Business Studies.

The empirical research is based on various methods, including desktop research, semi-structured interviews and in-depth firm-level case studies. A thorough market assessment provides the techno-economic background for the research. The hybrid framework is used as a guide throughout the empirical investigation and is also implemented in the analytical part of the study to organise and interpret the findings, in order to assess the overall functionality of the innovation system.

The analysis has underlined a range of processes that affect the development and diffusion of BIPV applications including inherent technological characteristics, societal factors and wider transitions within the energy and construction sectors. Future approaches for the assessment and governance of BIPV innovation will need to address its hybrid character and disruptiveness with regards to incumbent configurations, in order to appreciate its significance over the short and long term.

Methodological and conceptual findings show that the combination of insights from different analytical perspectives offers a broader understanding of the processes affecting innovation dynamics in emerging technologies. Different approaches can be used in tandem to overcome methodological weaknesses, provide different analytical perspectives and assess the performance of complex innovation systems, which may span multiple countries and sectors. By better reflecting complexities, tensions and synergies, the framework developed here offers a promising way forward for the analysis of emerging sustainable technologies.

Lay Summary

Increasing environmental awareness and concerns over long-term availability of fossil fuels have driven the demand for power generation systems that utilise renewable resources. A similar trend in the construction sector has increased the requirement for buildings with low energy consumption, either by increasing the efficiency of materials and devices, or by installing electricity and heat production systems.

Building-Integrated Photovoltaic (BIPV) systems are building materials that convert sunlight into electricity. As such, they have the potential to contribute to the sustainable development of both power and construction industries. However, this potential can only be realised if a wide range of BIPV applications with different characteristics can be manufactured at a cost that can encourage large-scale market deployment. This will require innovation at multiple stages and from different actors along the production chain.

This study investigates the technical, economic and social characteristics of the BIPV sector in order to identify processes that affect the development of such innovation. Multiple sources of evidence were used including academic and industrial literature reviews, interviews with different stakeholders and in-depth firm-level analyses. All data were synthesised and analysed using a novel methodology developed for this research. This method brings together elements from different literatures within social and business studies for the assessment of the BIPV sector at multiple levels and using different points of view.

The analysis of the BIPV sector highlights its particularities with regards to the development and market diffusion of new technologies and applications. Further growth will require more active involvement of actors from the construction sector in the early stages of product design and manufacturing, so that these can better reflect their needs. Additionally, regulations and policy will have to become more specific in order to address the characteristics of BIPV applications that make them different from traditional building materials and other renewable energy systems.

The study also reveals the advantages of integrating different analytical approaches for the assessment of innovation dynamics in complex technological sectors. The combined use of complementary elements may help overcome respective weaknesses of the methods, and can offer a deeper understanding of the processes affecting these dynamics.

Acknowledgements

Firstly, I would like to thank Dr. Mark Winskel and Dr. Chiara Candelise for their constant guidance and immense support at a professional and personal level. I owe them much more than this Ph.D. Many thanks also to Professor Gareth Harrison for his helpful advice and comments throughout this long process, and to Dr. Raphael Slade for his trust and support.

I would like to acknowledge the support from SUPERGEN PV21 consortium for funding this PhD research, and all its members for the valuable discussions. I am indebted to all those who I had the chance to talk to at the various events and meetings around Europe. I would also like to thank all the interviewees who provided a large part of the empirical data used in this thesis, and especially Hamish Watson, Steve Pester and Paul Gribben.

A special acknowledgement goes to my family Roula, Socrates and Elpida for giving me all the encouragement and inspiration I needed, and my friends back in Greece Christos, Nikos, Thymios, Agelos, Vasilis and Yanis for the emotional support.

I would like to thank my friends and colleagues at the Institute for Energy Systems for the help and all the memorable moments, especially Adam, Barry, Anup, Camilla, Nacho, Randy, George, Tom, Jorge, Dan, Masum and Punim. Also my new colleagues at the Imperial College London Becky, Jamie, Mat, Aidan, Phil, Paul, Bryony and Iris for their support throughout a very difficult time in this long process. Finally, my friends Kostas, George, Iro, Georgia, Catherine, Alexandros, Andrew and Maria who made my time in Edinburgh so enjoyable.

Most importantly, I would like to thank my wonderful wife Nena for keeping me sane throughout this process, and of course the beautiful Lydia-Chara for providing the motivation. This PhD is dedicated to them.

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

Evangelos Gazis

Contents

Appendices

Figures and Tables

Figures

Tables

Acronyms and abbreviations

AC	Alternating Current
a-Si	Amorphous Silicon
BAPV	Building Applied PV
BIPV	Building Integrated Photovoltaics
BOC	British Oxygen Company
BoS	Balance of System
BPVA	British Photovoltaic Association
BRE	Building Research Establishment
BS	Business Studies
CAGR	Compound Annual Growth Rate
CCGT	Combined Cycle Gas Turbine
CCTV	Closed-Circuit Television
CdTe	Cadmium-Telluride
CEO	Chief Executive Officer
CfD	Contracts for Difference
CIGS	Copper-Indium-Gallium-Selenide
CPD	Continuing Professional Development
CPI	Centre for Process Innovation
CPV	Concentrator Photovoltaics
CSG	Crystalline Silicon on Glass
c-Si	Crystalline Silicon
CZTS	Kesterite family of solar cells
DC	Direct Current
DECC	Department of Energy & Climate Change (UK)
DoE	Department of Energy (USA)
DSSC	Dye-Sensitised Solar Cells
EIPV	Electronics Integrated Photovoltaics
EPBD	Energy Performance of Buildings Directive

EPC	Engineering, Procurement and Construction
EPIA	European Photovoltaic Industry Association
EU	European Union
EV	Electric Vehicles
FBI	Federal Bureau of Investigation
FIT	Feed-in Tariff
FP	Framework Programme for Research and Technological Development
IC	Integrated Circuit
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IES	Institute for Energy Systems
IPO	Initial Public Offering
ISES	International Solar Energy Society
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCBP	Low Carbon Building Programme
LCOE	Levelised Cost of Energy
Li-ion	Lithium ion
LR	Learning Rate
LTS	Large Technical Systems
MCS	Microgeneration Certification Scheme
MJC	Multi-Junction Cell
MLP	Multi-Level Perspective
monoc-Si	Monocrystalline Silicon
MPP	Maximum Power Point
NPEC	National Centre for Printable Electronics
NIS	National Innovation System
NIC	National Innovation Capacity
NPV	Net Present Value
OECD	Organization for Economic Cooperation and Development
OEM	Original Equipment Manufacturer

OLED	Organic Light-Emitting Diode
OPV	Organic Photovoltaics
PETEC	Printable Electronics Technology Centre
PHEV	Plug-in Hybrid Electric Vehicle
polyc-Si	Polycrystalline Silicon
PR	Performance Ratio
PrR	Progress Ratio
PV	Photovoltaic
PVSEC	Photovoltaic Solar Energy Conference and Exhibition
R&D	Research and Development
RD&D	Research, Development and Demonstration
RHI	Renewable Heat Incentive
RIS	Regional Innovation Systems
ROC	Renewable Obligation Certificates
ROI	Return On Investment
RPS	Renewable Portfolio Standards
RTI	Research, Technology and Innovation
SCOR	Supply-chain operations reference-model
SCOT	Social Construction of Technology
SISER	Scottish Institute for Solar Energy Research
SME	Small and Medium Enterprises
SNM	Strategic Niche Management
SSI	Sectoral Systems of Innovation
ST-system	Socio-Technical System
STA	Solar Trade Association
STC	Standard Test Conditions
TC	Technological Capability
TEF	Triple Embeddedness Framework
TF	Thin-Film
TF-Si	Thin-Film Silicon

TIS	Technological Innovation Systems
TM	Transition Management
TRL	Technology Readiness Levels
TSB	Technology Strategy Board
UNFCCC	United Nations Framework Convention on Climate Change
UK	United Kingdom
UKERC	UK Energy Research Centre
USA	United States of America
UV	Ultra Violet

Nomenclature

Symbol	**Meaning**	**Units**
η	Conversion Efficiency	%
A	Area	m^2
EPBT	Energy Pay-Back Period	years
GWP	Global Warming Potential	g CO_2-eq/kWh
In	Insolation	$\mathrm{Wh/m}^2$
Ir	Irradiance	$\mathrm{W/m}^2$
Ir_i	In-plane Irradiance	W
P_p	Peak Power, Installed Capacity	Wp
Y	Energy Yield	Wh
Y_r	Reference Energy Yield	Wh

Chapter 1

Introduction

Energy systems around the world are experiencing a reconfiguration along a more sustainable path. This ongoing transition involves the deployment of a diverse set of renewable energy systems, with different technical features and implications to the wider society and economy. It is widely recognised that *innovation* will play a crucial role in the further development and market diffusion of these renewable energy technologies [Toman (1998); Menanteau *et al.* (2003); Tsoutsos and Stamboulis (2005)].

The construction sector on the other hand is experiencing a similar, though longer-term transformation, which will require the wide application of sustainable materials, as well as the adoption of new practices from both building developers and users. The integration of renewable energy systems in urban infrastructure is also considered to be a crucial component of a strategy for the de-carbonisation of the construction sector [EU (2010); EC (2013)].

Building-Integrated Photovoltaics (BIPV) are multifunctional building components that also generate renewable solar power. As such, BIPV technologies have the potential to play a role in sustainable transitions within the energy and construction sectors, both in the short and the long term [PVPS (2012); DECC (2014a)].

1.1 Research Motivation and Aim

Despite the increasing recognition of the role that renewable energy technologies will play in a sustainable energy future, and the importance of innovation in their further development and market diffusion, there is still limited understanding of how innovation occurs and can be stimulated through policy [Jacobsson and Johnson (2000); Menanteau *et al.* (2003); Jacobsson *et al.* (2004); Foxon *et al.* (2005); Hekkert *et al.* (2007a)].

BIPV is a segment of the renewable energy sector that is able to facilitate multiple sustainable transitions, particularly in urban environments. Despite this recognised potential, the BIPV sector has received limited attention in terms of innovation assessment and incorporation into policy design. A review of the literature has revealed a range of technical papers underlining the potential of the technology [inter alia Bazilian *et al.* (2001); Plastow (2006); Henemann (2008); Marsh (2008); Pagliaro *et al.* (2010)], though only one Masters project in Chalmers University of Technology was found which focuses on the assessment of its innovation dynamics [Crassard and Rode (2007)]. This thesis, and the related conference papers (e.g. see Appendix B) therefore aim to address a rather unexplored case in innovation studies.

This research is an empirical investigation of BIPV innovation dynamics, addressing not only their inherent techno-economic characteristics but also wider social, technical and economic developments. The BIPV sector was chosen as the object of analysis for this research not only because of its high deployment potential, since it is one of the few renewable energy systems that can be integrated in the built environment, but also because its cross-sectoral nature renders it interesting from an analytical point of view.

The evolution of the BIPV sector is affected by tensions within both the energy and construction industries. Additionally, the development and deployment of BIPV applications in the market requires the interaction of a diverse group of stakeholders with different backgrounds and priorities, including material scientists, manufacturers, architects and engineers.

This research is structured on a *two-level spatial perspective*. Most technological developments and manufacturing issues follow global dynamics, while the BIPV sector draws heavily on the international PV industry, especially upstream the supply chain (i.e. research, development, equipment and materials manufacturing).

On the other hand, downstream components of the supply chain (system development, market deployment and diffusion) and a range of economic, societal and political factors depend significantly on regulations and established practices at the national level, and therefore local characteristics could not be ignored. This study focuses on the UK because it offers an interesting analytical case. In spite of the relatively long association of the UK with the BIPV sector, market diffusion has been significantly slower in comparison to other national energy systems. From a methodological point of view, the choice of the UK as the focal country offers easier access to empirical evidence.

The motivation for this research is not related to the study of the BIPV innovation system alone. Early on during the review of the literature on existing approaches for the study of technological change, a methodological weakness was identified with regards to concepts that assess innovation dynamics at both the intra-firm level and within the broader socio-technical system. Additionally, these concepts offer limited insights when implemented for the analysis of innovation systems that span multiple sectors.

Although these shortcomings have been outlined in the literature, and the potential for an integrated approach has been discussed, the innovation literature is still missing an operational framework for the investigation of emerging, hybrid innovation systems. Therefore, a further aspiration was the development of a novel cross-disciplinary framework that could be applied for the evaluation of the BIPV innovation system and potentially other similar cases.

Therefore, the main aims of the study are to:

- Explore the drivers of innovation in an emerging technological sector by developing a cross-disciplinary analytical framework that focuses on both firm-internal processes and the broader socio-technical system.
- Identify enablers and barriers to innovation at both the international and the national-UK level by applying this framework to the BIPV sector, also reflecting on the method.
- Recognise more general patterns as a first step towards the development of recommendations regarding firm-level agency and policy intervention for the governance of innovation in the BIPV and other similar sectors.

1.2 Research Outline

As was explained earlier, BIPV innovation dynamics relate to both inherent techno-economic features, but also to wider developments in different markets, industries and landscapes. Fig. 1.1 illustrates the position of the BIPV sector within the wider socio-technical configuration, as well as the different tensions and dynamics at various levels. This illustration is used at this point to delineate the research focus. The contained abbreviations, dynamics and tensions will be explained over the course of this thesis.

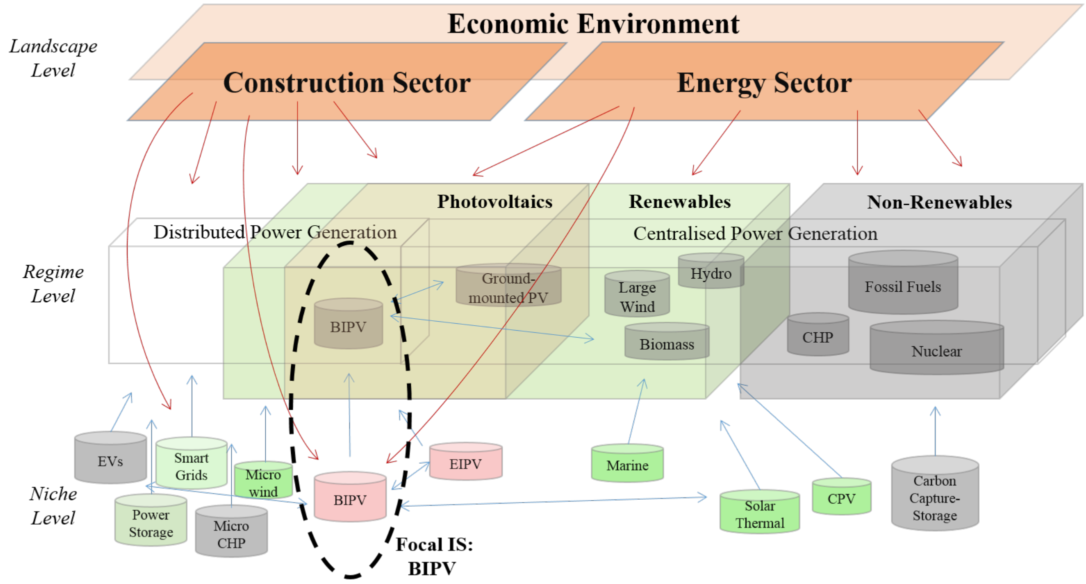

Figure 1.1: The BIPV innovation system within the wider socio-technical configuration (author's elaboration).

The complexity of the configuration and the identified tensions imply that the understanding of technological development and market diffusion requires the investigation of innovation processes not solely within the boundaries of individual firms or research institutes, but also taking into consideration their broader environment.

The realisation that innovation is both an individual and a collective act gives rise to systemic approaches for the analysis of its drivers. This research implements a multi-level methodology for the collection of empirical evidence, as well as a cross-disciplinary approach for the analysis of the findings.

Developing a theory for the understanding of technological change is a challenging task that often requires consolidation of insights across disciplines [Misa (1992)]. The conceptual starting point for this synthesis was the realisation that most existing theories that have been developed and applied in the analysis of technological change dynamics have either a certain purpose (comparative frameworks, normative analysis, policy advice) or focus (structuration, transitions, economics), offering only partial comprehension of these dynamics.

Although the aspiration is not to develop a new unified theory, this research will explore and seek for complementary insights within three distinct but related literature streams, in order to create an integrated framework for the investigation of innovation dynamics within complex, emerging sustainable technologies:

- *Innovation Theory* offers a systemic analysis of the mechanisms behind the development and market deployment of emerging technologies. It focuses on the feedback loops within the system and identifies patterns behind the drivers and barriers to its successful development and growth. Our methodology will draw upon Technological Innovation Systems (TIS), a comprehensive framework that has been applied in the assessment of the structure and functionality of emerging sustainable energy innovation systems similar to that of BIPV [Carlsson and Stankiewicz (1991); Hekkert *et al.* (2007b); Bergek *et al.* (2008a)].

- *Transitions Theory* focuses on the processes that affect the shift from one socio-technical configuration to another. It provides a broader scope than Innovation Theory, taking into consideration contextual factors including institutional changes and competition with other technologies. For the purposes of our research, concepts from the Multi-Level Perspective (MLP) have been used in tandem with the TIS in order to explore the dynamics at various conceptual levels, including accumulation of BIPV niches, destabilisation of the incumbent energy paradigms and tensions within the wider energy and construction sectors [Geels (2002); Schot and Geels (2008)].

- Finally, elements from the *Business Studies* research strand will be used to investigate the drivers behind individual actor choices and provide a micro-economic perspective to the analysis. Both elements are partially explored or missing from the other two theories. Emphasis will be given to the concepts of corporate strategy and business model, which will be used in the methodological foundation of the empirical research [Porter (1980); Osterwalder and Pigneur (2010)].

Fig. 1.2 illustrates the relative analytical focus of the three literature strands, with regards to the conceptual levels of aggregation.

During the empirical investigation, evidence was gathered from a multitude of sources including academic and grey literature, personal communications, semi-structured interviews and case studies. The data were then triangulated and organised in narratives,

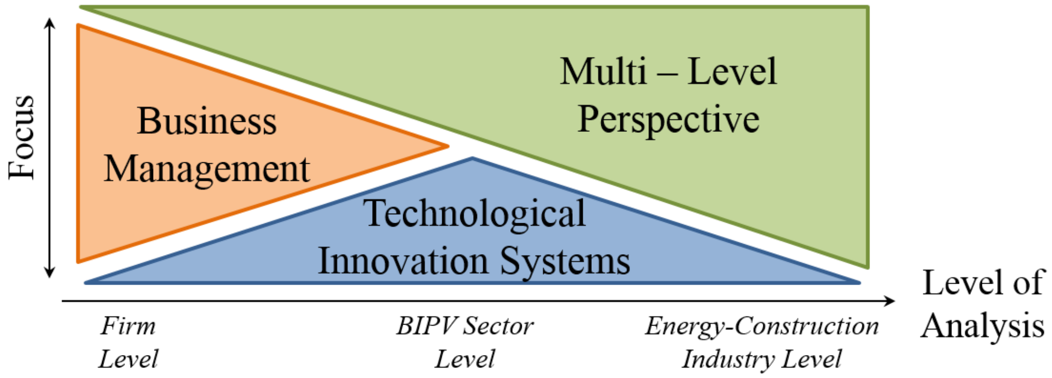

Figure 1.2: Literature strands within the hybrid analytical framework (author's elaboration).

in line with the *process theory* tradition. The novel hybrid framework was then implemented for the analytical synthesis of the findings, in order to provide reflections on both BIPV innovation dynamics and the adopted methodology.

1.3 Structure of the Thesis

The thesis consists of ten chapters organised in three distinct parts. This structure is summarised graphically in Fig. 1.3.

The first part of the thesis outlines the three literature strands that are used in the development of the hybrid analytical methodology. Chapter 2 provides an overview of different approaches for the analysis of innovation, focusing on systemic concepts and the TIS. Chapter 3 introduces the MLP methodology and the typology that has been developed for the characterisation of transition pathways. Chapter 4 draws upon the Business Studies literature, in order to describe some conceptual elements that will be used in the empirical and analytical parts of this research. Chapter 5 outlines the research design of this thesis, the merging of the conceptual approaches, and the methodologies used throughout the empirical research.

The second part contains the empirical base of this research. Chapter 6 provides an overview of the techno-economic features of BIPV applications, bridging the two discreet dimensions of the BIPV sector: energy and construction. Chapter 7 extends this overview by focusing on the BIPV industry, market and policy domains, and following the two-level spatial perspective (global and national-UK). Chapter 8 provides a more

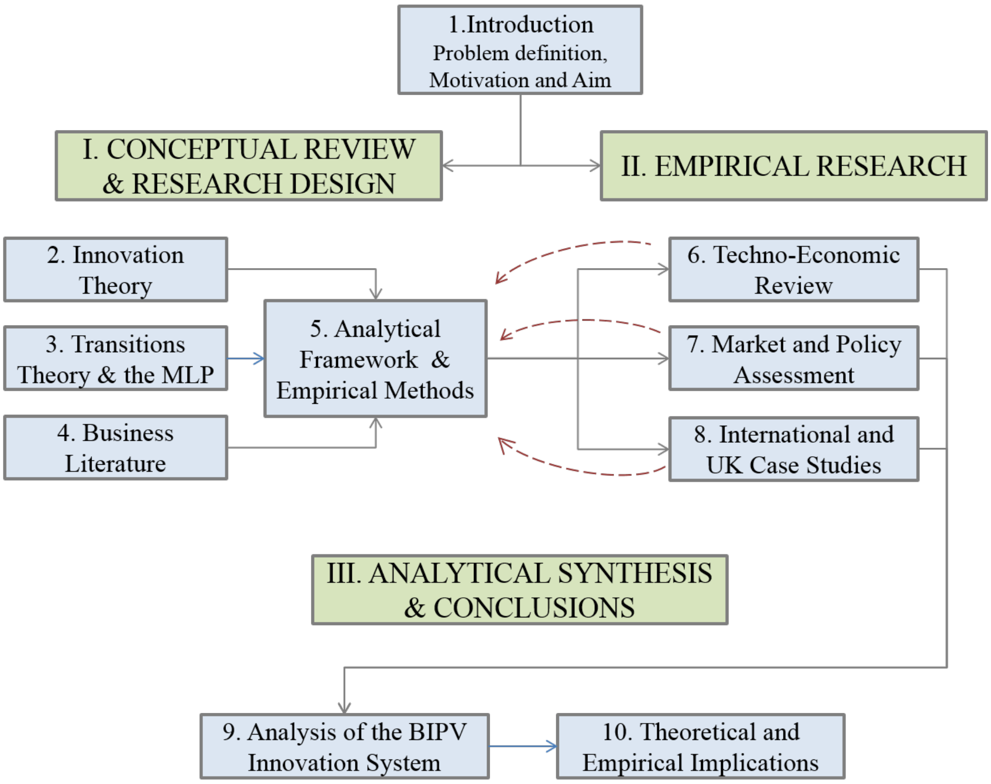

Figure 1.3: Thesis structure (author's elaboration).

micro-economic perspective, through the analysis of two in-depth firm-level case-studies.

Although this structure implies a linear flow, the research process has been characterised by feedback loops between the activities in the different chapters. The analytical framework was revised multiple times throughout the conduct of the empirical research in order to better capture real world innovation dynamics (see Fig. 1.3).

The final part of the thesis synthesises the empirical evidence for the analysis of the BIPV sector. Chapter 9 implements the hybrid analytical framework in order to assess the innovation system, and link its innovation dynamics to transitions in the broader socio-technical configuration. Chapter 10 consolidates the findings into wider themes, reflecting at the same time on both the case (BIPV innovation system) and the method (hybrid framework).

The thesis is complemented by two Appendices. Appendix A outlines the generic questionnaire and the product data-sheet that were used in the semi-structured interviews. Finally, Appendix B contains the research paper that was presented in the 28th EUPVSEC conference in 2013.

Part I

Conceptual Review and Research Design

Introduction to the Conceptual Part

As was explained in Section 1.1 the aim of this research is to provide a better understanding of the dynamics behind the development and market diffusion of BIPV applications and create an analytical framework that could be potentially applied in the research of similar emerging sustainable technologies. The methodology of this research is based on the collection and analysis of empirical evidence using different analytical concepts in order to address technical, social and economic factors that affect BIPV innovation dynamics.

In the following chapters, the theoretical basis of this thesis will be laid down and the choice of certain conceptual tools for the development of the analytical framework will be justified. The aim is not to provide an exhaustive review of the respective literatures, but rather explore approaches that are relevant to this research. Finally, the designed framework will be outlined, along with the methodologies implemented for the gathering of empirical evidence. Therefore, the purpose of this review is threefold:

- To discuss the relevant literatures and frameworks used in the analysis and management of technological change, especially within the sustainable energy and building sectors.
- To determine strengths and limitations of the respective theories, and identify those features that can be used in a complementary way to build a conceptual framework that can be applied for the analysis of the dynamics behind the development and diffusion of complex sustainable innovations.
- To outline the analytical framework and the methodologies that will be implemented throughout the empirical research.

The conceptual part of this thesis is structured as follows:

Chapter 2 describes the evolution of the concepts used in the understanding of innovation processes from early linear models to complex systemic approaches. The chapter then focuses on the development of the Technological Innovation Systems (TIS) framework and the way it is used to describe and assess the structural components and the functionality of emerging innovation systems.

Chapter 3 introduces the concepts of socio-technical transitions and the methods that have been developed to describe and manage them. After an introduction to the socio-technical system and regime concepts, the chapter focuses on Strategic Niche Management (SNM) and the Multi Level Perspective (MLP) for socio-technical transitions.

Chapter 4 provides an overview of the relevant parts of the Business Management literature, the third stream used in our analytical framework. The main focus of the chapter is strategic management, generic corporate strategies and intra-firm business models.

Finally, Chapter 5 outlines the purpose of this research and the rationale behind the combined use of insights from the three literature strands. It then provides a description of the integrated conceptual framework that will be later implemented for the analysis of the collected data and the specific methodologies used for the collection of empirical evidence.

Chapter 2

Innovation Theory

Introduction

Innovation is the principal source of economic growth, employment opportunities and skills as well as providing the potential for realising environmental benefits [Mokyr (2002); Foxon *et al.* (2005)]. The transition to a low-carbon society will require the development and market diffusion of multiple new sustainable energy technologies [Watson (2008)]. Capturing the mechanisms of how innovation works and can be supported is a crucial part of any strategy into this direction and thus, it is the obvious starting point for this conceptual review.

As is indicated in the literature, innovation occurs through a complex set of processes, the understanding of which determines to a high degree the effectiveness of policies that are designed to support it [Watson (2008)]. Several theories and analytical models have been developed in order not only to objectively describe its dynamics, but also to steer it by assessing its functionality.

This chapter presents an overview of the recent literature on Innovation Theory. After outlining basic definitions and taxonomies of innovations, it follows the evolution of theory from the early linear model of technology-push and demand-pull to the inclusion of an evolutionary perspective and other conceptual approaches in Section 2.1. It then narrows down the focus on contemporary system models and describes the various types of innovation system conceptualisations in Section 2.2.

Section 2.3 is focused on the TIS framework that has been used in the literature extensively for the description and characterisation of emerging innovation systems from the sustainable energy sector. It also reviews studies that apply the innovation system approach for the analysis of renewable energy technologies. Finally, the potential and the limitations of the framework within the scope of this thesis are identified.

2.1 Early conceptualisations of innovation

The first detailed efforts to analyse the innovation process can be traced back to the early 20^{th} century and the work of economist Joseph Schumpeter[1] who defines *innovation* as the commercial or industrial application of something new. He locates innovation in the middle of a three-stage process between *invention*, the first demonstration of an idea and *diffusion*, the deployment of the innovation into the market [Schumpeter (1934)]

Schumpeter also describes five types of innovations: new products, new methods of production, new sources of supply, exploitation of new markets and new models for organising businesses [Schumpeter (1934); Fagerberg *et al.* (2006)]. Another way to classify innovations also based on Schumpeter's work is according to how radical they are to the existing setup [Freeman and Perez (1988); Freeman and Soete (1997); Fagerberg (2003)]:

- *Incremental* innovations are continuous improvements, mainly resulting from 'learning-by-doing' and 'learning-by-using' processes. These innovations do not usually have dramatic effects independently, but their cumulative impact on the growth of productivity and technological change can be significant [Lundvall *et al.* (2002)].

- *Radical* innovations are discontinuous events that are usually the result of deliberate research and development activities. Their appearance is unevenly distributed over time and sectors and it can form the springboard for investment surges and new markets growth.

- *Changes of the technology system* affect several branches of the economy and may create entirely new sectors. They result from 'constellations' [Keirstead (1948)] of radical and incremental innovations combined with managerial and organisational innovations in more than one or a few firms.

- *Technological revolutions* or *Changes in the 'techno-economic paradigm'* [Freeman and Perez (1988)] are very far-reaching changes that have pervasive impacts on the behaviour of entire economies.

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[1] Schumpeter's seminal paper 'The theory of economic development' was published in German in 1911 and in a revised English version in 1934 [Fagerberg (2003)].

2.1.1 Linear models of innovation

Innovation includes several phases: research and development (R&D), prototyping, demonstration, commercialisation and deployment [Watson (2008)]. Although in many cases these stages are temporally undistinguishable, a significant time lag between them is not uncommon [Rogers (2010)]. These lags reflect the different resources and capabilities required by the innovator as well as the various commercialisation conditions that may be underdeveloped or even lacking [Fagerberg (2003)].

An early conception of the process was the 'linear model of innovation' which understands innovation as a unidirectional flow from basic research to applied research and technology diffusion through production and marketing (see Fig. 2.1). The first attempt to understand the drivers of this process was based on the *technology-push* model that emerged after the World War II. According to this model scientific advancements largely determine the rate and direction of technological change and therefore an increased allocation of resources on basic R&D could stimulate innovation and increase the output of technologies [Rothwell (1994); Nemet (2007)].

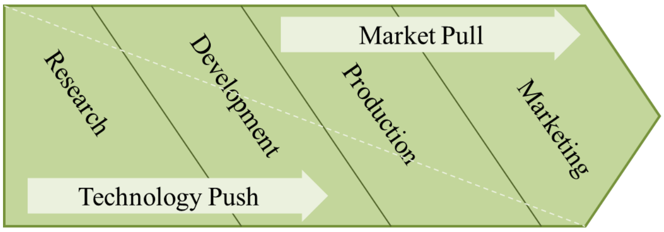

Figure 2.1: The linear model of Innovation (author's elaboration).

One main critique to this model is that it ignores prices and other changes of the market conditions that would affect the adoption of innovations [Nemet (2007)]. In the 1960's the *market-pull* model emerged, where technological change is rather steered by economic developments at the demand-side [Rosenberg (1969); Rothwell (1994)]. Although this second innovation model is able to justify the occurrence of incremental innovations, it fails to describe disruptive technological changes [Mowery and Rosenberg (1979)]. Additionally, it was criticised regarding the assumptions made related to the firms' capabilities to identify and address the latent needs within the end-market, and consequently their ability to trigger innovation [Simon (1959); Nemet (2007)].

Technology Readiness Levels (TRL) is another linear model used for the evaluation of the maturation level and deployment probability of a technology (see Fig. 2.2). It was first developed by NASA in the 1980s for use on emerging technologies in the aerospace industry [Sadin *et al.* (1989)]. It was later expanded by John Mankins and adopted by several industries including the military, oil and gas industries [Mankins (1995)].

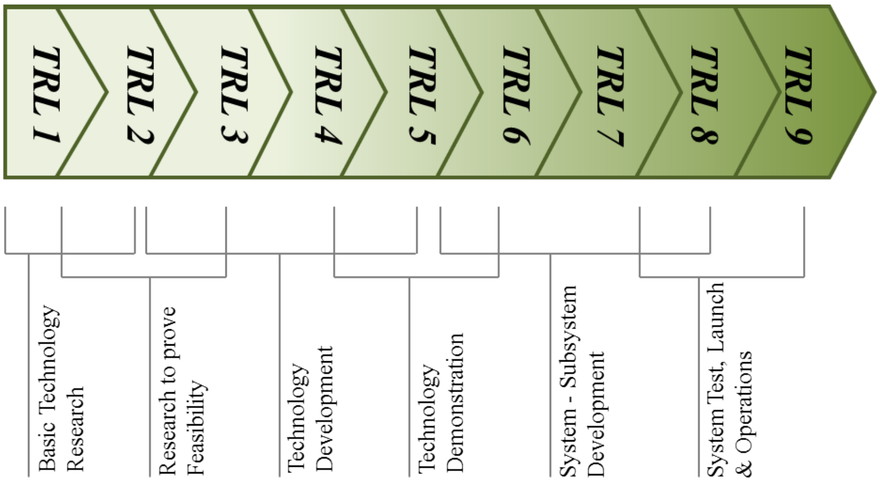

Figure 2.2: Technology Readiness Levels (adapted from NASA (2004)).

The model does not focus on the drivers of innovation, but rather on the current commercial state of the technology. According to the Science and Technology Committee appointed by the House of Commons of the UK Parliament, the nine levels that constitute the TRL framework are [Science and Technology Committee (2011)]:

1. Basic principles observed and reported.
2. Technology concept and/or application formulated.
3. Analytical and experimental critical function and/or characteristic proof-of-concept.
4. Technology basic validation in a laboratory environment.
5. Technology basic validation in a relevant environment.
6. Technology model or prototype demonstration in a relevant environment.
7. Technology prototype demonstration in an operational environment.
8. Actual Technology completed and qualified through test and demonstration.
9. Actual Technology qualified through successful mission operations.

Although these linear models of innovation have been characterised as over-simplistic, their main elements remained in later conceptualisations that provided more emphasis on the links and feedback loops between R&D, marketing functions, supply chains and customers. A key feature of these interactions is the mutual learning processes that may yield further improvements and solve problems that emerge at the stages of market diffusion of innovations [Rothwell (1994); Watson (2008)].

All these representations are not just descriptive conceptualisations of the innovation process, but also organisational models that reflect how understanding and focus of innovation has changed over time [Rothwell (1994)].

2.1.2 Diffusion Theory

Diffusion of innovations is a theory developed by Everett Rogers in 1962 that aims to explain and find patterns in the process of adoption of a new technology by a social system [Rogers (2010)]. He noticed that the diffusion rate of most innovations within a country forms an *S-curve*, following the standard logistic sigmoid function:

$$m_t = \frac{1}{1 + e^{-d \cdot t}} \tag{2.1}$$

where t is time, m_t is the market share and d the diffusion rate parameter [Valente (2005)]. He also identified groups of adopters with different characteristics: innovators, early adopters, early majority, late majority and laggards (see Fig. 2.3) [Rogers (2010)].

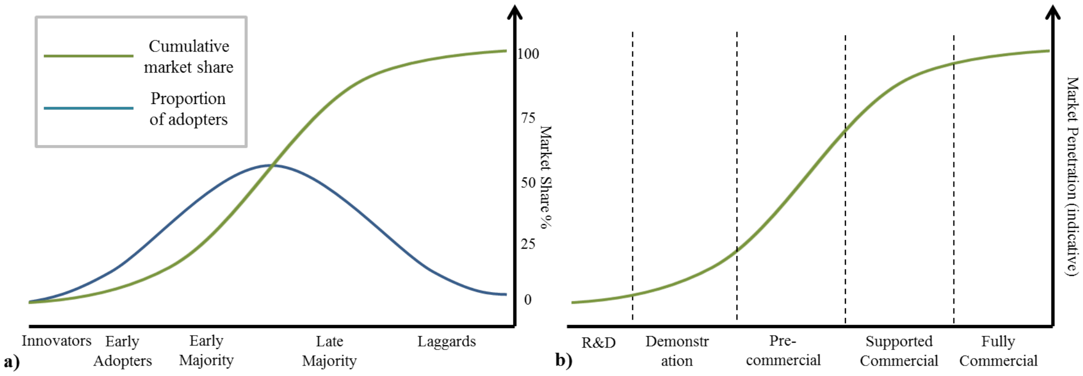

Figure 2.3: The diffusion of innovation according to a) Rogers (2010) and b)Foxon *et al.* (2005).

Adapting this general diffusion theory, Foxon *et al.* (2005) modelled the diffusion of renewable energy technologies in the UK. In their model, diffusion is not a function of time, but rather of technological maturity. Five stages of maturity are defined [Foxon *et al.* (2005)]:

- *Basic and applied R&D:* wide scope, no adoption.
- *Demonstration:* some attempts but still not proven technology.
- *Pre-commercial:* proven technology but uncertain scalability.
- *Supported commercial:* substantial diffusion, market pull.
- *Fully commercial:* fully mature, unsupported technology.

Performance of established and invading products

In another interpretation of the S-curve, Utterback (1996) visualised the performance of a technology in relation to time as shown in Fig. 2.4.

Incremental innovations improve the performance of an established technology. When a new technology appears (t_1), although its performance is inferior its rate of development is faster. Designers of the incumbent technology may respond by boosting its performance, but at some point in time (t_2 or t_3) the relentless improvement of the new technology will establish its superiority [Utterback (1996)].

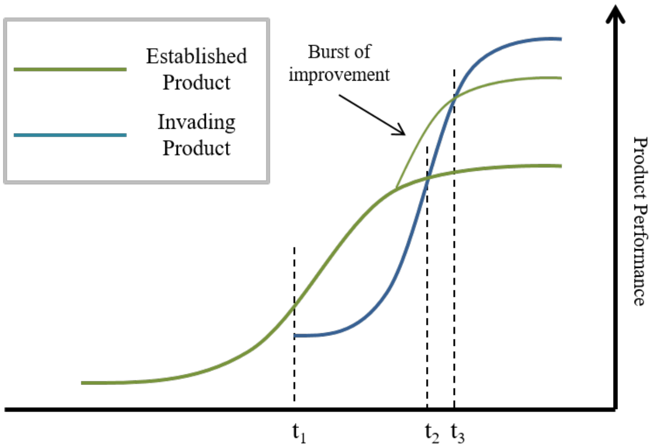

Figure 2.4: Performance of an established and an invading product (adapted from Utterback (1996)).

2.1.3 Later conceptual approaches

Further steps in the conceptualisation of the innovation process were taken in the second half of the 20^{th} century with the inclusion of approaches from the fields of evolutionary economics [Nelson and Winter (1982)], learning theory [Arrow (1962)] and the path-dependency model [David (1985); Arthur (1994)].

Evolutionary Economics

In contrast to the concept of economic processes being in a 'steady state' which is embedded in neo-classical economics theory, evolutionary economists use the 'steady change' approach [Nelson and Winter (1982)]. The theory introduced by Veblen (1898) and further developed by Alchian (1950) embodies in its economic analysis the principles of biological evolution and natural selection and the mechanisms of mutation, selection and retention found in Darwinian Theory. Milton Friedman proposed a model where firms compete for market share providing a variety of products and processes. Markets act as selection vehicles that push firms that fail to capture a significant share into bankruptcy. The routines used by the surviving firms are then imitated, creating an inheritance of successful practices [Friedman (1953); Mazzucato (2000)].

A concept from evolutionary economics that is central in later innovation theories is that of 'bounded rationality'. It suggests that firms have limited information access and processing capabilities and therefore, their *routines* are not optimal but rather try to satisfy their particular prioritised criteria [Nelson and Winter (1982)]. Common expectations shared by firms within an industry drive gradual changes and incremental improvements of these routines, creating a particular trajectory [Foxon (2003)].

Another concept which is particularly important in the early stages of the innovation process is uncertainty [Meijer *et al.* (2007)]. The high degree of uncertainty over the optimal design is responsible for creating a large variety of options, and also signifies the difficulty in determining and choosing a certain technological path [Rosenberg (1996); Meijer *et al.* (2007)].

Learning Theory

Learning is considered to be the main method through which organisations such as firms ('learning organisations' according to Lundvall *et al.* (2002)) accumulate skills and knowledge [Malerba (1992)]. The process of learning is one of the fundamental constituents of *increasing returns to adoption*, the notion that the more a technology is taken up by users, the more it is likely to be further adopted [Arthur (1994)].

The first type of learning to be formalised was 'learning-by-doing'. Kenneth Arrow proposed in 1962 that the productivity of a firm increases as the cumulative output of the industry grows [Arrow (1962)]. It normally takes place in the manufacturing stage and consists of incremental improvements of the production processes [Forbes and Wield (2004)].

Two other forms of learning are 'learning-by-using', which refers to the knowledge gains from the use of the product by consumers, and 'learning-by-interacting', which refers to the knowledge attainment through the communication of the manufacturer with both users and suppliers [Rosenberg (1982)]. Both types of learning imply feedback loops along the innovation process that drive a continuous development, challenging the conventional linear model of technology-push and demand pull.

In addition to those three informal types of learning that mainly give rise to incremental innovations, there is the development of formal knowledge through 'learning-by-searching' carried out by universities, research institutes and firms, and the purposeful 'learning-by-investing', which refers to the conscious effort of organisations to enhance their capabilities [Kamp *et al.* (2004); Carud (1997)]. Although radical innovations may emerge using that method, the main outcome is incremental development [Forbes and Wield (2004)].

An analytical tool used to represent the effects of experience gain is the *learning curve*, which represent a quantitative relationship between performance improvement and production [Wene (2008)]. *Experience curves* in particular measure the decrease in unit cost in relation to the cumulative production of a product. The concept is based on the empirical observation that every time cumulative manufacturing output doubles, the unit cost is reduced by a constant rate, called the learning rate (LR)[2] (see Fig. 2.5a

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[2] Another metric frequently used is the progress ratio (PrR) which mathematically is the complement

and 2.5b)

If C is the unit cost function (cost of the n_{th} product), C_0 the cost of the first product, P the cumulative production and ϵ the learning coefficient, then:

$$C = C_0 \times P^{\epsilon} \quad where \quad \epsilon = \frac{logLR}{log2}$$

When the cost function is plotted on a logarithmic scale for production using historical cost data, the experience curve is almost linear, and can be utilised for future cost projections when used in conjunction with market expansion scenarios [Nemet (2007); Candelise *et al.* (2013)].

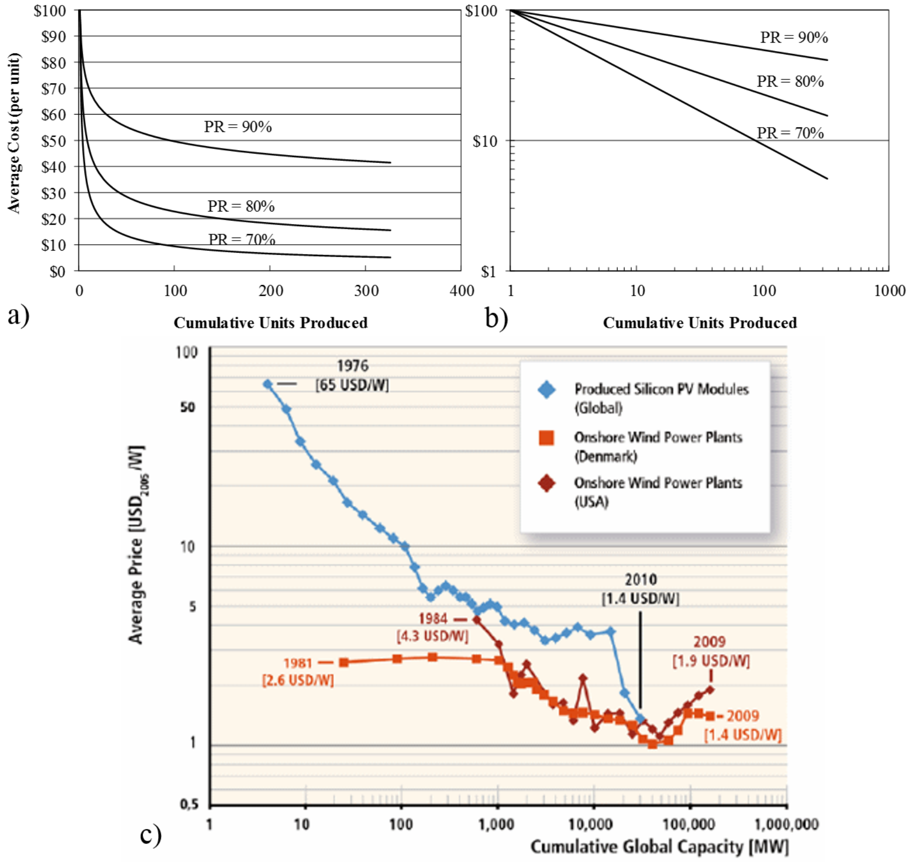

Figure 2.5: a) and b) Indicative experience curves, c) Historical experience curves for renewable energy technologies [Edenhofer *et al.* (2011)].

Another type of learning curve is the S-curve that illustrates the market diffusion of

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to the learning rate i.e. $PrR = 1 - LR$

innovation (see Subsection 2.1.2).

Path dependency

The concept of path dependency provides a historical dimension to decision-making by suggesting that a set of decisions is limited by decisions made in the past, even though past circumstances may no longer be relevant [David (1985); Arthur (1994)]. Both innovating entities and institutional rules may become path-dependent. They may also strengthen as explained by 'increasing returns to adoption' (see Subsection 2.1.3) giving rise to technological trajectories which come to resemble self-fulfilling prophecies [Foxon and Pearson (2008)]. This co-evolution and mutual reinforcement processes between the innovation and its institutional environment leads to the development of *socio-technical regimes* [Kemp and Foxon (2007)], a concept that will be further analysed in the Transitions Theory chapter (see Section 3.1.2).

One of the outcomes of path dependency is the emergence of a *dominant design*, a technological or institutional configuration that is widely adopted, even in the presence of a range of equally feasible alternatives [Utterback (1996)]. The virtuous circle of increasing returns 'locks-in' and favours the incumbent configurations that may otherwise be sub-optimal. Within this co-evolution of technologies and institutions, involved firms become inflexible to change and may 'lock-out' radical innovations, dampening at the same time the entrance of new-comers [Unruh (2000); Foxon (2002)].

It has to be made clear at this point that the concept of lock-in is not just a neutral description, but also involves normative features, reflecting priorities within the socio-economic environment, and having policy implications. The characterisation of a technological design as optimal or not depends on contextual variables. With respect to the focus of this research, the phenomenon of technological lock-in is particularly important. Energy systems that rely on renewable energy sources, and especially distributed energy systems challenge the existing technical and institutional architecture of the energy and, in the case of BIPV, the building sectors. Therefore, they cannot compete with other technological options that are more compatible to the incumbent configuration, without policy intervention [Watson (2008)].

2.2 Systems-based conceptualisations of innovation

As is evident from the preceding discussion, a central finding in the innovation literature is that processes and routines within firms are heavily affected and depend on contextual factors [Fagerberg (2003)]. Contrary to the rather oversimplified early understanding of innovation as a linear sequence of invention, innovation and diffusion, models developed in the last two decades of the 20th century conceptualised it using a systems approach[3], trying to include these externalities [Hughes (1993); Lundvall (1985); Freeman (1987); Dosi *et al.* (1988); Nelson (1993); Edquist (1997); Carlsson *et al.* (2002); Bergek *et al.* (2008a)].

The first implication of applying a systems-perspective to the study of innovations is the focus on the *structure* of such a process. An innovation system consists of interconnected social and technical sub-systems [Tushman and Murmann (2002)]. The linkages within the system will facilitate certain interactions reinforcing a stable configuration and constrain others that destabilise it.

A second implication is the complementarity and interdependency of the system components [Fagerberg *et al.* (2006)]. Lack of an important component may cause time-lags and bottlenecks that lead to the failure of the system to develop and grow [Rosenberg (1982)]. Thomas Hughes introduced the concept of 'reverse salients' to describe the phenomenon where sub-systems that develop at a slow pace hinder the overall development of the system [Hughes (1987, 1993)]. Two well-documented examples are the delayed electricity diffusion because of its dependency on extensive infrastructure and the failure of the adoption of electric vehicles due to limitations posed by battery technologies [Mowery and Rosenberg (1979); Fagerberg (2003)].

With respect to the focus of this research, the systems approach offers a broad understanding of the elements affecting the development and deployment of emerging sustainable energy systems. Rather than simple technical and economic factors, successful adoption of such technologies depends on infrastructural adaptation, development of new links and institutional change [Foxon (2003); Watson (2008)].

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[3] It is suggested in Edquist and Johnson (1997) (pp.28-29) to use the term 'approach' or 'conceptual framework' to describe the innovation system perspective and not the term 'theory', in the sense that it does not offer specific propositions regarding the causal relations among variables.

2.2.1 The Chain-Linked model of innovation

The first attempt to illustrate the dynamic nature of the innovation process and represent these feedback loops was the 'chain-linked' model introduced by Kline and Rosenberg (1986) and adopted by the Organization for Economic Cooperation and Development (OECD) [OECD (1992)] (see Fig. 2.6).

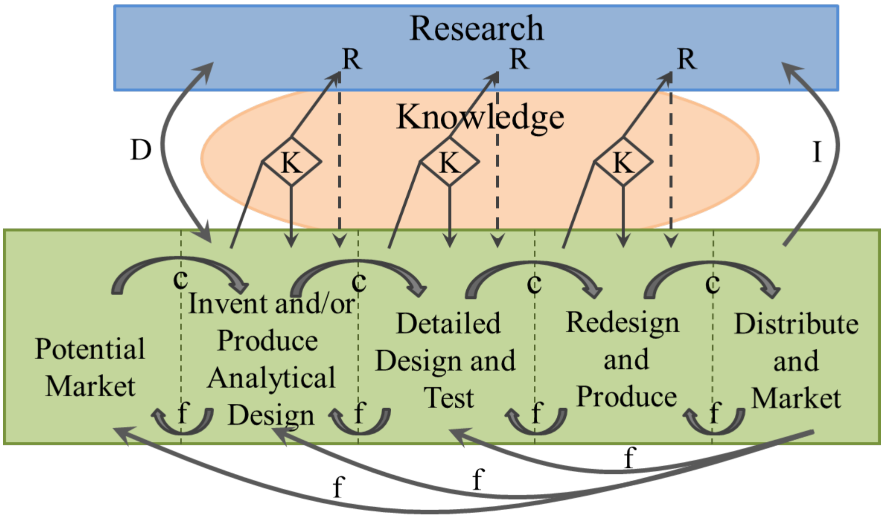

Figure 2.6: The Chain-Linked model for the innovation process (adapted from Kline and Rosenberg (1986)).

This complex model identifies five paths of knowledge flows instead of the conventional 'technology-push' and 'market-pull' drivers. In addition to the central innovation path (c) from identification of a potential market to invention, development, production and finally market distribution, several feedback loops (f) exist along these stages. The third path indicates links from the innovation stages to research through knowledge (found within firms and elsewhere). Unless problems arising at a certain stage can be solved using the existing knowledge, they are directed to research bodies that in turn feed back their findings (K-R)[4]. The last two paths include a direct interaction of research and invention that gives rise to radical innovation (D), and a feedback loop that refers to the utilisation of the technological products from science (I) [Kline and Rosenberg (1986)].

The model recognises interactions within a firm or a network of firms (paths c and

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[4] This conditional path is responsible for the name 'chain-linked model'.

f), and between a firm and wider science and technological system (paths D, K-R and I). However, it still does not take into consideration interactions with the wider political, economic, social and cultural landscape [ICCEPT/E4tech (2003)].

2.2.2 National Innovation Systems

The *National Innovation Systems* (NIS) approach was the first model of innovation systems to emerge in the literature. It was developed in the late 1980s and was applied on the Japanese industrial sector [Freeman (1987)]. NIS is defined as 'the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies' and highlights the role of government and cultural factors in the successful development of the post-war industrial sector [Freeman (1987, 1995)].

Bengt-Åke Lundvall created in 1992 a theoretical framework based on quantitative indicators of innovation including statistical data on R&D spending, patents and growth rates. The work stressed the importance of interactions, knowledge flows and different types of learning processes [Lundvall (1992); Lundvall *et al.* (2002)].

Richard Nelson in 1993 published a comparative analysis of the NIS of 15 different countries based on empirical evidence and inductive reasoning. The main finding was that differences in the innovation systems reflect the differences in the institutional set-ups including R&D organisations, financial institutions, management skills, public infrastructure and policies [Nelson (1993); Foxon (2006)].

This strategic concept of innovation has been used extensively by the OECD. The report 'Dynamising National Innovation Systems' published in 2002 highlights the importance of interactions among all entities within the system and especially the 'market and non-market knowledge transactions among firms, institutions and the human resources involved' [Remoe and Guinet (2002)]. A generic model of NIS is presented in Fig. 2.7.

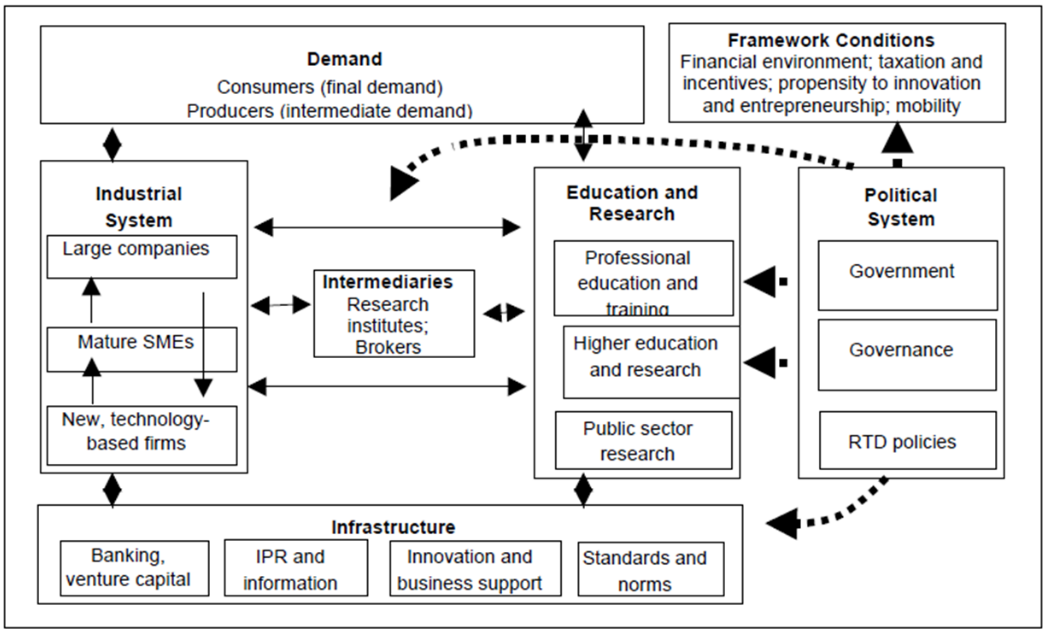

Figure 2.7: A model of a National Innovation System [Kuhlmann and Arnold (2001)].

2.2.3 The Innovation System Frame

The OECD published in 1997 'The Oslo Manual', a document that provides guidelines for the measurement of technological innovation at the firm-level [OECD (1997)]. The manual uses the so-called 'Innovation System Frame' to conceptualise and classify the conditions that affect the propensity of firms to innovate into four domains [Speirs *et al.* (2008); OECD (1997)]:

- *Framework Conditions* that include external to the firm factors (basic educational system, communication infrastructure, financial institutions, legislative and macro-economic settings, market accessibility and industry structure).

- *Science and Engineering Base* that underpins the firm's activities (technical training, universities, basic research, public good R&D, strategic R&D and non-appropriable innovation support).

- *Transfer Factors* that influence the knowledge flows and learning processes (linkages between firms, presence and mobility of technological experts, international links, access to public R&D, spin-off company formation, codified knowledge and community value-systems)

- *Innovation Dynamo* that outlines the complex system of factor that determine a firm's capacity to innovate (strategy, R&D and non-R&D activities).

Fig. 2.8a illustrates a graphical representation of the framework as presented in the third edition of 'The Oslo Manual' [OECD (2005)]. The location of the 'innovation dynamo' in the centre of the framework highlights the importance of the firm throughout the innovation process. In order to be succesful, the innovator will have to recognise opportunities, set-up strategies, and transform inputs into real applications faster than competitors [Speirs *et al.* (2008); OECD (1997)].

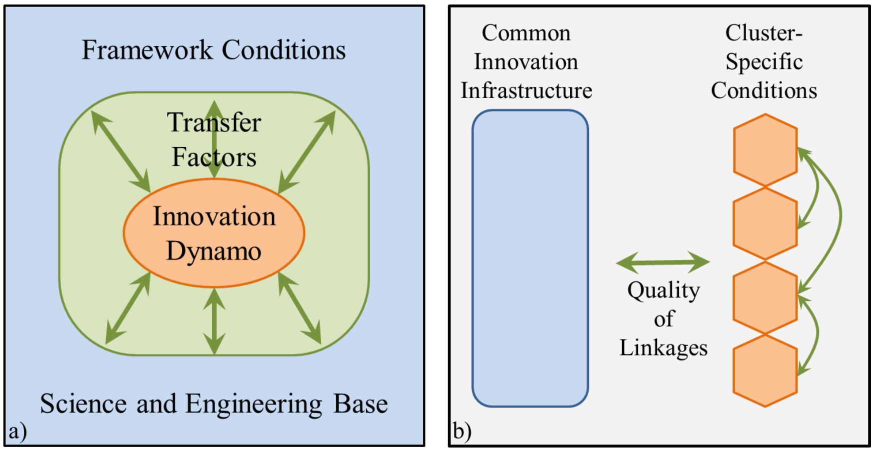

Figure 2.8: a) The Innovation System Frame (adapted from OECD (2005)) and b) the National Innovation Capacity (adapted from Porter and Stern (2001)).

2.2.4 National Innovation Capacity

The 'National Innovation Capacity' (*NIC*) is another system-based conceptualisation of the innovation process similar to the *Innovation System Frame* and the *National Innovation System* [Porter and Stern (2001)]. It refers to a country's potential as an economic and political entity to generate commercially relevant innovation. Affecting factors lay on three dimensions, highlighting the location-bias and the firm-level focus [Speirs *et al.* (2008); Furman *et al.* (2002)]:

- *Common Innovation Infrastructure* refers to innovation-specific human and financial resources, policies and economy's level.
- *Cluster-Specific Conditions* refers to the conditions specific to a geographic concentration of interconnected firms and institutions.

- *Quality of linkages* refers to the bidirectional relationship of the clusters to the infrastructure.

A graphical representation of the elements comprising the NIC is presented in Fig. 2.8b.

2.2.5 The Triple Helix of Innovation

The Triple Helix is another model of analysis that explains innovation in its social context developed by Etzkowitz and Leydesdorff (1997). Similarly to the NIS, the framework adopts a national boundary, but instead of focusing on the firm as the main source of innovation it underlines the dynamic network of institutional arrangements among universities, industries and governmental agencies.

According to the model, universities and businesses have diverged from their traditional roles as research bodies and value creators respectively. Instead, their activities currently overlap, while governments moderate and direct to some extent these activities [Etzkowitz and Leydesdorff (1997)].

Etzkowitz and Leydesdorff (2000) go on to distinguish three Triple Helix configurations (see Fig. 2.9):

- In the first configuration the state encompasses universities and industries and directs their links. Bottom-up innovation initiatives are limited.
- In the second policy model the activities of the three actor bodies are delineated by strong borders (‘laissez-faire’ policy).
- In the third and most common contemporary configuration, the three institutional spheres overlap creating trilateral networks and hybrid organisations.

2.2.6 Regional and Sectoral Systems of Innovation

The concept of ‘Regional Innovation Systems’ (*RIS*) was developed by Philip Cooke in 1992 after he observed the emergence of dense localised clusters of interconnected firms, for which regional rather than state-scale supportive regulations were more appropriate [Cooke (1992); Asheim and Isaksen (2002)]. The concept is based on the phenomenon

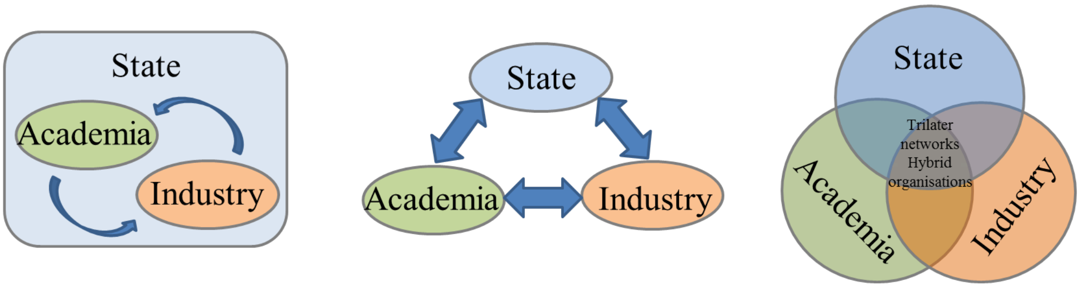

Figure 2.9: The three Triple Helix configurations (adapted from Etzkowitz and Leydesdorff (2000)).

of *industrial clusters* identified earlier by Michael Porter, who also highlighted internal competition, localised supply chains and strong local markets as their main properties[5] [Porter (1990)].

Cooke identifies three types of clusters: *local* small firms, *globalised* large firms and *interactive* clusters of both small and large firms. He also identifies three types of governance: locally organised *grassroots*, centrally planned *dirigiste* and *network* coordination that can be local, national or international [Braczyk *et al.* (1998); Cooke *et al.* (1997); Cooke (2001)].

Using a different perspective, 'Sectoral Systems of Innovation' (*SSI*) define the *technological sector* as the unit of analysis and focus on groups of firms that are active in developing and utilising a sector's products and technologies [Breschi and Malerba (1997); Chang and Chen (2004)]. Franco Malerba goes on to develop a framework for the analysis of an SSI focusing on its structural elements and dynamics [Malerba (2002)]:

- Structural Elements:
  - Products
  - Agents (firms, universities, financial institutes, etc.)
  - Knowledge and Learning
  - Basic Technologies, Inputs, Demands and the related Links and Complementarities
- Dynamics:

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[5] A review of these concepts introduced by Porter is presented in Section 4.1.

  - Interaction Mechanisms (both internal and external to firms)
  - Competition and Selection processes
  - Institutions (formal and informal rules, standards and practices specific to the sector)

Setting the technological sector as the focal point of analysis, an SSI transcends both specific technological and national boundaries. Although sectors may be limited in regional clusters, they often span global networks, as for example within multinational corporations [Speirs *et al.* (2008)].

2.2.7 The systems perspective of innovation

Later approaches reflect more accurately the complexity and interdependency of actors and networks engaged in innovation, which is identified as a dynamic process of matching technical possibilities to market opportunities [Freeman and Soete (1997)]. The *innovation system* can be defined as the set of elements and relationships that interact for the production, diffusion and use of new and economically-useful knowledge [Lundvall (1992)].

According to this systems perspective, innovations still go through a number of development stages (research, development, demonstration, commercialisation and diffusion). However, in addition to the conventional *technology-push* and *demand-pull* drivers, bidirectional knowledge flows provide feedback loops and networks of the involved actors not only across various stages but also to the framework conditions, including governmental policy and investment conditions [ICCEPT/E4tech (2003); Edquist (2005)]. Fig. 2.10 presents an illustration of this dynamic, multi-agent, non-linear systemic model.

2.3 Technological Innovation Systems

The ‘Technological Innovation Systems’ (TIS) concept was first developed by Bo Carlsson and Rikard Stankiewicz in 1991 [Carlsson and Stankiewicz (1991)], who associated the growth potential of a nation with the technological systems it includes, where

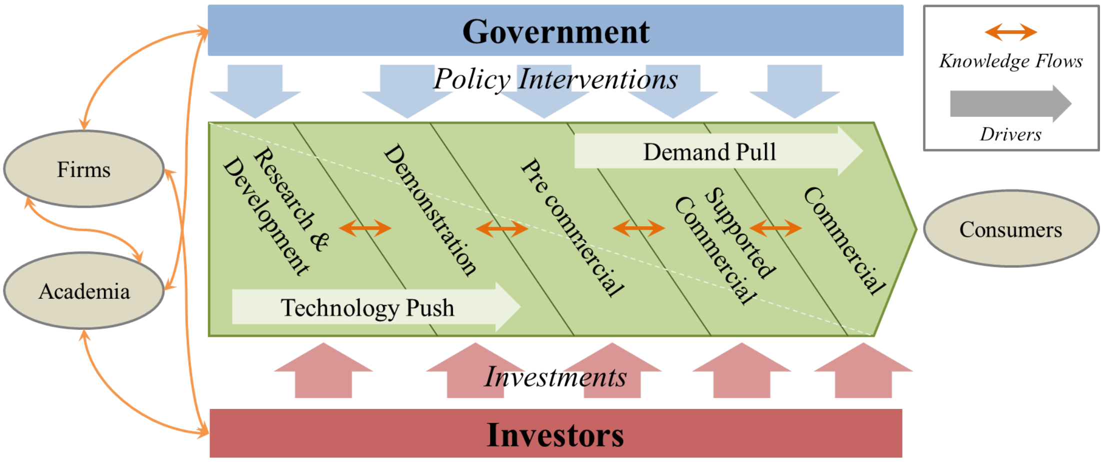

Figure 2.10: The stages of the innovation chain (adapted from ICCEPT/E4tech (2003)).

> A technological system is defined as a dynamic network of agents interacting in a specific economic/ industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology.

The main difference from other innovation-systems approaches is the level of analysis. A TIS does not have a geographic or national boundary and in contrast to sectoral systems it focuses on a specific technology and the knowledge field around it rather than the entire sector [Hekkert and Negro (2009)]. TISs are characterised by networks of knowledge and competence flows rather than flows of products and services. Provided there is sufficient entrepreneurial activity and a certain density of resources (a 'critical mass'), these dynamic networks can transform into synergistic clusters of firms and technologies (or 'development blocks') that may give rise to new business opportunities [Carlsson and Stankiewicz (1991)].

Although in this initial conceptual framing of TISs Carlsson and Stankiewicz do not provide a methodological framework for their analysis, they do highlight economic competence, clustering of resources and institutional infrastructure as their main features [Carlsson and Stankiewicz (1991, 1995)]. The first preliminary work on an analytical framework was made by Staffan Jacobsson and Anna Johnson[6] in [Jacobsson and Johnson (2000)] where they identify the structural elements of a TIS as actors, networks

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[6] Johnson is the maiden name of Anna Bergek, used in early publications.

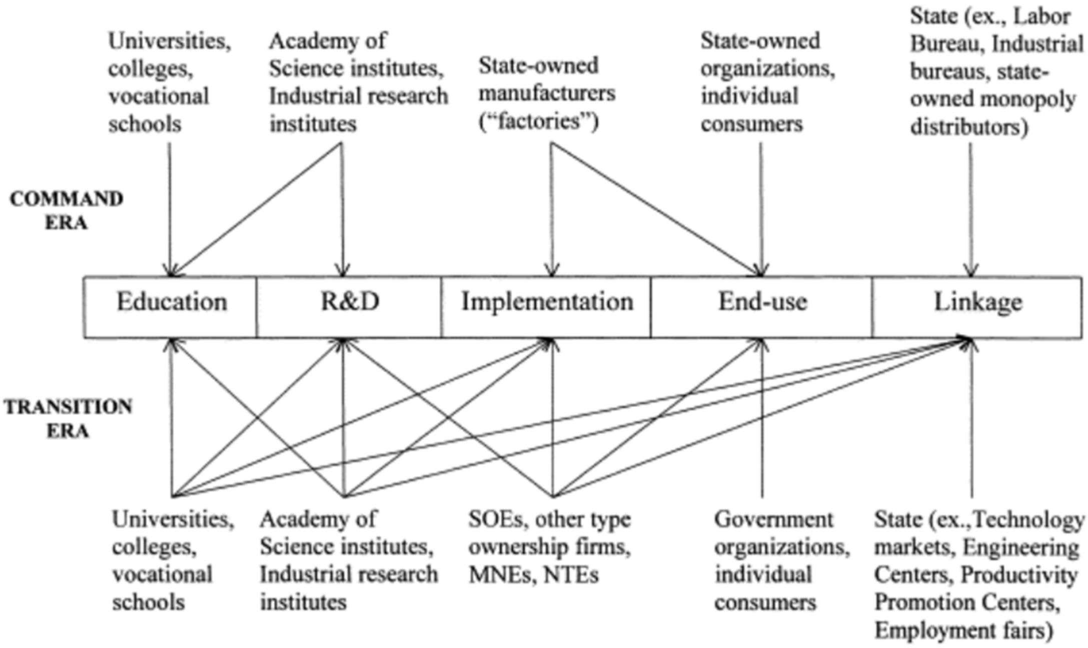

Figure 2.11: TIS elements and analytical framework as described in Liu and White (2001).

and institutions[7]. They also determine some of the factors that may lead to a system failure including poor connectivity, local search processes and legislative failure; however they do not describe possible actions that would avert such failures.

Another analytical framework was attempted by Xielin Liu and Steven White in Liu and White (2001), where the authors suggest a similar focus on the structural elements of the TIS. In their study of the Chinese innovation system a national boundary is taken due to the location-specific interest of policy-makers. They also go on to identify five system-level processes or 'fundamental activities' that arise from the collective behaviour of organisations: R&D, implementation, end-use, education, linkage. Fig. 2.11 illustrates how the linkages between actors and these activities changed after the Chinese economic reform from central planning to the current transition era.

Continuing previous work on structural analysis of TISs [Jacobsson and Johnson (2000)], Anna Johnson specified in 2001 seven basic functions that can be used for the evaluation and comparison of the dynamic performance of innovation systems [Johnson (2001)]. This was part of an extensive body of work on the development of

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[7] Further analysis of the structural components of a TIS as they were described by Jacobsson and Johnson-Bergek in Section 2.3.1.

a methodological scheme of analysis. After several refinements of these functions[8] a comprehensive framework for the assessment of the TIS was introduced in 2008 [Bergek *et al.* (2008a,b)].

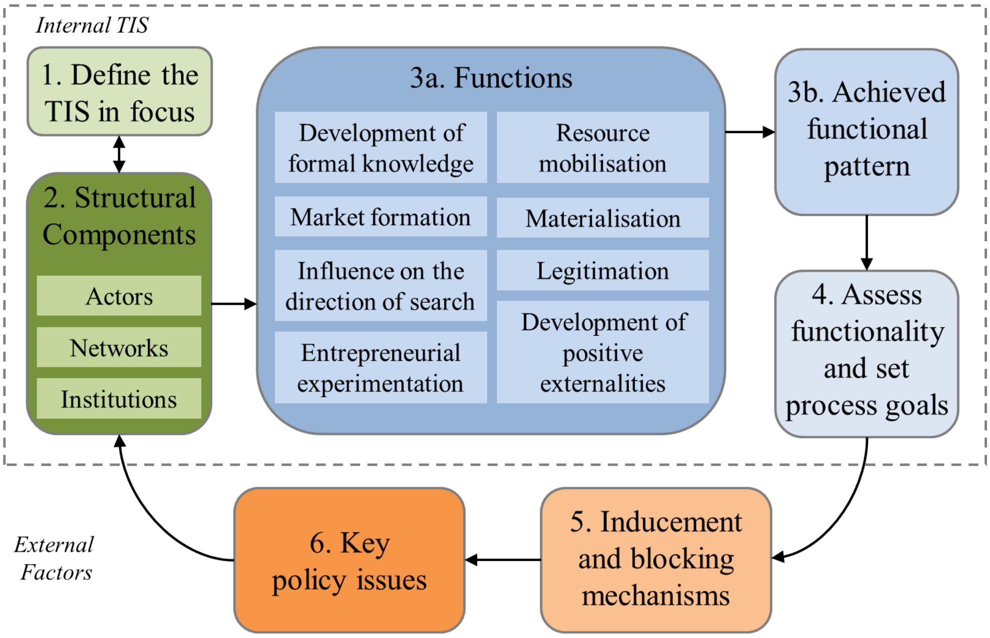

Figure 2.12: The TIS framework as described in Bergek *et al.* (2008a) and Bergek *et al.* (2008b) [author's adaptation].

The 6-step framework is illustrated graphically in Fig. 2.12:

1. Defining the TIS in focus involves choosing the knowledge field or product, the level of aggregation of the analysis, the range of applications that will be included and the spatial boundaries (if any) of the study.

2. The structural analysis involves the identification and assessment of the actors, the networks and the institutions related to the TIS (see Subsection 2.3.1).

3. The third step involves the description of the functional pattern of the TIS in terms of a set of key processes (see Subsection 2.3.2). This does not include a normative assessment of how well the system performs, but rather an analysis of how many functions are fulfilled and to what extent.

4. In the fourth step the functional pattern is evaluated based on its phase of

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[8] Further analysis of the work on the functionality of a TIS in Section 2.3.2.

development and on how it compares to other similar TISs (see Subsection 2.3.4). Process goals are also defined.

5. The following step includes the identification of external factors that accelerate or impede the development of the TIS (see Subsection 2.3.3).

6. Finally, based on the potential structural deficiencies and functional weaknesses identified in earlier stages, policy implications are drawn towards the process goals defined in step 4 (see Subsection 2.3.5).

The TIS approach has been chosen as one of the pillars of the analytical framework of this research as it is appropriate for the study of emerging innovation systems, where the number of actors and aligned institutions is limited. In contrast to the NIS and SSI perspectives, the TIS focuses on fewer elements and interactions reducing the complexity of the analysis [Hekkert and Negro (2009)]. Particularly, it has been widely used in the literature to study the development of innovation systems of renewable energy technologies [Jacobsson and Johnson (2000); Johnson and Jacobsson (2001); Bergek and Jacobsson (2003); Jacobsson and Bergek (2004); Jacobsson *et al.* (2004); Foxon *et al.* (2005); Negro *et al.* (2007, 2008)].

Additionally, it offers a structured methodology containing a range of indicators (structural elements, functions, inducement and blocking mechanisms) that can be used in conjunction with indicators from other frameworks in longitudinal and process analyses for the assessment of the state and performance of innovation systems [Negro *et al.* (2007); Suurs *et al.* (2009); Suurs and Hekkert (2009); Tigabu *et al.* (2013)]. The synthesis of these indicators will be further discussed in Section 5.2.3.

2.3.1 Structural components of a TIS

The three main structural components (or elements) of a TIS were defined in [Carlsson and Stankiewicz (1991)] as *actors*, *networks* and *institutions* excluding material components such as infrastructure. Bergek *et al.* (2008b) include *technology* in their analysis as an additional component, in line with previous authors [including Hughes (1987); Geels (2004)].

The components of a TIS may be exclusively dedicated to the TIS or be part of several different systems. Especially in sectors with emerging technologies that have not been stabilised and proven, including the sustainable energy sector, there is significant structural overlap and interdependence of several systems [Bergek *et al.* (2008b)].

Although the TIS perspective may suggest a collective collaboration among the components, it should be noted that it is only a conceptual tool for a system that might not explicitly exist or may just include weak and unintentional interactions among the actors [Bergek *et al.* (2008a)]. These structural elements are all abstractions of reality and refer to heuristics that are used to facilitate the analysis.

Technology

Technology includes both knowledge and artefacts. This knowledge can be formal such as the intentional output of research, or explicit, embedded in experience-gained competencies [Asheim and Isaksen (2002)]. Artefacts can be both hardware (products, tools and machinery) and software (procedures, processes and protocols) [Bergek *et al.* (2008b)].

Actors

Actors (or organisations) are consciously created formal structures that have an explicit purpose [Edquist (2005)]. In a TIS they are responsible for the stimulation, development and diffusion of innovation [Carlsson and Stankiewicz (1991)]. In newly developed innovation systems, the entry of actors into various stages of the value chain is considered as a fundamental process [Jacobsson *et al.* (2004)]. Agency in the form of individual choices is the main utility of actors and directly affects the performance of the TIS. However, in many cases, the mere presence of actors provides an indication of whether a certain system function is fulfilled (e.g. legitimacy, see Subsection 2.3.2) [Bergek *et al.* (2008b)].

Actors include all entities within the value chain of the innovation system such as firms, users, suppliers, investors, banks, universities research organisations, government bodies, industry associations and interest organisations [Carlsson *et al.* (2002); Jacobsson and Bergek (2004); Bergek *et al.* (2008b)].

Institutions

Institutions are entities that define the environment within which all actors operate, and regulate their interrelations[9] [Edquist and Johnson (1997); Jacobsson and Bergek (2004)].

Formal representations are controlled by judicial systems and include rules or laws that determine and affect the behaviour of the actors such as patent legislation and tax laws [Bergek *et al.* (2008a,b)]. Informal demonstrations are norms and cognitive rules controlled by social systems, including habits, norms, routines and personal values [Edquist (2005); Bergek *et al.* (2008a)].

These normative and cognitive structures provide the patterns of social interaction, define the value base, reduce social uncertainty and structure learning processes [Carlsson and Stankiewicz (1991); Bergek *et al.* (2008a)]. When new technologies emerge, institutional change is fundamental. Consequently, in such cases, competing companies struggle for increased influence not only in the marketplace, but also in the institutional landscape [Bergek *et al.* (2008a)].

Networks

Networks are channels among the system's components created and used to transfer tacit and explicit knowledge and information, financial resources, people, market resources etc. [Lundvall (1992); Niosi (2002); Jacobsson and Bergek (2004, 2006)]. They are an intermediate form of organisation between hierarchies (internal organisation within entities such as firms) and markets [Carlsson and Stankiewicz (1991)]. They emerge when the links that transform a group of separated components into a system are created [Bergek *et al.* (2008b)].

Formal networks are created in order to perform specific tasks including standardization networks, technology platform consortia and public-private partnerships. Informal networks appear and evolve in a less structured way and include buyer-seller relationships, university-industry links, etc. [Bergek *et al.* (2008a)]

Bergek *et al.* (2008a) distinguish two types of networks of equivalent importance for

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[9] In that sense institutions are comparable to *framework conditions* and *innovation infrastructure* (see Subsections 2.2.3 and 2.2.4).

the performance of a TIS: learning and political. They also note that networks (such as alliances or coalitions) may be specific to a certain technology or generic for the broader sector.

2.3.2 Functions of a TIS

Despite the importance of the structural analysis of a TIS, the mere description of the elements poorly represents dynamics and differences across systems [Liu and White (2001)]. Analysis should also focus on the mapping of activities within the TIS in order to understand innovation processes and raise appropriate policy recommendations [Edquist (2005); Hekkert *et al.* (2007b)]. This *functionality* analysis allows for the understanding of the relation between the structure of a system and its performance [Jacobsson and Bergek (2004); Jacobsson *et al.* (2004)].

The main functions of a TIS are the generation, diffusion and use of innovation [Edquist (2005)]. Various scholars have also identified a range of sub-functions or processes that are crucial for the achievement of innovation [Liu and White (2001); Jacobsson and Bergek (2004); Hekkert *et al.* (2007b)]. Thorough reviews of the literature highlight the importance of the analysis of these processes in the understanding of the overall performance of the system [Johnson (2001); Johnson and Jacobsson (2001); Hekkert *et al.* (2007b); Bergek *et al.* (2008a)].

Functional analysis helps to capture the dynamics of what is actually achieved in the system and identifies its strengths and weaknesses. Functions are created and influenced by the different structural elements and by exogenous factors. Policy makers try to strengthen the system and overcome barriers to development by influencing these functions, not by just changing the set-up of the structural components. Functions are interconnected; the fulfilment of one influences the fulfilment of others. Virtuous interactions strengthen the system, while flawed ones may lead to its collapse [Hekkert *et al.* (2007b); Bergek *et al.* (2008a,b)]. The concept of *cumulative causation* explains how the development of a TIS is accelerated by the interaction and mutual reinforcement of system functions [Jacobsson and Bergek (2004); Suurs *et al.* (2009); Suurs and Hekkert (2009)], while the concept of *reverse salients* may explain how failure of just one function might jeopardise the overall performance of the system [Hughes (1993)].

Table 2.1 summarises the key functions as these have been conceptualised by various authors. Recently, there has been a significant overlap in the literature, and differences reside in the particular way of clustering activities [Suurs and Hekkert (2009)]. However, this conceptualisation is only provisional and needs to be verified or falsified by empirical evidence [Edquist (2005)].

The following paragraphs will focus on the description of the eight functions that have been developed and refined by researchers of the Chalmers University of Technology in Sweden. They have been implemented in the analysis of TISs of renewable energy technologies [Johnson (2001); Bergek and Jacobsson (2003); Jacobsson and Bergek (2004); Bergek *et al.* (2005, 2008a,b)]. They have also been confirmed in empirical analyses by researchers from Utrecht University in Netherlands [Negro *et al.* (2007); Hekkert *et al.* (2007b); Suurs and Hekkert (2009)]. Based on the relative consensus on these functions and on their wide application in empirical studies, they have been chosen along with four new ones for the development of indicators for the performance of the BIPV innovation system in this research (see Section 5.2.3).

Development of formal knowledge

This central activity of the TIS concerns the breadth and depth of the knowledge base, and its evolution, diffusion and use within the TIS over time [Bergek *et al.* (2008a,b)].

It includes all types of learning, as they were explained in Section 2.1.3, from formal scientific R&D occurring in universities or within the industry to informal processes including learning-by-using and learning-by-doing [Edquist (2005); Hekkert *et al.* (2007b)]. The latter informal process is also the result of another TIS function, *entrepreneurial experimentation*; however, the main focus of that function is the reduction of uncertainty from those activities, rather than the development of knowledge [Bergek *et al.* (2008a)].

Bergek *et al.* (2008a,b)	Johnson (2001); Johnson and Jacobsson (2001); Bergek and Jacobsson (2003); Jacobsson and Bergek (2004)	Rickne (2000)	Carlsson *et al.* (2004)	Edquist (2005)	Galli and Teubal (1997)	Hekkert *et al.* (2007b)
Development of formal knowledge	Create new knowledge, facilitate information and knowledge exchange	Create human capital	Creating a knowledge base	Provision of R&D, competence building	R&D diffusion of information, knowledge and technology	Knowledge development
Entrepreneurial experimentation	Create knowledge		Promoting entrepreneurial experiments	Creating and changing organizations needed (e.g. enhancing entrepreneurship)		Entrepreneurial activities
Influence on the direction of search	Identify problems. Guide the direction of the search process. Provide incentives for entry. Recognise the potential for growth	Direct technology, market and partner search. Create and diffuse technological opportunities	Creating incentives	Articulation of quality requirements (demand side). Creating/changing institutions that provide incentives or obstacles to innovation		Guidance of the search
Market formation	Stimulate and facilitate the formation of markets	Create market/diffuse market knowledge. Facilitate regulation (may enlarge market and enhance market access)	Creating markets or appropriate market conditions	Formation of new product markets. Articulation of quality requirements (demand side)		Market formation
Development of positive external economies	Facilitate information and knowledge exchange, creation of positive external economies	Enhance networking	Promoting positive externalities, or ‘free utilities’	Networking	Diffusion of information, knowledge and technology. Professional coordination	Knowledge diffusion through networks
Legitimation	Counteract resistance to change	Legitimize technology and firms		Creating/changing institutions that provide incentives or obstacles to innovation	Design and implementation of institutions. Diffusion of scientific culture	Creation of legitimacy - Counteract resistance to change
Resource mobilisation and Materialisation	Supply resources	Facilitate financing. Create a labour market. Incubate to provide facilities, etc. Create and diffuse products (materials, parts, compl. products)	Creating resources (financial and human capital)	Financing of innovation processes, etc. Provision of consultancy services. Incubation activities	Supply of scientific and technical services	Resources mobilisation

Table 2.1: TIS functions within the literature (adapted from Bergek *et al.* (2008a,b)).

Entrepreneurial experimentation

Entrepreneurial experimentation is the main source of reduction of uncertainty, a fundamental feature of technological and industrial development. This uncertainty in terms of markets, applications and technologies is present throughout the evolution of a TIS [Rosenberg (1996)].

Feedback from different actors improves the knowledge base and thus decreases uncertainty [Raven (2005)]. Despite the inevitable failures, the presence of many entrepreneurs initiates a social learning process, transforming knowledge into concrete actions and business opportunities [Kemp *et al.* (1998); Junginger *et al.* (2010)]. In this sense, this TIS function is similar to the *development of formal knowledge*, however it refers to the tacit dimension of knowledge [Polanyi and Sen (1983)], the one gained in a more exploratory, applied and varied way [Bergek *et al.* (2008b)]. Experimentation occurs not only in small emerging firms but also in established diversifying companies.

Materialisation

Materialisation refers to the development and investment in artefacts including products, production plants and processes, prototypes, components and physical infrastructure [Bergek *et al.* (2008b)]. It can be considered as the third dimension of knowledge development (along with the *development of formal knowledge* and tacit learning from *entrepreneurial experimentation*), the one embedded in physical outputs.

This function was not included in the first conceptualisations of the TIS [Bergek *et al.* (2005, 2008a)], but was introduced later in Bergek *et al.* (2008b).

Influence on the direction of search

This TIS function involves the level, sources and directionality of influence on the knowledge development processes. Although it is closely related to the function of *legitimation* (see below), this influence is linked to legitimacy levels not only of the system in focus, but also of other competing TISs [Bergek *et al.* (2008a)].

The first category of such influences concerns the combined effect of incentives and pressures on external actors to direct their investments and search towards the TIS. Changes in the socio-technical landscape [Geels (2004)], e.g. an announcement of a policy goal, may increase the appeal of an emerging technological sector, increasing its growth potential and triggering *resource mobilisation* towards it. Other examples of such sources include assessments and expectations for future opportunities, regulations, articulation of demand from leading customers, technical bottlenecks and other industry crises [Bergek *et al.* (2008a)].

Another form of influences upon the direction of search activities is the internal to the TIS guidance of the technological paradigm [Dosi (1982)]. This influence on the 'search heuristics' includes the selection of certain technologies, markets and business models and affects mainly the problem-solving community of the TIS, particularly those involved in R&D. [Bergek *et al.* (2008a,b)].

Market formation

Markets in emerging TISs may be underdeveloped or even non-existent. Incumbent technologies may block the access of novel products to the market [Hekkert *et al.* (2007b)]. Additionally, these novel products usually lack the technical advantages that would make them competitive in the free market. Therefore, artificial protective spaces are needed to foster their development. Protection may come in the form of technological protection where niche markets (segments in which novel technologies have a competitive advantage) are identified [Schot *et al.* (1994)], or institutional protection where policy-makers create a usually short-term competitive advantage.

The formation of markets is a long process that may span several decades and includes three stages, from 'nursing' markets through 'bridging' to 'mass' markets [Kemp *et al.* (1998); Andersson and Jacobsson (2000); Bergek *et al.* (2008a)]. A similar evolutionary process is conceptualised as *socio-technical transitions*, as described in Geels (2004) (see Section 3.3).

Resource mobilisation

This function quantifies the inputs mobilised to assist the development of a TIS. It refers to the human capital including skills developed through scientific and technological education, the financial capital injected including venture capital and research grants, and complementary assets from other sources than suppliers and users including products, services and network infrastructure [Bergek *et al.* (2008a,b)].

The function is related to the 'factor conditions' as described in Porter (1990). However, it is not as universal, referring to the overall infrastructural facilities that a nation provides to innovation systems, but rather focuses on the TIS-specific resources.

Legitimation

This function reflects the level of legitimacy of a TIS, namely the alignment between expectations created around a technology and its actual performance. It relates to the social acceptance of the new technology, as well as the compliance with existing regulations. It is important for the mobilisation of resources and the development of market demand and political strength [Bergek *et al.* (2008b)].

New entrants to the market may face significant barriers posed by incumbent actors with vested interests. In such cases, advocacy coalitions may become catalysts that foster the legitimation process that will lead to the integration into, or even the overthrowing of the existing regime [Hekkert *et al.* (2007a); Bergek *et al.* (2008a)].

Development of positive externalities

This function refers to benefits gained by a TIS resulting from developments in external industries that may be proximal not only geographically but also in terms of knowledge space and value chains shared with the TIS. Such 'free utilities' [Carlsson *et al.* (2002)] include spillovers in terms of knowledge and technology, uncertainty reduction, strengthened legitimacy, all of which are fundamental for the development and growth of a TIS [Bergek *et al.* (2008a,b)].

Central to the development of positive externalities is the entry of new firms. New entrants trigger *knowledge development*, increase the overall *entrepreneurial experimentation* and TIS *legitimacy*, reduce technological and market uncertainty, thereby strengthening the functions *influence on the direction of search* and *market formation*. Hence, this function is not independent, but rather indicates the collective dimension and the strengthening dynamics of the other TIS functions [Bergek *et al.* (2008a)].

2.3.3 Inducement and Blocking mechanisms

TIS functions describe *how well* a system performs with respect to the goal of achieving innovation. However, their analysis is not sufficient for the understanding of the factors that affect the functioning dynamics of the system. These *inducement* or *blocking* mechanisms may relate to the structural components of the system or the wider context surrounding it[10] [Bergek *et al.* (2008a)].

The characterisation of these mechanisms as either inducement or blocking contains normative features, since an overall function of the TIS is implied. Therefore, their identification is important from a policy-making perspective. Fig. 2.13 illustrates how inducement and blocking mechanisms affect the functions of a system, as well as give rise to specific policy issues.

Bergek *et al.* (2008a) identify three types of blocking mechanisms:

- **Advocates** of the new technology may be weak and fail to align institutions. Insufficient levels of *legitimacy* then lead to limited *market formation* and poor overall functionality of the system.
- **Customers** may have underdeveloped competencies, leading to poor demand levels and affecting the dynamics of *market formation*, *influence on the direction of search* and *entrepreneurial experimentation*.
- **Networks** may either be poor and fail to aid new technologies or very tight and drive out potential suppliers and customers through *lock-in* mechanisms.

Although the inclusion of these mechanisms in the functional analysis offers a connection of the internal dynamics with the environment of the TIS, the possible insights are still limited. Particularly in sectors where the phenomenon of technological

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[10] *Context* here is similar to the *regime* and *landscape* concepts of the Multi-Level Perspective (see Section 3.3) [Geels (2004)].

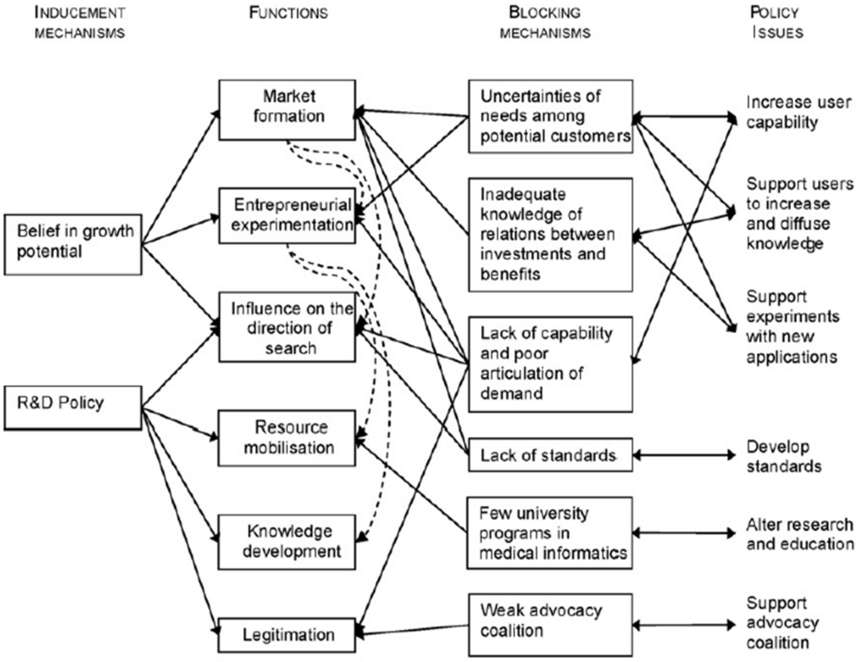

Figure 2.13: Example of inducement and blocking mechanisms as well as policy issues from the 'IT in homecare' TIS [Bergek *et al.* (2008a)].

lock-in is prominent, including the sustainable energy sector, the influences from the socio-technical environment play a substantial role, and need to be further analysed [Gross *et al.* (2012)].

2.3.4 Evolution of a TIS over time

In line with earlier evolutionary conceptualisations that describe innovation as a cumulative process, the growth of an emerging TIS can be divided for analytical purposes in three distinct development phases: formative, growth and steady phase. Each stage of the system evolution requires focus on different functions and respective policy implications [Bergek *et al.* (2008a)]. Later phases have a greater degree of stability and resistance to change due to stronger interactions among the system elements [Foxon (2003)].

The **formative phase** is characterised by three structural processes: entry of firms into the system, formation of networks and markets and institutional alignment [Jacobsson and Bergek (2004)]. The underdeveloped configuration allows for significant exogenous influences, creating a high degree of uncertainty. Therefore, at this phase the understanding of the blocking and inducement mechanisms is very important for further development of the system [Bergek *et al.* (2008a)].

Entrepreneurial experimentation is probably the most crucial function at this phase. A variety of experimenting firms helps the *development of knowledge*, which is steered by the *direction of search*. Finally, a certain degree of *legitimacy* and *resource mobilisation* is needed to help the activities of the firms.

A TIS enters its **growth phase** (or expansion phase) after a technological breakthrough or institutional change that 'changes the evolution gear' of the system [Bergek *et al.* (2008a)]. During this self-sustained evolution phase, all components are in place [Carlsson (1997)] and give rise to virtuous circles, where more endogenous factors are strengthened and the system can overcome blocking mechanisms more easily [Sandén and Jonasson (2005)].

Throughout its growth phase a TIS requires a high degree of *resource mobilisation*, *materialisation* and *legitimation*, and therefore policy interventions should focus on triggering these functions.

Finally, a mature TIS reaches a **steady phase**, where it is stable against external forces. Nevertheless, this stability may give rise to lock-in mechanisms preventing entry of new actors and further evolution of the system [Unruh (2000)].

2.3.5 System failure and policy implications

Insights from early models of the innovation process led to a number of rationales for policy intervention regarding its support. Most of these rationales are based on the existence of *market failures*, i.e. economic arrangements that are not efficient, or Pareto-optimal[11] [Bator (1958); Watson (2008)]. Two examples of such market failures from the sustainable energy sector arise from the non-internalisation of social costs related to carbon emissions, causing a disadvantage to expensive low-carbon technologies, and the tendency of the private sector to under-invest in R&D and public goods such as energy security, due to the limited returns of such investments. Addressing these market failures, governments have developed policy frameworks that set a price on

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[11] A state of allocation of resources and services is Pareto-optimal when it is impossible for any market participant to become better-off without making at least another participant worse-off [Musgrave (1959)].

carbon emissions and provide public funding to research activities [Watson (2008)].

More recently and in line with the systemic conceptualisation of innovation, various authors have identified potential system imperfections that might impede the process and require external intervention through policy [Carlsson and Jacobsson (1997); Smith (1997); Edquist *et al.* (1998); Smith (1999); Johnson and Gregersen (1995); Jacobsson and Bergek (2011)]. Klein Woolthuis *et al.* (2005) distinguish four categories of such *system failures*:

- *Infrastructural failures* occur when the knowledge and communications infrastructure is unreliable [Smith (1999); Edquist *et al.* (1998)].
- *Institutional failures* can either be due to hard/formal institutional mechanisms (e.g. technical standards, regulations or the wider legal system) [Edquist *et al.* (1998); Johnson and Gregersen (1995)] or to soft/informal norms and values [Carlsson and Jacobsson (1997); Smith (1999)].
- *Interaction failures* can be caused by either weak networks that do not allow for the full exploitation of complementarities among partners or by very strong networks that might cause lack of flexibility and over-dependence on a non-optimal dominant design [Carlsson and Jacobsson (1997); Klein Woolthuis *et al.* (2005)].
- *Capabilities failures* occur when system actors lack the competences, the capacity or the resources to innovate or adapt to new technological developments [Smith (1999); Klein Woolthuis *et al.* (2005)].

The identification of these system failures gives rise to more concrete rationales for public support and intervention [Klein Woolthuis *et al.* (2005)]. However, both the evolution path outlined in Section 2.3.4 and this categorisation of system failures do not imply the presence of one development pattern or an omnipotent policy instrument that could be applied on all innovation systems [Bergek *et al.* (2008a); Jacobsson and Bergek (2011)]. On the contrary, the functional dynamics approach recognises the diversity of challenges that different technologies face over time. Successful intervention adapts to the various development phases and allows for continued monitoring and revision [Juma and Clark (2002); Foxon *et al.* (2005)].

The systemic understanding of innovation also suggests a similar approach to policy intervention. Since the various elements of the socio-technical system co-evolve and affect each other, it follows that policy framework should also reflect this dynamic and systemic nature [Juma and Clark (2002); Foxon *et al.* (2004)].

The most common system failure in the sustainable energy sector is the phenomenon of technological lock-in (see also Paragraph 2.1.3) [Unruh (2000)]. Many parts of the energy sector comprise long-standing assets, infrastructure and behaviours that favour incumbent technologies. Options that challenge the technical and institutional configuration have limited access to political and economic resources and will be harder to develop and deploy [Watson (2008)].

2.3.6 TISs of renewable energy technologies

The TIS framework has been used extensively for the study of the development and diffusion of emerging renewable energy technologies. Several researchers have recognised the increasing role of such technologies in the international energy mix and have identified innovation as a key element for their development [Toman (1998); Menanteau *et al.* (2003); Tsoutsos and Stamboulis (2005)]. Many also highlight the limited understanding of these innovation processes and the need for new theoretical frameworks that study the transformation of the energy regime [Jacobsson and Johnson (2000); Jacobsson *et al.* (2004); Foxon *et al.* (2005); Hekkert *et al.* (2007a)].

Many of these studies adopt a national perspective to analyse the country-specific characteristics that affect the diffusion potential of renewable energy systems [ICCEPT/E4tech (2003); Kamp *et al.* (2004); Foxon *et al.* (2005); Negro *et al.* (2008)], while others adopt a technological perspective [Bergek and Jacobsson (2003); Jacobsson and Bergek (2004); Negro *et al.* (2007); Hekkert *et al.* (2007a)].

A common finding in these studies is the identification of *legitimation* as one of the most important factors for the success of an emerging energy technology [see particularly Jacobsson *et al.* (2004)]. Establishing social legitimacy by developing a shared vision among industry actors, the research community and the government is key to create positive momentum for the novel technology [Foxon *et al.* (2005)]. Other inducement mechanisms are stimulation of technological variety and experimentation in the early stages of system development and policies that encourage market formation and feedback loops [Bergek and Jacobsson (2003); ICCEPT/E4tech (2003); Jacobsson *et al.* (2004)]. Assessing the cogeneration technology in the Netherlands, Hekkert *et al.* (2007a) highlight the importance of the fulfilment of all innovation system functions for the successful adoption of the technology.

Factors that impede the development of successful renewable energy innovation systems have also been identified by scholars from the Chalmers University of Technology in Sweden. They include technological, economic and market uncertainty, weak connectivity, lack of legitimacy and absence of clear and consistent policy [Jacobsson and Johnson (2000); Jacobsson *et al.* (2004)]. The latter has also been identified as the main obstacle for the diffusion of biomass gasification technology in the Netherlands [Negro *et al.* (2008)]. In the case of the UK, Foxon *et al.* (2005) highlight the difficulties in moving technologies from the pre-commercial phase to full commercialisation. This may be due to insufficient financing, inappropriate policy, lack of certain skills and the hesitancy of entrepreneurs to scale-up these high-risk technologies [Foxon *et al.* (2005)].

2.3.7 Potential and limitations of the TIS approach

Throughout its various applications, the TIS concept has demonstrated a high potential as an analytical tool for the understanding of technological change. The main strength of the systems-perspective is the understanding of innovation as a dynamic process where a network of agents interact for the development, diffusion and utilisation of a new technology. It has also demonstrated the ability to identify various system weaknesses and suggest policy interventions. In this research it will provide the guidelines for the development of indicators that will be used in the assessment of the emerging BIPV sector (see Section 5.2).

An early criticism of the TIS approach was the lack of standardised analytical methods that led to inconsistencies across studies in system delineation and characterisation of system performance [Carlsson *et al.* (2002); Chang and Chen (2004)]. Responding to this criticism, later contributions [Hekkert *et al.* (2007b); Bergek *et al.* (2008a)] developed a prescriptive framework for the analysis of the structural components and the functional performance of the system (see Sections 2.3.1 and 2.3.2).

The TIS model has also been criticised for being inward-oriented and not paying sufficient attention to the system's context. As a consequence, the framework is unable to address externalities adequately, ignoring for example strategic intervention from the incumbent actors or emerging technologies outside the system that could work in a complementary way to the system in focus [Markard and Truffer (2008a)]. Furthermore, TISs are conceptualised in a rather static way and transitions between different phases of development or even from one system to another are poorly explained [Bergek *et al.* (2008a); Winskel *et al.* (2014a)]. The analysis focuses on the performance of the system, neglecting its dynamics that may lead to changes in the socio-technical configuration [Geels (2004)]. This drawback will be addressed in this research by the inclusion of insights from the Multi-Level Perspective, another conceptual framework that has a more dynamic and outward-oriented approach, highlighting the influence of other technological systems to the TIS in focus (see Section 3.3)

Another major criticism to the innovation system approach has been the limited ability to capture the various forms of learning processes that may differ significantly depending on the technology in focus [Winskel *et al.* (2014a)]. It also fails to capture the knowledge creation processes that occur within firms, which can be critical in emerging industries [Christiansen and Buen (2002); Marigo (2009)]. In order to address these issues, the analytical framework that was developed for this research integrates concepts from the Business Management literature including corporate strategies and business model innovation (see Section 4.1).

Finally, another weakness of the TIS framework that has been identified in the literature is that it mostly relies on ex-post qualitative analysis and fails to produce quantitative metrics that could be used effectively in policy-making [Marigo (2009); Winskel *et al.* (2014a)].

2.4 Summary and conclusions

Innovation is an important source of economic growth and a competitive advantage for nations. However, normal market rules do not always facilitate innovation, particularly the development of technologies that may initially disrupt the incumbent socio-economic configuration, but offer a more efficient configuration in the long-run. This failure of conventional economic models has led to the development of frameworks that highlight the potential of the innovation process and intend to capture its dynamics. Often times, these models contain normative features, providing the rationale for policy intervention and financial support.

This chapter provided an overview of innovation conceptualisations from early linear models to the inclusion of insights from various disciplines including evolutionary economics and social sciences. Subsequent systemic perspectives understand innovation as a complex process involving feedback loops linking several actors and institutional structures.

Technological Innovation Systems (TIS) is the prevailing approach within the innovation-systems literature for the analysis of emerging technologies. The developed methodology offers a prescriptive framework, providing indicators for the characterisation of the structure, the performance and the factors that affect its development. The assessment of these indicators gives rise to insights that can be used to inform policy-making for the support of the innovation system or its steering towards certain directions.

The TIS framework has been used extensively for the analysis of renewable energy technologies. However, the framework in its current form is a rather static approach, focusing on the performance of innovation systems, rather than potential changes and transitions to more efficient socio-economic configurations. It is also inadequate to address pressures external to the TIS in focus, including competition and complementarities with other sustainable technologies, which are of significant importance in the case of cross-sector application fields. On the other hand, it offers a rather structure-oriented perspective, underestimating the importance of individual choices and responses to change within firms, and failing to capture micro-economic dynamics and business model innovation. Addressing these conceptual deficiencies, the analytical framework developed in this research will explore the potential integration to the TIS approach of insights from other literature strands, including Transition Theory and the Business Studies.

Chapter 3

Transitions and the Multi-Level Perspective

Introduction

The literature on technological transitions is the second major strand of conceptual and empirical work that has been developed for the study of technological change.

If the Innovation System approach addresses the *emerging technology perspective*, where the focus is on identifying patterns behind the drivers and barriers for the successful deployment of a new technology or product, then the Technological Transitions approach addresses a wider *socio-technical perspective*, investigating the factors that could possibly lead to a reconfiguration or even substitution of the established sectoral set-up [Markard and Truffer (2008a); Geels (2002)].

Socio-technical transitions are major technological transformations that lead to a fundamental shift in a socio-technical configuration[1] [Geels (2002)]. These do not include only technological changes, but also broader changes along several dimensions: organisational, institutional, economic, cultural etc. They involve a range of actors and span significant time-periods. Along with the technical and institutional structures there is a change in users' practices and perceptions [Markard *et al.* (2012)]. Historical examples of such transitions are the shift from carriages to automobiles [Geels (2005)] and the introduction of sewer systems [Geels (2006a)].

Three main theoretical approaches that have been developed within transition studies are Transitions Management (TM), Strategic Niche Management (SNM) and Socio-Technical Scenarios. After an introduction to the basic concepts relevant to the socio-technical system in Section 3.1, these approaches will be reviewed in Section

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[1] The concept of a *socio-technical configuration* where firms and technologies are embedded within wider social and economic configurations was introduced in [Rip and Kemp (1998)].

3.2. Section 3.3 focuses on the Multi-Level Perspective (MLP), a context-oriented framework for the analysis of socio-technical transitions based on the SNM approach, which links dynamics at various levels and offers a conceptual complement to the rather inward-oriented TIS. The Section also reviews implementations of the MLP on cases from the sustainable energy sector and finally, discusses the strengths and weaknesses of the MLP.

3.1 Basic concepts

In this Section some basic socio-technical concepts are introduced in order to provide a better understanding of the theoretical approaches that will be discussed later.

3.1.1 Socio-Technical Systems

The first implication of widening the analytical perspective in order to include the societal domain is the shift of the unit of analysis from the sectoral or technological system of innovation to the socio-technical system (ST-system). ST-systems are defined in an abstract sense as the linkages between elements necessary to fulfil societal functions [Geels (2004)]. In this approach, the creation, diffusion and utilisation of technology are secondary yet crucial sub-functions that contribute to the overall purpose[2].

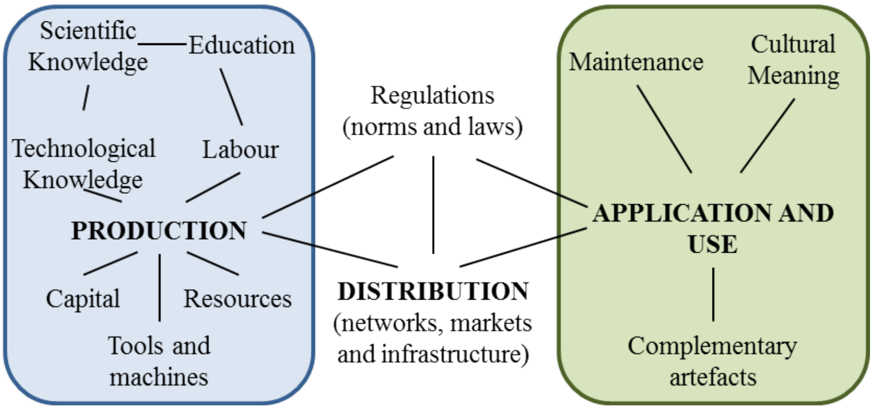

Figure 3.1: The basic components of a socio-technical system (adapted from Geels (2004)).

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[2] A similar sociology-influenced approach is the *large technical systems* (LTS) approach. Apart from physical artefacts, the components of an LTS include organisations, natural resources, scientific elements, legislative artefacts and university teaching programmes [Hughes (1987)].

The inclusion of a higher number of contributing inputs (compared to other approaches within Innovation Studies) for the analysis of technological change has both positive and negative consequences. Although it offers a more comprehensive framework that is less susceptible to externalities, it is very operationally complex and theoretically heavy, thus compromising its applicability on real case-studies, unless the socio-technical system is successfully bounded and delineated [Geels (2004); Markard and Truffer (2008a)].

3.1.2 Socio-technical Regime

A central concept to the transitions research is that of regimes. A *technological regime* as it was first conceptualised in the literature of evolutionary economics by Nelson and Winter (1982), referred to the aligned and coordinated activities of different groups within a sector. This coordination was based on organisational and cognitive routines embedded in the practice of actors [Nelson and Winter (1982); Geels (2002); Markard *et al.* (2012)].

This notion was later widened by Rip and Kemp (1998) to include insights from the history and sociology of technology [Bijker *et al.* (1987); Hughes (1987)]. The new definition of a technological regime highlights demand aspects and societal issues [Kemp *et al.* (2001)]:

> A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures [Rip and Kemp (1998)].

This conceptualisation of a regime as a coherent set of rules underlines the institutional character and the stability of these aligned search heuristics, production processes and user practices and does not include physical elements [Markard and Truffer (2008a)]. Other scholars have further extended the definition to include infrastructures, artefacts and actor groups[3] [Hoogma *et al.* (2002); Konrad *et al.* (2006); Verbong and Geels

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[3] This perspective has significant conceptual similarities to the Innovation System approach (cf. Section 2.2) [Markard and Truffer (2008a)].

(2007)].

Socio-technical regimes as they were defined in Geels (2002) exclude physical components, thus conceptually differentiating regimes from systems which are considered to include these elements. The regime focus is narrowed to the semi-coherent sets of rules embedded in the activities of social groups such as engineers, scientists, suppliers, financiers, users, policy makers etc. (see Fig. 3.2a). These sets are linked together and therefore aligned within the ST-system. This meta-coordination is responsible for the stability of the socio-technical regime (see Fig. 3.2b) [Geels (2004)].

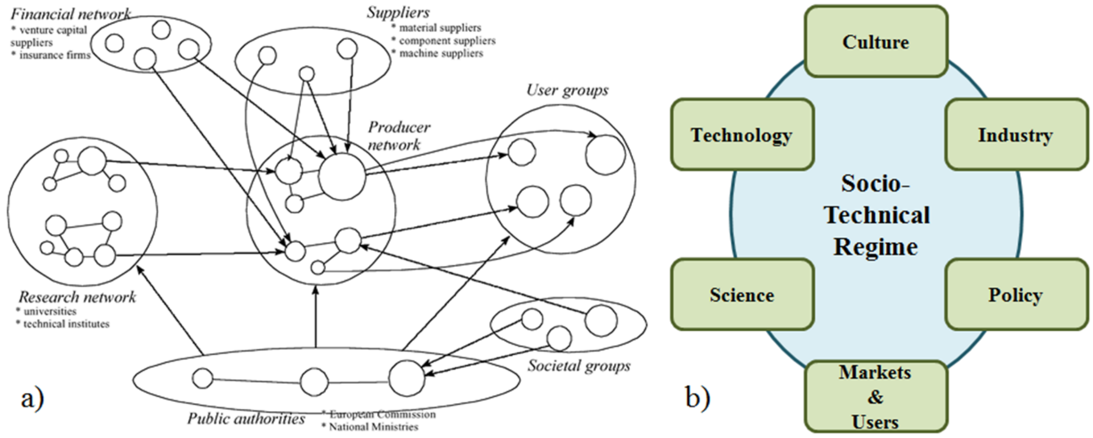

Figure 3.2: a) The multi-actor network involved in socio-technical regimes [Geels (2002)] and b) Meta-coordination through socio-technical regimes (adapted from Geels (2004)).

Although an exhaustive overview of all the possible sets of rules is impractical, it is useful for analytical purposes to distinguish three main categories [Scott (2001); Geels (2004)]:

- *Regulative* rules include formal, explicit regulations, usually with a national breadth, which constrain behaviour and interactions (e.g. patents, contracts, trade laws, tax structures).
- *Normative* rules relate more to societal norms (e.g. values, expectations, codes of conduct).
- *Cognitive* rules are more culturally embedded and refer to the ways actors perceive reality (e.g. language and jargon, beliefs, priorities).

3.1.3 Technological Trajectories

The basic idea behind the socio-technical regime concept is that the aligned practices of different groups within a sector impose a certain logic and direction to incremental change along established *technological trajectories*[4] [Dosi (1982)].

Building on previous contributions in the field of long-wave theory [Freeman and Louça (2001)], Geels (2004) distinguishes six subgroups within a socio-technical regime: science, technology, industry, culture, policies and markets[5] (see Fig. 3.3). These subgroups develop following steps along a path-dependent direction. The accumulations of these steps lead to technological trajectories. Understanding the transition dynamics within ST-systems involves the examination of the interdependencies and the co-evolution of these trajectories [Geels (2004)].

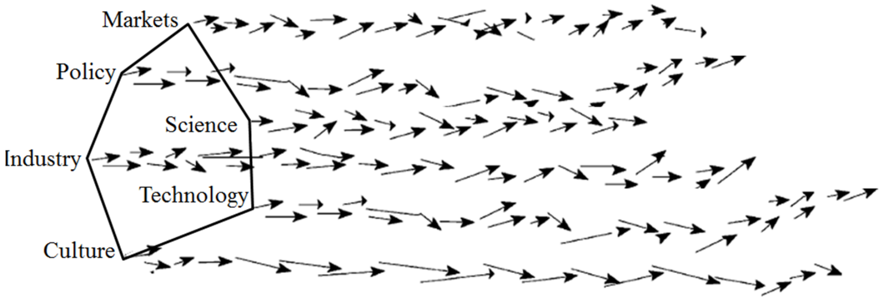

Figure 3.3: Alignment of trajectories in different sub-groups of a socio-technical regime (adapted from Geels (2004)).

3.1.4 Niches

Another key concept within transition studies is that of *niches*. These specific markets or application domains have been described as protected spaces or incubation rooms, where new technologies or socio-technical practices develop insulated from market selection pressures that are normal at the regime level [Kemp *et al.* (1998); Schot (1998)]. Niches shield innovations against premature rejection until they gain momentum and are robust enough to compete with established technologies in unprotected market conditions,

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[4] This notion is in line with the ideas of path dependency and lock-in which were explained in Subsection 2.1.3.

[5] Previous inclusion of infrastructure as a seventh dimension of the regime (see Geels (2002)) is not consistent in later literature. The discussion on the definition of regimes and their delineation from other analytical concepts is ongoing.

potentially leading to a regime shift (see Fig. 3.4) [Geels (2006a); Smith *et al.* (2014)]. Later approaches challenged this largely bottom-up perspective and highlighted the dynamic interaction of niches with prevailing regimes and how this affects their growth and stabilisation or decline over long periods of time [Raven (2006); Geels (2006a); Schot and Geels (2008)].

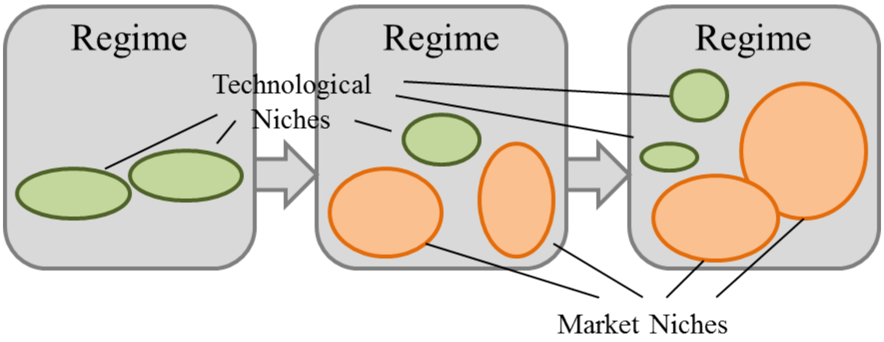

Figure 3.4: From technological to market niches and regime shifts (adapted from Weber *et al.* (1999); Schot and Geels (2008)).

While regimes are usually the spaces where incremental change occurs (as was explained in Subsection 3.1.3), radical innovations take place mainly in niches. The rules in niches are less articulated and clear, creating uncertainty and allowing for experimentation with technological designs and search heuristics [Geels (2004)]. Radical novelties emerge as 'hopeful monstrosities' that initially have low technical performance, are expensive and often cumbersome [Mokyr (1990)]. Niches offer protected domains for such novelties to create knowledge through learning processes, develop social networks and articulate expectations[6] [Geels (2002)]. Based on these expectations, governments and other actors may accept disadvantages and invest resources to develop such 'hopeful monstrosities' [Schot and Geels (2008)].

Depending on the particular selection criteria, scholars have distinguished two types of niches. *Technological niches* are deliberately created by actors, supported by institutions and often include policy-makers and entrepreneurs [Geels (2005)]. They are societal experiments of new technologies outside the lab in a user context [Schot *et al.* (1994)]. The potential advantages of these technologies are neither certain nor well articulated among involved actors [Hoogma *et al.* (2002)]. In the case of PV technologies,

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[6] More on these niche-internal processes on the Strategic Niche Management Subsection 3.2.1.

such niches have been created by governmental programmes in the form of investment grants or subsidies (e.g. feed-in-tariffs for building-integrated PV) [Markard and Truffer (2008a)].

These 'proto-markets' may trigger the development of *market niches* (see Fig. 3.4), where technology design and user demands have been stabilised [Schot and Geels (2008)]. In these niches, where both producers and users recognise the potential of the new technology, regular market selection criteria prevail. However, these may deviate significantly from usual practices, due to particular application contexts or user preferences [Hoogma *et al.* (2002)]. Using again the example of solar PV technologies, two distinct market niches that have been developed are the off-grid applications for electrification of remote locations, and the group of pioneering customers who were willing to install panels on their roofs without any financial subsidy despite the extra costs [Markard and Truffer (2008a)].

Market niches should also be distinguished from local socio-technical projects. Instead, they should be conceptualised as the aggregate progression of such projects that lead to the emergence of a global community that shares cognitive, formal and normative rules (see Fig. 3.5) [Raven (2005); Schot and Geels (2008)]. This *global niche level* may involve several niches that reinforce each other through mutual influences [Geels and Raven (2006)].

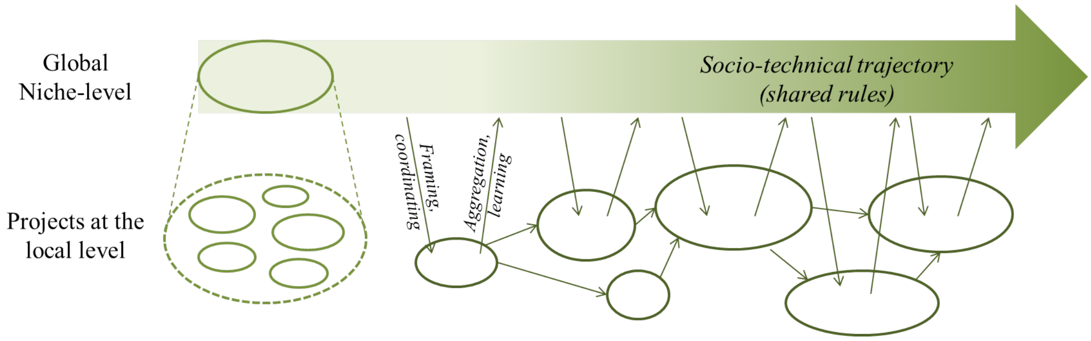

Figure 3.5: Local projects, global niche-level and the emergence of a global niche trajectory from local projects (adapted from Geels and Raven (2006)).

3.1.5 Landscape

In Transition Studies, the *landscape* concept represents all the external processes and factors that affect both regimes and niches. These background variables, which are largely independent, form the environment of the socio-technical system and channel the transition processes [Kemp and Rotmans (2005)]. Examples of such factors include economic growth, environmental problems, oil prices, wars, cultural and normative values etc. [Geels (2002)].

Socio-technical landscapes add deeper structuration than regimes, providing 'gradients' for action. They are more resistant to change and are not influenced by the outcome of the innovation processes in the short to mid term basis [Geels (2004); Markard and Truffer (2008a)]. However, landscapes do change, though more slowly than regimes [Geels (2002)].

3.2 Transition Studies

Within the literature of Transition Studies, three main theoretical streams can be identified: Strategic Niche Management (SNM) (along with its contextualised framework, the Multi-Level Perspective - MLP), Transition Management (TM) and Socio-technical Scenarios [Foxon *et al.* (2010)]. The first two focus on the governance of ongoing transitions, while the latter focuses on creating future visions for technological change.

3.2.1 Strategic Niche Management

Strategic Niche Management (SNM) is a form of reflexive governance that involves the deliberate creation, development and controlled phase-out of protective spaces (niches) in order to trigger shifts at the regime level [Schot and Geels (2008); Markard *et al.* (2012)]. These niches are considered to be crucial for the understanding of the desirability of new technologies and for bridging the 'valley of death' between R&D and market diffusion by enhancing their development and rate of application [Schot *et al.* (1994); Kemp *et al.* (1998); Schot and Geels (2008)].

Although SNM has a theoretical basis in evolutionary economics acknowledging the concepts of variation, selection and protection, it assumes that these processes are not blind, but directed to some extent [Schot and Geels (2008)]. Borrowing insights from the Social Construction of Technology (SCOT) approach [Pinch and Bijker (1984); Bijker *et al.* (1987)] and the sociology of expectations [Brown and Michael (2003); Borup *et al.* (2006)], SNM describes technological change as a socially enacted process where three operations occur [Kemp *et al.* (2001); Hoogma *et al.* (2002); Verbong *et al.* (2008); Schot and Geels (2008)]:

- The articulation of shared visions and expectations that attract attention, legitimate niche protection and nurturing and steer the learning processes.
- Learning at multiple dimensions (e.g. technical, market, cultural and policy) and of multiple forms (e.g. learning-by-doing, using and interacting).
- Building of social networks that facilitate interactions and provide resources.

These niche-internal processes are crucial for its successful development from a technological to a market niche, and its potential incorporation in the socio-technical regime (see also Fig. 3.4). Niches are not inserted by governments but rather emerge through collective enactment. Although they cannot be controlled, they can be modulated and steered by societal groups of users acting within the niche [Schot and Geels (2008)]. Governmental policy may contribute to this process by setting up experiments with a number of new technologies. Such policy consists of five phases [Kemp *et al.* (1998)]:

- *Choice of the technology.* The new technology has to be able to solve the social problem that it is called for, demonstrate technological opportunities, exhibit increasing returns over time, be compatible with the existing institutional configuration and be attractive in certain applications.
- *Selection of the experiment.* The setting of the experiment should be selected in a way that the advantages of the new technology are more prominent than its disadvantages.
- *Set-up of the experiment.* The right balance between protection and selection pressures needs to be found, with a focus on the factors that hinder the market diffusion of the new technology.

- *Scaling up.* The extent of policy support at this phase is crucial.
- *Breakdown of protection* when it is no longer needed, or when the prospects for the new technology are dim.

Although the applicability and success of SNM as a management tool has yet to be tested in real cases, there are several studies that show that it can be a useful ex-post analytical framework[7]. Most of the criticism towards the SNM approach highlighted its focus on the niche-internal processes and the disregard of external factors that are often responsible for regime transformations [Schot and Geels (2008)]. This led to the development of the Multi-Level Perspective (MLP) which contextualised the SNM model and linked niche-internal processes with contextual factors (see Section 3.3).

3.2.2 Transition Management

Transition Management (TM) is a similar approach to SNM that also promotes the role of active intervention. TM scholars argue that in contrast to conventional policy-making that focuses on short-term and mid-term goals, TM incorporates long-term processes more actively in policy development [Meelen and Farla (2013)]. It provides a prescriptive, participatory, practice-oriented model for steering transitions towards sustainable directions [Kemp and Loorbach (2006); Loorbach and Rotmans (2010)]. TM is a theoretical combination of technological transitions with complex systems theory and governance approaches [Smith *et al.* (2005); Markard *et al.* (2012)]. According to TM, *sectors* are conceptualised as complex adaptive societal systems and *management* as an evolutionary reflexive governance process [Nill and Kemp (2009)].

In TM activities may be of three types [Raven *et al.* (2010)]:

- **Deepening** activities aim at maximising learning from experiments.
- **Broadening** activities extend the applicability of an experiment to different contexts.
- **Scaling** activities aim at transferring the technology from the niche into a higher (regime) level.

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[7] For an account of such studies see Schot and Geels (2008).

Furthermore, measures are taken at three levels [Rotmans *et al.* (2001); Loorbach (2007); Meelen and Farla (2013)]:

- At the **strategic level** there is the creation of *transition arenas*, in which actors work together on long-term visions and of different transition paths.
- At the **tactical level** there is the definition of a *transition agenda* with intermediate objectives. Measures at this level focus on the preparation and adaptation of the socio-technical regime to the introduction of a new technology from a niche.
- At the **operational level** experiments are carried out. These experiments should be in line with the vision and the transition paths defined at the higher levels [Loorbach (2007)].

TM differs from SNM in that it highlights the importance of creating long-term visions before triggering actual experimentation [Rotmans *et al.* (2001); Kemp *et al.* (2007); Loorbach (2007)]. Although SNM develops an evolutionary approach that uses socio-technical diversity to overcome lock-in mechanisms, TM suggests a more ambitious approach based on goal-oriented modulation. However, it could be argued that such an approach is less applicable, having little real influence [Schot and Geels (2008)].

3.2.3 Socio-technical Scenarios

A third theoretical strand within Transition studies along with TM and SNM, is the *socio-technical scenarios.* Similarly to the transition pathways approach (see Subsection 3.3.1), these scenarios describe transitions by exploring links among multiple technological options, strategies and behaviours of stakeholders [Elzen *et al.* (2002)].

Elaborating on the scenarios approach, and adding elements from innovation systems and co-evolutionary research, Foxon *et al.* (2010) describe a methodology for the development of transition pathways to sustainable energy systems, based on three elements:

- Characterisation of the existing energy regime, including its internal tensions and landscape pressures.
- Identification of dynamic processes at the niche level.

- Specification of interactions that give rise or influence transition pathways.

The framework has also been applied for the study of potential transitions to a more sustainable electricity sector [Elzen *et al.* (2002); Hofman *et al.* (2004); Elzen *et al.* (2004)].

3.3 The Multi-Level Perspective for socio-technical transitions

The Multi-Level Perspective (MLP) is an analytical framework based on the SNM approach used to study long-term historical transitions. It explains technological transitions as the interplay of dynamics at three different levels: niche, regime and landscape (as were outlined in Subsection 3.1.1), which can be understood as a nested hierarchy (see Fig. 3.6) [Geels (2002); Markard and Truffer (2008a)]. As a theoretical framework, MLP can be considered a hybridisation of Science and Technology Studies and Evolutionary Economics [Geels (2002); Coenen *et al.* (2012)].

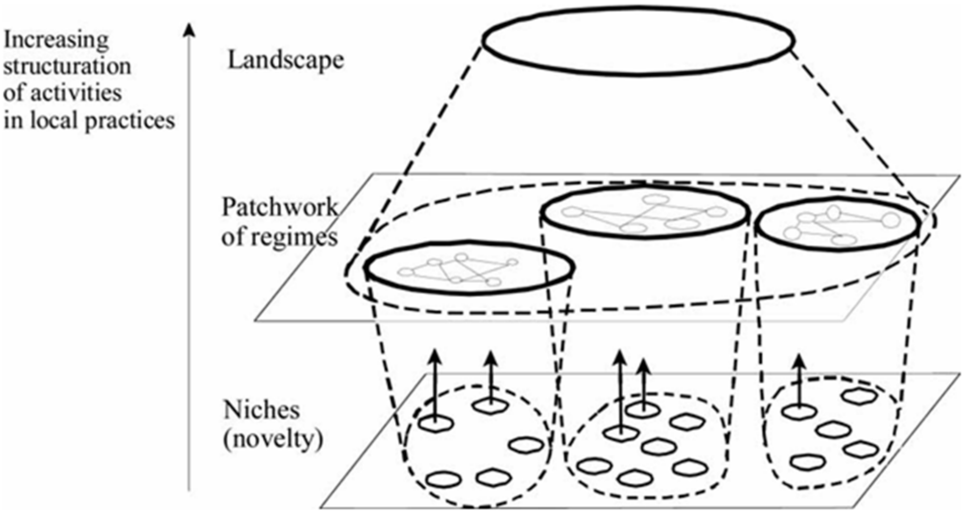

Figure 3.6: Multiple levels as a nested hierarchy [Schot and Geels (2008); Geels (2002)].

In this nested representation, each level is embedded in the one above it. The levels are not ontological representations of reality, but rather analytical conceptualisations of the complex dynamics behind socio-technical change. Higher levels imply more stable configuration of its components and higher resistance to change [Geels (2002)]. Apart from providing descriptive heuristics, this nested hierarchy contains normative features, providing directions on how to prioritise actions.

Niches form the micro-level of the hierarchy and are the most unstable configurations. They are responsible for the generation and development of radical innovations, providing the seeds for change [Geels (2002)]. At their early stages, niches often demonstrate low performance [Geels and Schot (2007)] and therefore, require protection from external pressures [Kemp (1994); Raven (2006)].

Regimes are at the meso-level of the hierarchy and account for the stability of technological development through the creation of trajectories [Geels (2002)]. They consist of established technologies, knowledge, rules and practices. Using an evolutionary perspective, regime could be thought of as the selection environment that hinders the diffusion of radical innovations [Markard and Truffer (2008a)].

The macro-level of the MLP is the *landscape*, the exogenous environment that provides the gradients for the trajectories [Geels (2002)]. It consists of all those technology-external factors that influence innovation, including macro-economics, macro-politics and cultural patterns. These are hardly affected by lower levels of the hierarchy, and changes take place over long periods of time, in the order of decades [Schot and Geels (2008); Markard and Truffer (2008a)].

3.3.1 Transition dynamics using the MLP

The object of analysis in socio-technical transition studies is the shift at the regime level. The MLP suggests that such shifts occur through the interactions between the three conceptual levels of the hierarchy. A graphical summary of these interactions is illustrated in Fig. 3.7.

Socio-technical regimes consist of several interconnected subgroups that function in a coordinated way (see Subsection 3.1.2). The linkages of these subgroups are responsible for the path-dependent technological development along certain trajectories and the overall stability of the socio-technical system. However, misalignment of activities within a regime might occur due to either internal or contextual tensions. The main reason for such tensions is changes at the landscape level. Other reasons include changes in user preferences, pressures from other systems, internal technical problems, strategic conflicts among actors etc. These tensions are mirrored in the regime as a misalignment

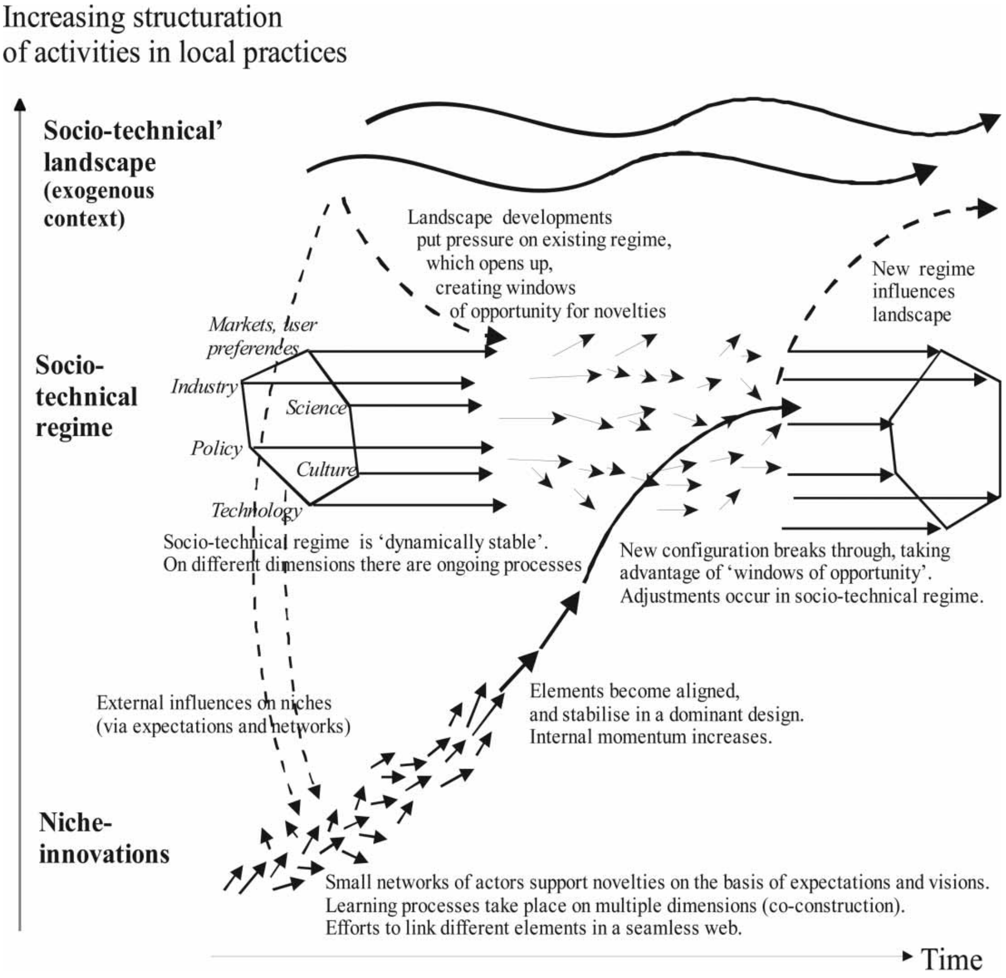

Figure 3.7: The Multi-Level Perspective on socio-technical transitions [Schot and Geels (2008)].

of rules and norms, creating space for flexibility of the actors, and opening a 'window of opportunity' for the breakthrough of radical novelties [Geels (2002, 2004)].

In order for this breakthrough to occur, along with the pressure from the landscape level and the destabilisation of the regime, a certain level of maturity or cumulation is required at the niche level[8]. Correct timing is essential: unless niches build up sufficient internal momentum, regimes will not shift, and the internal coordination may be restored [Geels (2002); Schot and Geels (2008)]. If all these conditions are satisfied, then the selection environment is disrupted and the socio-technical system is adjusted [Geels and Schot (2007)]. According to that representation, niches conceptualise the source of potential bottom-up changes and landscapes the source of top-down exogenous change [Genus and Coles (2008); Geels (2010)].

Regime shifts do not always occur in the same fashion. Scholars have suggested various *transition pathways*. Berkhout *et al.* (2004) and Smith *et al.* (2005) suggest a typology based on two dimensions: availability of resources and degree of coordination of resource deployment[9]. Foxon *et al.* (2010) elaborate certain pathways for the transition of the electricity system towards sustainability in the UK. Finally, Geels and Schot (2007) and Verbong and Geels (2010) suggest a typology[10] based on the criteria of timing and nature of interactions, which is more in line with the analysis of technological change up to now. The five pathways are:

- *Reproduction:* In the case of no contextual pressures from the landscape, the regimes remain dynamically stable, experiencing incremental development of the dominant design. Radical innovations have little chances of breaking through.

- *Transformation:* If there is moderate pressure from the landscape level and niches are not mature enough to take advantage of the destabilisation of the regime, then regime actors respond by modifying their practices and gradually changing the regime trajectory.

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[8] Some indicators of niche maturity that have been suggested include the establishment of a dominant design, involvement of powerful actors, promising learning curves, existence of market niche with some market share, etc. [Geels and Schot (2007)].

[9] The four types of transitions are endogenous renewal (high coordination, internal resources), reorientation of trajectories (low coordination, internal resources), emergent transformation (external resources, low coordination) and purposive transition (external resources, high coordination).

[10] The typology is based on the work of Suarez and Oliva (2005) on environmental changes.

- *Reconfiguration:* In the case of moderate pressures from the landscape level, the regime may adopt technologies and practices from mature niches and reconfigure its internal architecture.

- *De-alignment and re-alignment* If the tensions from the landscape level are sufficient to completely de-align the regime, and niches are not mature enough to substitute the dissolving configuration, then multiple niches co-exist in an uncertain environment until one dominant design emerges and re-aligns actors into a new regime.

- *Technological Substitution:* If niches are sufficiently developed when a major change in the landscape level occurs, then they may substitute the configuration with a disruptive change at the regime level.

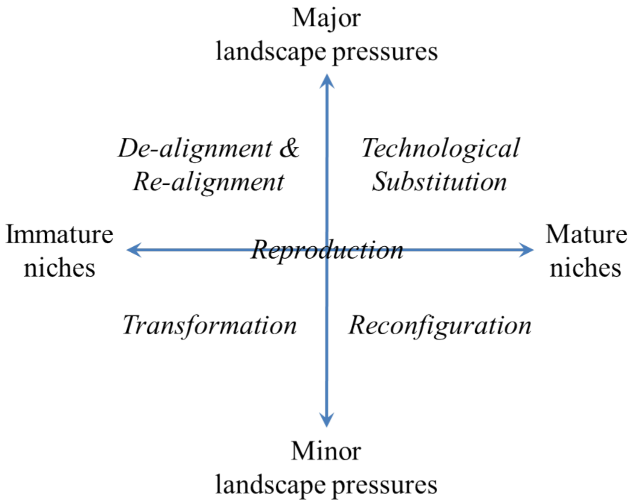

Figure 3.8: Types of transition pathways (based on Geels and Schot (2007); Verbong and Geels (2010)).

These mechanisms are not deterministic, and this conceptualisation does not imply that the sequence of events is automatic. Furthermore, these pathways are ideal types of transitions, rarely encountered as such in technological change analyses. Real cases involve a combination of the aforementioned dynamic mechanisms [Geels and Schot (2007)].

3.3.2 Application of the MLP on sustainability transitions

The shift towards a sustainable and low-carbon society requires technological, infrastructural and behavioural changes in a range of sectors, including the energy, the transport and the construction industries [Watson (2008)]. These changes have been studied extensively using frameworks from the Transition Theory literature.

The SNM approach in particular has been applied in the sustainable transport sector [Hoogma *et al.* (2002); Ieromonachou *et al.* (2004); Truffer *et al.* (2002)] and in renewable energy case studies [Raven (2005); Verbong and Geels (2007); Verbong *et al.* (2008); Van Eijck and Romijn (2008)]. These studies demonstrate the strength of the concept as an ex-post analytical framework, but also highlight the shortcomings of the method with regards to the limited representation of the socio-technical context [Schot and Geels (2008)].

Since its first conceptualisation as an analytical framework in the early-2000s, the MLP has been used to describe past [Geels (2002, 2006a,b, 2007)] and contemporary transitions [Kern (2012); Yuan *et al.* (2012); Nakamura *et al.* (2013)]. Sustainability transitions in the energy sector have been used as case studies to assess the transition mechanisms of niche accumulation and hybridisation [Raven (2007)] and evaluate the suggested typology of pathways [Geels and Schot (2007); Verbong and Geels (2010)].

3.3.3 Strengths and weaknesses of the MLP approach

The main advantages of the MLP as an analytical framework are found in its wide scope and generalisability that help the simplification of the analysis of complex structural transformations and allow for reflexive intervention [Smith *et al.* (2010); Lachman (2013)].

On the other hand, the framework has also been questioned on multiple levels by transition scholars. Smith *et al.* (2010) recognise the allure of the MLP, but also express concerns about the possibility of becoming counter-productively simplistic. Its defenders have responded and used this criticism in a constructive way, publishing adaptations of the framework, aswas described earlier in this section.

A usual comment on the MLP approach is that it emphasises the niche level as the source of regime shifts [Berkhout *et al.* (2004); Smith *et al.* (2005)]. This bottom-up understanding of technological change underestimates the internal dynamics of the various regime subgroups, and the downward tensions from the landscape level. The introduction of different types of transition pathways (see Section 3.3.1) partially addressed this weakness [Geels and Schot (2007)], though MLP still tends to overemphasise changes originating from radical and disruptive niches [Winskel *et al.* (2014a)]. Niche-level dynamics are particularly important for this research, since most of the BIPV applications have achieved limited deployment, and mainly compete and interact within technological and market niches.

Another major criticism is the lack of rigour in the definition of the socio-technical regime and its delineation from the socio-technical system [Berkhout *et al.* (2004); Genus and Coles (2008); Markard and Truffer (2008a)]. Although it is a common problem in innovation and transition studies to clearly draw boundaries and define the topic of analysis, MLP scholars have tried to distinguish systems as the set of tangible and measurable elements (e.g. artefacts, infrastructure and regulations) from the analytical concept of regimes, that include the intangible components (e.g. beliefs, routines, visions and norms) [Geels (2004); Geels and Schot (2007); Geels (2011)].

It has also been noted that MLP focuses more on societal factors and does not pay much attention to economic drivers (e.g. cost), as other perspectives on energy transitions do [Foxon (2011); Fouquet (2010)]. Winskel *et al.* (2014a) suggest bridging the perspective with cost-based methodologies such as learning rates. The model has also been criticised for limited representation of agency [Smith *et al.* (2005); Genus and Coles (2008)], for being homogeneous or monolithic [Smith *et al.* (2005)] and limited to offering just a heuristic device [Genus and Coles (2008)].

3.4 Summary and conclusions

Transition studies provide insights for the analysis of long-term changes in socio-technical configurations. The theoretical approaches and frameworks that have been developed not only offer descriptive heuristics but also contain normative features in the form of action prioritisation and niche development and management. These features are particularly relevant in the case of the energy and building sectors and their steering towards a sustainable path.

The Multi-Level Perspective is a framework that has been widely applied for the historical analysis of socio-technical transitions. It focuses on the interplay of dynamics on three conceptual levels: technological and market niches, established regimes and socio-technical landscapes. In that way, it offers a wide perspective of the context affecting the development of emerging technologies, including reciprocal aid and competition with other emerging technologies, interactions with incumbents and influences from the wider socio-technical configuration.

This context-oriented MLP is considered to be a suitable complement to the rather inward-oriented and less dynamic TIS framework. However, both approaches still focus on structure rather than agency, underestimating the importance of individual choices and micro-economic factors in socio-technical change. Addressing these shortcomings, concepts from Business Studies will be explored in the analytical framework of this research. The combined use of insights from the three perspectives aims to provide a better understanding of the internal dynamics and the contextual influences that affect the development and diffusion of emerging BIPV technologies.

Chapter 4

Business Studies

Introduction

As was highlighted earlier in this literature review (see Subsections 2.3.7 and 3.3.3), the TIS approach and the MLP provide useful analytical tools with complementary strengths for the study of technological change and innovation in socio-technical systems. However, they offer a structural explanation with a focus on determinism, rather than an evolutionary framing that would address *agency* in the form of individual choices, development of business strategies and responses of firms to external drivers and barriers [Foxon (2011); Geels (2011)].

Another dimension that is rather neglected in the innovation systems and especially in the transitions literature is the *economic environment* in which firms operate. Although both approaches offer a systemic macro-economic understanding, they do not focus on the micro-economic factors that drive knowledge creation and technological improvements within firms [Marigo (2009); Foxon (2011)].

In order to address these two dimensions in the assessment of the BIPV sector in the UK, it is deemed important to include insights from the Business Studies literature. Particularly the concepts of corporate strategy and business model allow for an analysis of the practices that are developed and adopted by firms in order to innovate or adapt to change. In evolutionary terms, business literature explains how *variation* through continuous entrepreneurial experimentation (*mutations*) is created, while innovation systems and transition studies explain the mechanisms of environmental *selection* and long-term *retention*.

This chapter does not aim to be an exhaustive literature review of Business Studies, but rather an introduction to the basic concepts that will be used in the development of the analytical framework of this research. Section 4.1 is an introduction to the Business

Literature with a focus on strategic management. Section 4.2 focuses on Porter's typology of business strategies, and the characteristics of successful firms. Finally, Section 4.3 introduces the Business Model approach and relates it to the concept of innovation.

4.1 Basic concepts of Strategic Management

The notion of coordinating managing activities within an organisation originates in the late 1950s. Philip Selznick in 1957 was the first to formalise the idea of matching the internal factors of a corporation to its external influences [Selznick (1984)]. His work led to the development of the SWOT analysis, a popular framework used to evaluate the Strengths, Weaknesses, Opportunities and Threats involved in a business venture.

Alfred Chandler in 1962 presented the first comparative and systematic account of growth and change in companies [Chandler (1962)]. He also highlighted the importance of a long-term strategy that encompasses all activities and gives structure, focus and direction[1]. Building on this work Igor Ansoff introduced in 1965 a typology of corporate strategies and the concepts of vertical and horizontal integration (see Fig. 4.1).

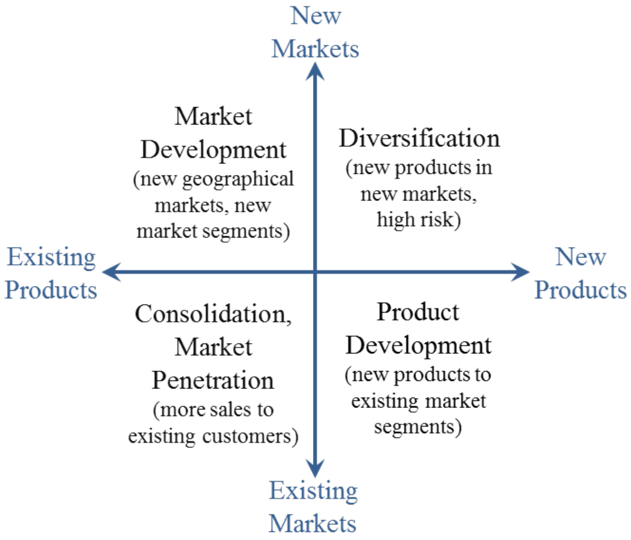

Figure 4.1: Corporate strategy grid (adapted from Ansoff (1965)).

Kenneth Andrews was the first to differentiate between corporate and business

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[1] Other scholars challenged this 'strategy before structure' thesis later, and suggested an inverted 'strategy follows structure' [Hall and Saias (1980)] or reciprocal view [Mintzberg (1990)].

strategy. He defined the latter as the product and market choices made by a division of a diversified company. Therefore, a company may have several business strategies. Corporate strategy on the other hand is unique and determines the firm's direction over the long term [Andrews (1971); Chesbrough and Rosenbloom (2002)].

In a similar vein, strategy theorist Michael Porter conceptualised business strategy using a five-forces model and introduced the concepts of competitive advantage and value chain [Porter (1979, 1985)]. These concepts are particularly relevant to this research and will be further explained in the following subsections.

4.1.1 Five-forces model

In 1979 Porter (1979) suggested an analytical framework that could be used for the development of business strategies and the evaluation of the attractiveness of a market in terms of competitive intensity and profitability.

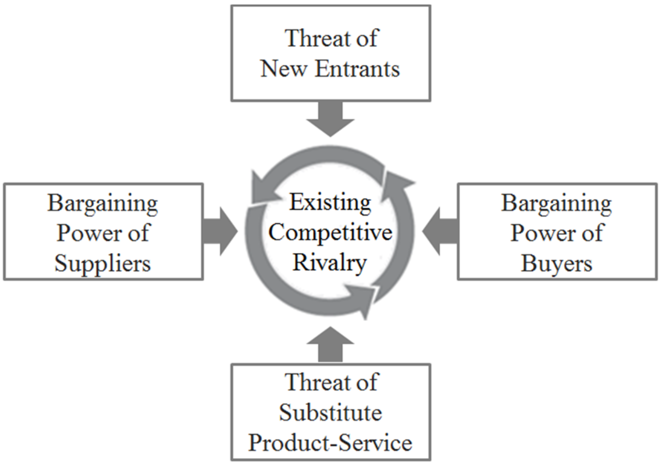

Figure 4.2: Five-Forces model (adapted from Porter (2008)).

The framework is based on five forces that determine market dynamics within an industry, substantially influencing the micro-economic environment of a firm and directly affecting its business choices. These forces are:

- *Threat of new entrants:* Profitable markets attract new entrants, leading to lower profitability for everyone.
- *Threat of substitute products or services:* The existence of paradigm-shifting products outside the sector reduce the overall returns.

- *Intensity of rivalry among existing competitors:* The most significant determinant of the competitiveness of an industry.
- *Bargaining power of suppliers:* Suppliers have a direct influence on the existence and profitability of an industry.
- *Bargaining power of customers:* Customers also have the ability to affect the prices and therefore the profit margins within an industry.

Other scholars have suggested the extension of the model to include influences from government and pressure groups, though Porter refers to those influences as factors that affect the five-forces [Porter (2008)].

4.1.2 Competitive advantage

The concept of competitive advantage refers to the ability of an organisation to outperform its competitors. This ability may be based on the access to natural resources, technological advancements or the implementation of efficient production processes. Competitive advantage is reflected in superiority of performance and ensures a prominent placing of the firm in the market [Porter (1985)].

Scholars have argued that access to scarce resources and sophisticated processes is not enough to offer a competitive advantage to a firm. Rather, the implementation of a viable business strategy that effectively manipulates these resources and processes is needed. In order to ensure market leadership, this value-creating strategy has to be exclusive to that firm [Barney (1991); Clulow *et al.* (2003)].

4.1.3 Value and supply chains

The value chain concept was also developed by Michael Porter to describe the process of how value is added to a product or service within a firm. This process is considered to be a chain or system of activities or subsystems, each one involving inputs, processes and outputs. Each of the activities adds value to the product/service, and determines its total cost. However, the final value will not be just the sum of the costs of each activity, since the added-value from each activity is higher than its cost[2] [Porter (1985)].

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[2] One indicative example is the diamond cutting process: the value difference between a rough and a cut diamond is much higher than the cutting cost itself.

Applying this model at the firm level, activities of a business unit can be visualised as in Fig. 4.3. The primary activities of a firm are inbound and outbound logistics, marketing and sales, operations and service. Secondary activities include infrastructure, human resources, procurement and technological development [Porter (1985); Rowe *et al.* (1986)].

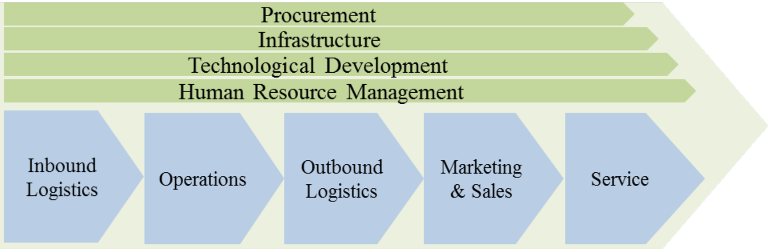

Figure 4.3: Value chain (based on Porter (1985)).

At the industry level, value chains of several firms are interconnected in a complex and dynamic value-system [Porter (1985)]. This stream of activities from the suppliers to the end-consumer is the *supply chain* and involves natural resources, materials, components, processes, marketing, sales and delivery of the product or service (see Fig. 4.4) [Nagurney (2006)]. Understanding and utilising efficiently the components of the supply chain is crucial for maximizing the returns of a firm. The supply-chain operations reference-model (SCOR) is the most widely used diagnostic tool for supply chain management [Cazier and Poluha (2007)].

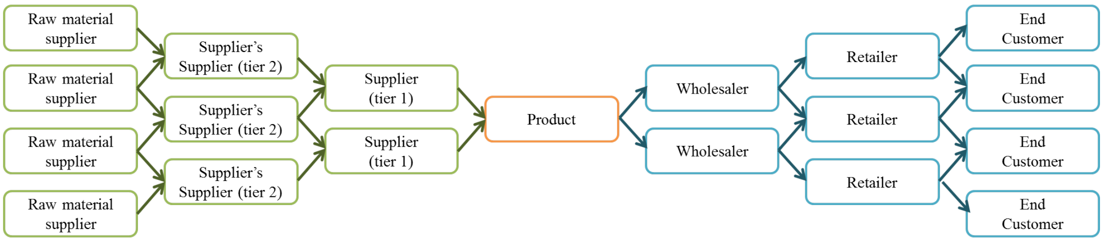

Figure 4.4: Supply chain (adapted from Wieland and Wallenburg (2011)).

4.2 Business strategy

Business strategies are the ways firm organise their activities in order to fulfil their socio-economic purposes. This wide definition includes not only commercial firms, whose goal is to maximise their profit[3], but also social enterprises oriented at delivering services to the public [Foxon (2011)]. Therefore, strategy defines to a large extent a firm's choices in terms of resource-allocation and responses to external developments.

The business strategy concept has been included in the empirical analysis and analytical framework of this research as a proxy for intra-firm agency, an element arguably under-acknowledged in the TIS and MLP approaches (see Subsections 2.3.7 and 3.3.3). More specifically, the typology of generic strategies proposed by Michael Porter was used in the PV market assessment for the mapping of the strategic orientation of main industry actors (see Section 7.3) and for the selection and analysis of the case studies (see Sections 5.3, 8.2 and 8.3).

4.2.1 Generic strategies

Similarly to the earlier work of Igor Ansoff (see Section 4.1), Michael Porter developed a typology for generic business strategies that are adopted by firms to create and maintain their competitive advantage. According to that typology, strategies fall into three categories according to their strategic strength (low production cost or differentiation) and strategic scope (narrow markets or broad, industry-wide) as illustrated in Fig. 4.5 [Porter (1980)].

Michael Porter argued against the use of more than one strategies in a single business unit[4], as this would lead to the 'stuck in the middle' phenomenon where the firm fails to create a sustainable competitive advantage. However, other strategists have found empirical evidence that companies pursuing both differentiation and cost leadership might be more profitable than firms adopting a single strategy [Wright *et al.* (1990)].

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[3] According to the concepts of uncertainty and bounded rationality (see Subseciton 2.1.3), firms are profit-oriented rather than profit-maximisers [Foxon (2011)].

[4] Apart from the combined use of segmentation and differentiation which he found viable.

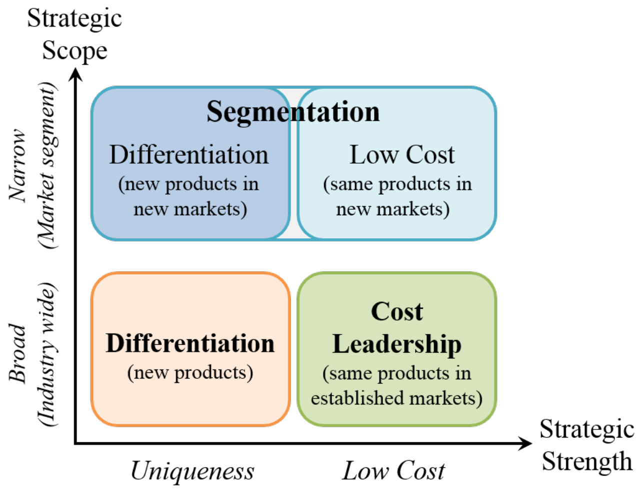

Figure 4.5: Generic strategies (adapted from Porter (1980)).

Cost Leadership

A cost leadership strategy is adopted by companies targeting price-conscious consumers. The firm captures market share by producing at a cost that is lower than average, without significantly compromising quality. Practices that reduce production cost include high throughput (i.e. economies of scale and experience curves), lower operational costs (through e.g. standardisation) and control over the supply chain (through e.g. vertical integration).

Differentiation

The differentiation strategy involves the development of products or services that have unique attributes different from others available in the market. Potential customers have to recognise the added value brought by these attributes and be willing to pay a premium price for them. Firms that adopt this strategy need to have access to technological expertise, own protected intellectual property, implement successful marketing and have a good reputation for quality.

Segmentation

The third generic strategy involves the narrowing of the firm's focus into serving specific specialised market segments. Within these segments firms may pursue differentiation or market leadership depending on their resources and capabilities. Radical innovations are more crucial when adopting this strategy than incremental efficiency improvements.

4.2.2 Strategies and characteristics of new entrants

Based on the diffusion theory and the categorisation of firms introduced by Rogers (2010) (see Section 2.1.2), but focusing on the factors that determine long-term success of companies, Golder and Tellis (1993) carried out a historical analysis on fifty product categories[5]. Their research challenged the established belief that *market pioneers*[6] have enduring advantages in market shares. They identify another class of *early leaders*, firms that enter the market after pioneers but assume leadership during the early growth phase of the product diffusion process [Golder and Tellis (1993); Tellis and Golder (1996)].

The historical research on 500 brands revealed that early leaders have a significantly lower failure rate, three times larger market share than pioneers and a high rate of market leadership in the long-run. Tellis and Golder (1996) go on to identify five factors that drive the superior performance of early leaders:

- Vision of the mass market that provides economies of scale and allows for the exploitation of the full potential of the new product.
- Persistence of the management on the new product over a long period of slow incremental progress.
- Financial commitment over the early stages of the product life-cycle.
- Continuous improvement of the product to match its changing environment.
- Asset leverage through dominance in a related product category.

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[5] A product category is a set of competing brands whose products are perceived by customers as substitutes [Tellis and Golder (1996)].

[6] Pioneers are defined as the firms that are the first to sell in a new product category [Tellis and Golder (1996)].

These findings are of particular importance for this research which focuses on the BIPV sector, an emerging technological field largely shaped by the activities of new entrants rather than incumbents in the energy sector. They are also relevant to the analysis of the current consolidation of the PV industry, a phenomenon that will be further discussed in Section 7.1.

4.3 Business model

Although there is no consensus in the literature for the definition of the business model concept, it can be broadly understood as the description of the firm's organisational and financial architecture [Chesbrough and Rosenbloom (2002); Burkhart *et al.* (2011)]. It is the application of a business strategy in terms of structure and established behaviours that characterise a firm's operations. It represents the firm's perception of what is needed by the market, and outlines its actions to meet that need and generate revenue in return [Hannon *et al.* (2013)].

The business model, as a description of how a firm creates, delivers and captures value, can be a valuable tool for the analysis and comparison of companies and markets in a structured way [Osterwalder and Pigneur (2010)]. It can also be used as a classifying method, a management instrument and a useful tool for innovation [Osterwalder and Pigneur (2002); Richter (2013)].

Despite earlier attempts to conceptualise it, the modern business model framework is based on the work of analysts in the early 2000s. Osterwalder and Pigneur (2002) outline the four main questions that a business model is called to answer: what does the firm offer, who are the potential buyers (including distribution channels), how value is created (including capabilities and partnerships) and how much does the firm charge for the final product or service.

Stähler (2002) separates the strategic components (value proposition, product or service and revenue model) from the organisational ones (market design, internal and external value architecture), while Chesbrough and Rosenbloom (2002) identify the six functions of a business model:

- to articulate the *value proposition*,

- to identify a *market segment*,
- to formulate the *competitive strategy*,
- to define the structure of the *value chain*,
- to describe the position within the *value network*,
- to estimate the *cost structure* and the *profit potential.*

In a similar vein, but broadening the unit of analysis to multiple firms (or to *value system constellations*) rather than the value chain of a single firm, Schweizer (2005) identifies the three dimensions of business models: the firm's positioning within the value system, its competitive advantage or market power and its revenue model. He then goes on to identify common types of models and develop a typology (see Fig. 4.6).

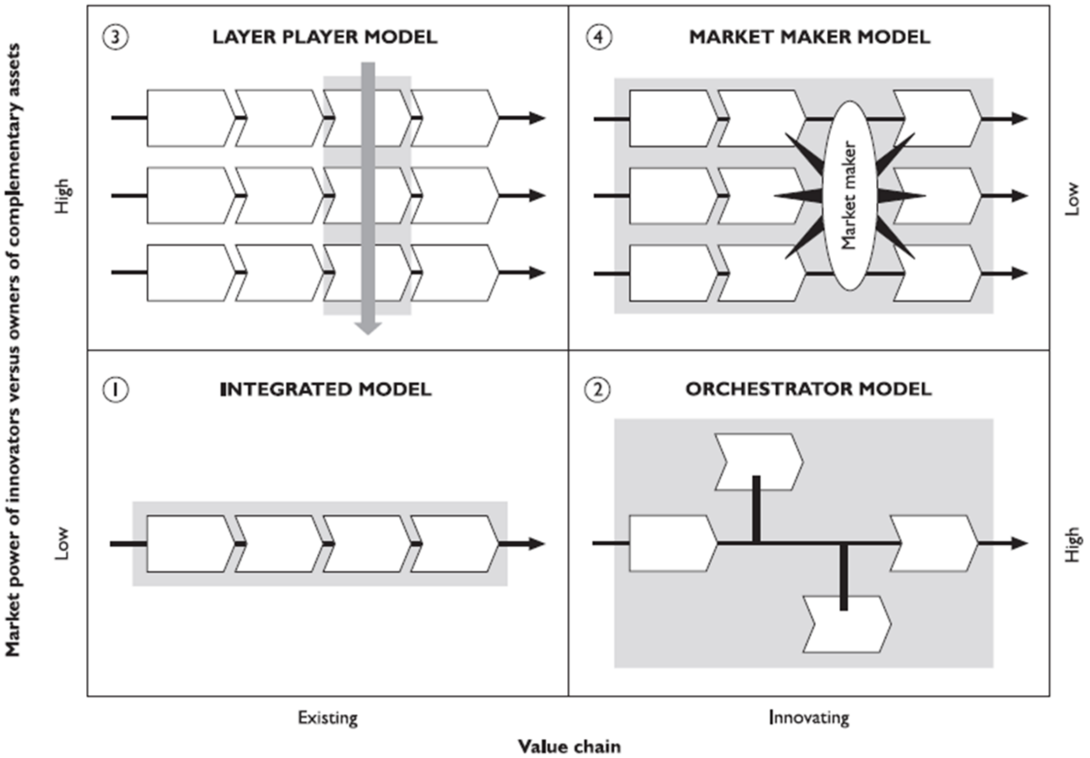

Figure 4.6: Typology of business models [Schweizer (2005)].

A more structured analytical framework that addresses the wider environment of the firm was developed by Osterwalder and Pigneur (2010). They identify nine building blocks of a business model (see Fig. 4.7):

- *Customer segments* define the groups the firm aims to serve,
- *Value proposition* is the product or service the firm offers,
- *Channels* are the ways the firm reaches its customer segments,
- *Customer relationships* are the established links to each customer segment,
- *Revenue streams* refer to the compensation of the firm from the customers,
- *Key resources* include all the firm's assets,
- *Key activities* are the ways the firm creates and delivers value,
- *Key partnerships* refer to the activities and resources that are outsourced,
- *Cost structure* is defined by the elements of the value chain of the firm.

This framework is particularly useful for firm-level analysis, providing insights for both its internal organisation and eco-system. In this research it will be used in the empirical investigation to provide description guidelines and heuristics for the case studies (see Subsection 5.3.4).

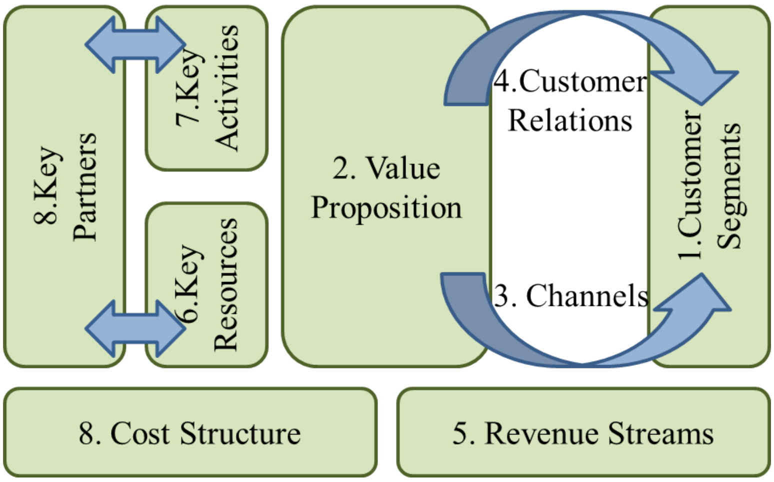

Figure 4.7: Building blocks of a business model (adapted from Osterwalder and Pigneur (2010)).

4.3.1 Business model and innovation

Technological innovation by itself is not sufficient to guarantee corporate or economic success, despite the contrary common perception [Teece (1986)]. In order to be successful, innovation needs to be coupled with a viable business model that defines commercialisation and value-capturing strategies. The dynamic market environment and the ever-changing customer needs, imply that such models cannot be static, but rather undergo constant adaptations. Therefore, the design of a business model requires not only creativity, intuition and supply-chain intelligence but also tacit knowledge created through experimentation and learning processes [Teece (2010); Christensen *et al.* (2012)].

There have been attempts by scholars to open-up the business model and develop an outward-oriented framework that would address pressures external to the firm that could cause a shift in strategy. The *business model innovation* approach relates to the innovation research in order to investigate how firms adapt to opportunities and barriers [Chesbrough (2010); McGrath (2010); Huijben and Verbong (2013)].

Established businesses tend to focus their resources on optimising their ongoing activities through incremental innovations. This strategy is safer and offers wider profit margins than developing new technologies [Chesbrough (2010)]. However, disruptive innovations may change the architecture of the market and render the incumbent business model obsolete [Christensen and Bower (1996); Richter (2013)].

In order to establish a sustainable growth in the long term, firms have to develop *organisational ambidexterity*, a quality that suggests the combined exploitation of existing capabilities and formation of new competences [O Reilly and Tushman (2004); Tushman *et al.* (2006)]. Through business model learning and experimentation processes, firms are able to reconfigure their assets and activities in order to take advantage of latent opportunities [Chesbrough (2010); McGrath (2010)]. An example from the energy sector would be the development of renewable energy technologies by utilities along with efficiency improvements in their conventional power systems, in order to benefit from the ongoing energy transition towards a more sustainable pathway.

4.4 Summary and conclusions

Despite the complementary strengths of the TIS and MLP frameworks in conceptualising technological change and the innovation process, they both over-emphasise the role of structural determinism. Although collective choices of actors are represented in the models, they are not driven by individual agency, but rather the structural characteristics of the socio-economic system. Additionally, the micro-economic environment that surrounds firms and shapes their actions is neglected.

Business studies on the other hand, focus on individual choices and responses to technological change. The five-forces model and the supply chain concept provide insights on the economic dynamics at the industry level. Business strategies describe how companies intend to fulfil their socio-economic purpose, while business models are the application of these strategies in terms of organisational and financial architecture.

More recent conceptualisations bring insights from the Innovation Systems studies to the Business Literature, highlighting the dynamic nature of business models and the importance of adaptation to contextual developments. This adaptation is achieved through experimentation, learning processes and feedback loops among firms and the end-market.

Chapter 5

Research Design

Introduction

The broad aim of this research is to improve the understanding of the processes that influence the development and market diffusion of sustainable energy technologies, using BIPV as the main technological domain. The evolution of this emerging technology is affected by developments in a range of scientific and technological fields, as well as changes in the construction industry and the wider energy system. This multi-sectoral nature of BIPV renders traditional innovation analysis insufficient, and suggests the inclusion of insights from a range of theoretical fields.

The methodological foundation of this research lies in the collection and analysis of empirical evidence using different analytical frameworks in order to address innovation dynamics within the BIPV sector. The combination of elements from the TIS (see Section 2.3) and MLP (see Section 3.3) approaches will be explored in order to synthesise an original hybrid functional framework. This framework will be used along with concepts from the Business Studies literature (see Chapter 4) as search heuristics that will guide the collection and analysis of empirical data.

This chapter will first formulate the research questions and outline the research process in Section 5.1. Section 5.2 focuses on the development of the hybrid functional framework by describing the rationale of combining three different literature strands for the development of an analytical framework, exploring similar integrated approaches in the literature, reviewing the main elements of the suggested framework and illustrating its application on this research. It then outlines the basic principles of process theory and event history analysis which form the foundation for the development of the narratives.

Finally, in Section 5.3 the empirical methods of desk-based research, personal communications with academic and industry experts, semi-structured interviews and case studies are outlined.

5.1 Research questions

The main motivation for this research is to explore the drivers of innovation within the BIPV sector (see Section 1.1). Despite the recognised potential in driving the sustainable transformation of energy systems in urban areas [inter alia Bazilian *et al.* (2001); Plastow (2006); Henemann (2008); Marsh (2008); Pagliaro *et al.* (2010)], the technological domain has attracted minimal academic interest with only one Masters thesis from Chalmers University of Technology focusing on its innovation dynamics [Crassard and Rode (2007)].

An additional research motivation was the implementation of methods from different disciplines for the study of innovation processes, taking into consideration the particularities of the BIPV sector. Two are the main characteristics that render BIPV a complex, yet interesting, case from a methodological point of view. Firstly, it is an emerging sector with no apparent established technological trajectories. Therefore, particular focus needs to be given to innovation processes within firms, in order not only to capture the dynamics of developing niches that may consolidate into a dominant design, but also reflect on the discussion regarding incremental and disruptive innovation. Secondly, the deployment of BIPV applications into the market is highly affected by developments in both the PV and construction industries. Consequently, the analysis should also take into consideration the broader socio-technical system.

In line with this dual research motivation, the study is guided by three research questions. The first one is methodological and relates to the potential integration of conceptual approaches for the assessment of complex innovation dynamics:

R.Q. 1 How can the Technological Innovation Systems conceptual framework be enhanced through the incorporation of elements from the Multi-Level Perspective and Business Studies, for the development of an original hybrid approach to better evaluate the emerging and cross-industry BIPV sector?

The second research question relates to the understanding of BIPV innovation, as well as the performance of the hybrid new method:

R.Q. 2 What insights emerge regarding innovation dynamics within the BIPV sector in the UK and globally, through the implementation of the extended new framework for the analysis of multi-level empirical evidence, and what are the methodological implications regarding the compatibility of the approaches within the framework?

The third question is more applied, and refers to the different types of innovation in sustainable innovation systems:

R.Q. 3 What insights emerge regarding the argument of incremental versus disruptive innovation, and what are the implications for the assessment and governance of hybrid sustainable innovation systems more generally?

Section 5.2 of this Chapter aims to respond to the first question by building a hybrid analytical framework based on the conceptual review outlined in Chapters 2 to 4. Extensive empirical evidence presented in Chapters 6 to 8 will provide the background for answering the second and third questions, which will then be explicitly addressed in Chapters 9 and 10. An outline of the research process including its main tasks is illustrated in Fig. 5.1.

5.2 Analytical framework

The analytical part of this research is based on the interpretation of several narratives, constructed by (mostly) qualitative empirical data. Drawing upon the process theory approach [Pettigrew (1990); Van de Ven and Poole (2005); Verbong *et al.* (2008)] and using an event history analysis [Poole *et al.* (2000); Suurs *et al.* (2009); Suurs and Hekkert (2009)] the narratives will link *events*[1] to a framework of *functions*[2]. These functions will be used as indicators, designed to reflect and operationalise research questions 2 and 3 as outlined in Section 5.1.

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[1] Events are instances of change with respect to the socio-technical system under investigation, enacted by actors who have preferences, interact and make decisions (see Subsection 5.2.4).

[2] The notion of *function* is used here (and in most occurrences within this thesis) stressing its heuristic value rather than its positivist implication that the social world can be studied as a mechanistic system. Functions can be considered as system-level variables representing sets of activities that influence the overall performance of the system. As such, they help the identification, understanding and comparison of certain processes and provide insights for the dynamics within socio-technical systems [Hekkert *et al.* (2007b)].

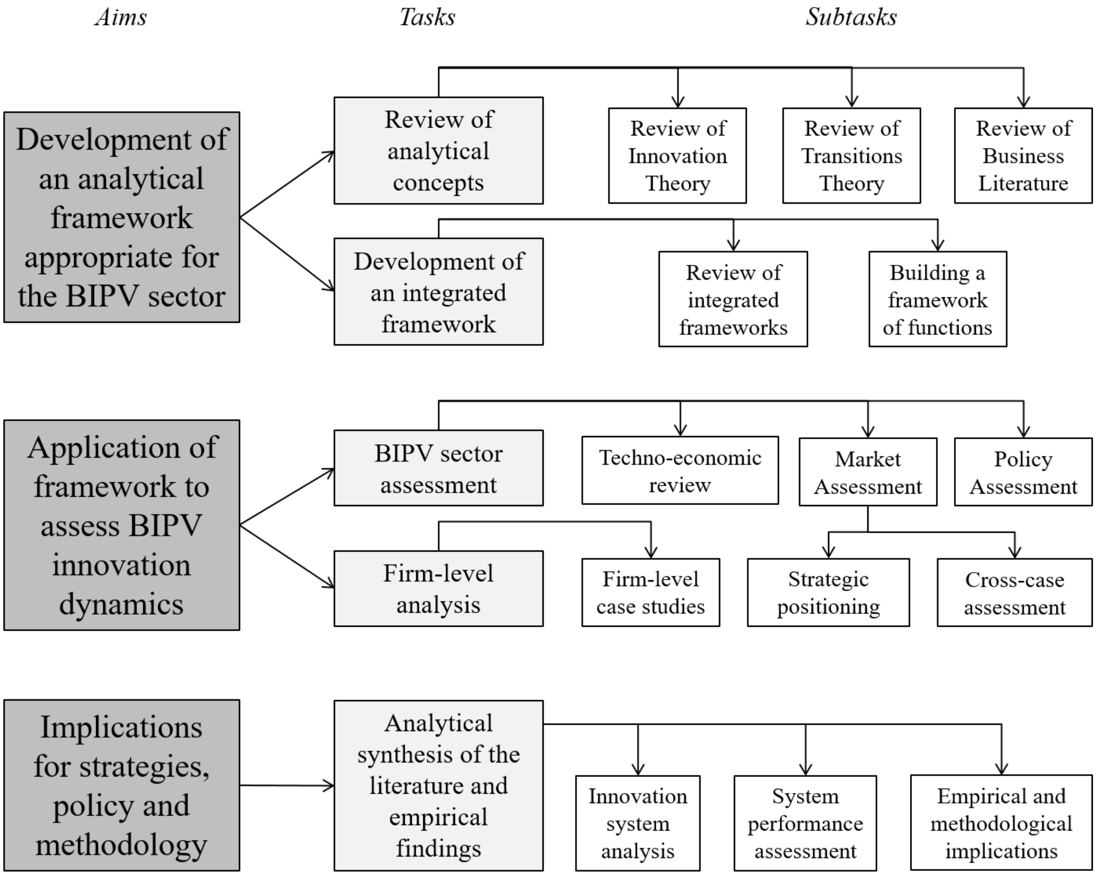

Figure 5.1: Research process (author's elaboration).

Therefore, the purpose of the developed hybrid functional framework is to guide the empirical evidence collection as well as interpret the findings in a meaningful way with respect to the research aims.

5.2.1 The need for a multi-conceptual analytical framework

The outline of the analytical framework was not clear in the initial stages of this research, and was reviewed throughout the empirical data collection process. This iterative process included the addition of new indicators and elements that were not initially obvious and that emerged due to not only the increasing understanding of the multi-industry BIPV sector, but also due to its rapidly changing nature and the wider developments in the energy and construction industries.

Innovation Systems as the starting point

Despite the increasing recognition of the importance of innovation in the development and diffusion of renewable energy technologies [Toman (1998); Menanteau *et al.* (2003); Tsoutsos and Stamboulis (2005)], there is still limited understanding with regards to its development and governance [Jacobsson and Johnson (2000); Menanteau *et al.* (2003); Jacobsson *et al.* (2004); Foxon *et al.* (2005); Hekkert *et al.* (2007a)]. BIPV in particular has received minimal academic attention in terms of evaluation of the innovation drivers and incorporation in energy policy design, even though its potential to drive the sustainable energy transition in urban environments is widely recognised.

A significant implication of this poor understanding is the insufficient capability to inform and steer energy policy design in order to effectively stimulate the development of the sector and increase its contribution to the future energy mix [Jacobsson *et al.* (2004)]. In consonance with this issue, this research aims not to prove the importance of renewable energy technologies, and BIPV in particular, but to investigate the processes that influence (accelerating or hindering) their development and market deployment. In this context, an innovation-systems perspective can offer a rich theoretical basis for the study of the BIPV sector [Sagar and Holdren (2002); Marigo (2009)] and therefore, it was chosen as the conceptual point of departure for this analytical framework.

As was earlier outlined in Section 2.3, the main contribution of the innovation-systems approach is the understanding of innovation as a systemic process where a network of agents interact for the development, diffusion and utilisation of a new technology [Carlsson and Stankiewicz (1991)]. The concept references societal drivers alongside macroeconomic developments, offering a broader appreciation of the innovation process than traditional quantitative indicators.

The strengths of TIS in particular as an analytical approach lie in the provision of an elaborate framework of functions that can direct the assessment of the structure, the performance and the processes that hinder or contribute to the successful development of emerging innovation systems. Contrary to earlier conceptualisations, TIS highlights the importance of specific technological characteristics as drivers of innovation, and provides a more evolutionary illustration, addressing (although partially) responses of actors to external drivers and barriers. Assessment of the suggested functions can help in the identification of various system weaknesses and may give rise to policy interventions for its support or steering towards certain directions.

The need for a Multi-Level Perspective

Despite the many advantages of the TIS approach, the literature review also revealed a weakness with respect to this research. The methodology is rather inward-oriented, paying insufficient attention to the system's environment. External forces are partially included in one of the functions (*development of positive externalities*), but their nature and sources are neglected. The analytical focus on the structure and performance of the system is appropriate for the conceptualisation of its emergence and growth, but is unable to fully address the dynamics that may lead to systemic changes and transitions offering a rather static representation of the innovation process [Geels (2004); Bergek *et al.* (2008a); Markard and Truffer (2008a); Winskel *et al.* (2014a)].

This weakness is particularly relevant to this study. BIPV and renewable energy technologies in general, challenge fundamentally the established technical and institutional architecture of the energy and construction industries, suggesting wide socio-technical reconfiguration [Watson (2008)]. Therefore, externalities (e.g. the strategic activities of incumbent energy actors, synergy and competition among technological options) are of increased importance and need to be taken into consideration in the analysis of the socio-technical system [Markard and Truffer (2008a); Gross *et al.* (2012)].

In order to address this shortcoming, an obvious solution was to draw upon the

Transitions Theory literature for further insights. MLP provides a broad contextual scope, offering a more dynamic illustration of technological change. By conceptualising interactions between various levels, the framework allows for the inclusion in the analysis of institutional pressures and processes at multiple socio-technical configurations. An additional strength of the MLP with respect to this research is its focus on the niche-level. Although this bottom-up approach has been criticised for providing a partial understanding of transition dynamics [Berkhout *et al.* (2004); Smith *et al.* (2005); Winskel *et al.* (2014a)], it is very relevant for the study of BIPV, a sector where innovation dynamics are shaped by developments occurring at the domain of technological and market niches.

At this point it is important to clarify that in contrast with most implementations of the MLP in the literature, the scope of this research is not to look into the overall transition of the energy or construction sector towards a sustainable configuration. This would require inter-sectoral analysis and a combination of bottom-up and top-down assessments, which are beyond the scope of this thesis. This research rather focuses on the dynamics of this transition that affect the development of the BIPV sector, and hence it partially draws on the MLP framework. MLP elements are used loosely and more pragmatically, in order to construct functions for the analytical framework similar to the ones used in the TIS approach providing further insights on the performance of the sector.

Agency and the micro-economic perspective

One other weakness of the TIS methodology is related to its macro-economic focus. In spite of providing a good overview of the system, this perspective underestimates the importance of single component parts, allowing only for a limited representation of intra-firm activities. Knowledge creation through various learning activities and agency, in terms of individual decisions, actions and development of strategies, are both critical processes of technological change, especially in emerging industries where there is great uncertainty with respect to the optimal technological design [Christiansen and Buen (2002); Marigo (2009); Winskel *et al.* (2014a)].

The issue is not addressed properly in the MLP either. The individual activities of actors in the MLP are constrained by a multi-dimensional web of normative, cognitive and regulative rules, while agency is conceptualised merely as the ability of involved actors to not only follow but also modify these rules. In evolutionary terms, although both MLP and TIS offer a deterministic understanding of the *selection* and *retention* processes in terms of explaining the dynamics that shape technological trajectories, they do not pay proper attention to the *variation* and *adaptation* mechanisms in terms of learning creation within firms, knowledge management and organisational routines.

It should be made clear that it is not argued that agency and free will dominate over determinism and structure as drivers of technological change. On the contrary, a balanced representation of both analytical concepts is suggested, with focus on the processes of interaction, negotiation, adjustment and compromise governing individual actions [Misa (1992)].

In order to provide a better account of intra-firm and firm-level dynamics, this research draws upon the Business Studies literature, and borrows insights that can be used to organise and structure the presentation of the empirical evidence. These concepts are more descriptive and less reflexive in comparison to the TIS and MLP; therefore, they are used to facilitate the narratives and enhance the analytical framework. More specifically, the concepts of supply chain and business strategy are used in the industry and market assessment, while the business model notion provides a descriptive framework for the case studies.

The inclusion of a Business Studies perspective in this research also offers a better comprehension of the micro-economic drivers of innovation, especially in the fast-growing sectors of PV and BIPV. The appreciation of contextual processes that steer the choices of the involved actors including recent developments in manufacturing costs and prices, the consolidation of the industry and the globalisation of the supply chain, provides a practical framing that can be used to inform the socio-economic analysis.

5.2.2 Integrated frameworks in the literature

A review of the literature revealed a wide recognition of the need for a merging of concepts across disciplines, and various attempts to develop integrated frameworks for the study of technological change. These frameworks have been used extensively for the analysis of sustainability transitions within the energy sector.

Markard and Truffer (2008a) recognise that TIS and the MLP share common theoretical roots and analyse similar empirical phenomena. They explore their commonalities and differences, and suggest an integrated framework that allows addressing the particularities of radical innovation. In their scheme, TIS encompasses a cluster of niches, emergent institutions and resources forming a fourth element in the MLP nested hierarchy (see Fig. 5.2). The approach combines the analytical strengths of each concept: structural and functional performance analysis from the TIS and conceptualisation of the system environment from the MLP. It also allows for the consideration of multiple regimes and complementary innovation systems.

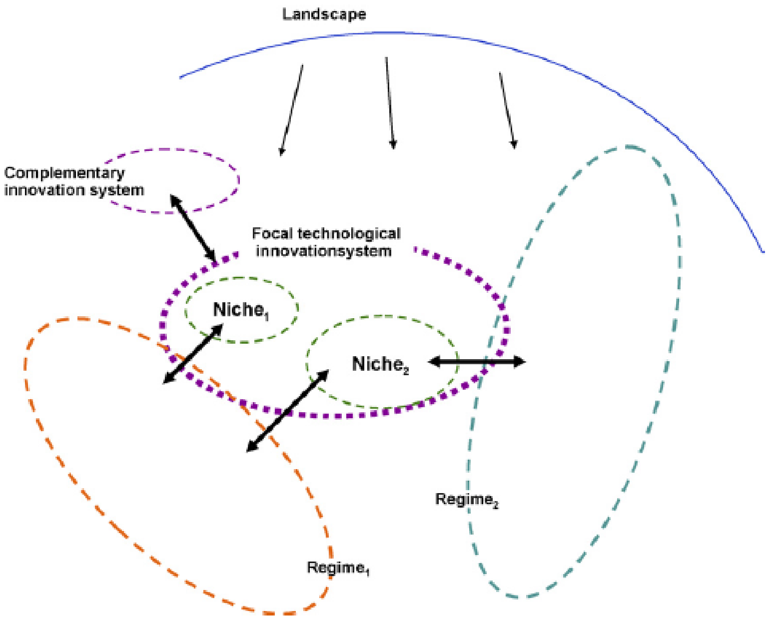

Figure 5.2: TIS and interactions with the conceptual elements of the MLP [Markard and Truffer (2008a)].

Weber and Rohracher (2012) combine insights from TIS and the MLP to develop a comprehensive *failures* framework. The approach focuses on the design of research, technology and innovation (RTI) policy. In the same theoretical vein, Meelen and Farla (2013) suggest an integrated approach to sustainable innovation policy design based on the analytical framework developed by Markard and Truffer (2008a) (see Fig. 5.3a).

The work of Crassard and Rode (2007) is the most relevant to this study. It implements a combined TIS and MLP methodology to investigate the development of the BIPV innovation system in Germany and France (see Fig. 5.3b) and is based on extensive empirical evidence collected using semi-structured interviews. However, the depth of the analysis is restricted due to the limited space and time provided by a Master's thesis.

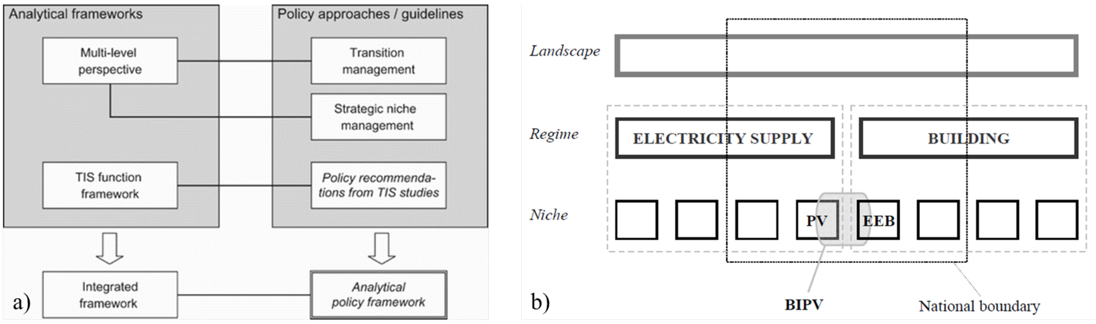

Figure 5.3: a) Integrated analytical framework [Meelen and Farla (2013)] b) The BIPV TIS within the MLP [Crassard and Rode (2007)].

Foxon *et al.* (2008) explore the possibility of bridging three research bodies: long-term socio-technical transitions (using the MLP, TM and socio-technical scenarios as conceptual instruments), TIS and co-evolutionary dynamics. Their integrated framework is used to develop three core pathways for the transition of UK to a low carbon electricity future (see Fig. 5.4).

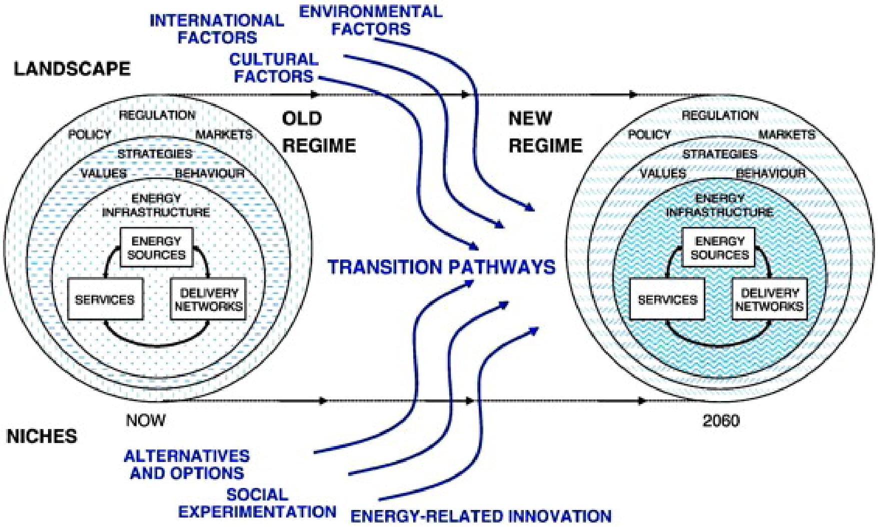

Figure 5.4: Factors influencing transition pathways from a high-carbon to a low-carbon regime [Foxon (2013)].

Foxon (2011) recognises the focus of socio-technical transitions approaches on structural conceptualisations of technological change and suggests a more evolutionary framing. His framework identifies *ecosystems, technologies, institutions, business strategies* and *user practices* as key co-evolving systems, relevant for the analysis of a transition to a low-carbon economy (see Fig. 5.5a). Hannon *et al.* (2013) combine this approach with the business model framework proposed by Osterwalder and Pigneur (2010) to centralise the business dimension and analyse the strategies of incumbent and emerging firms (see Fig. 5.5b).

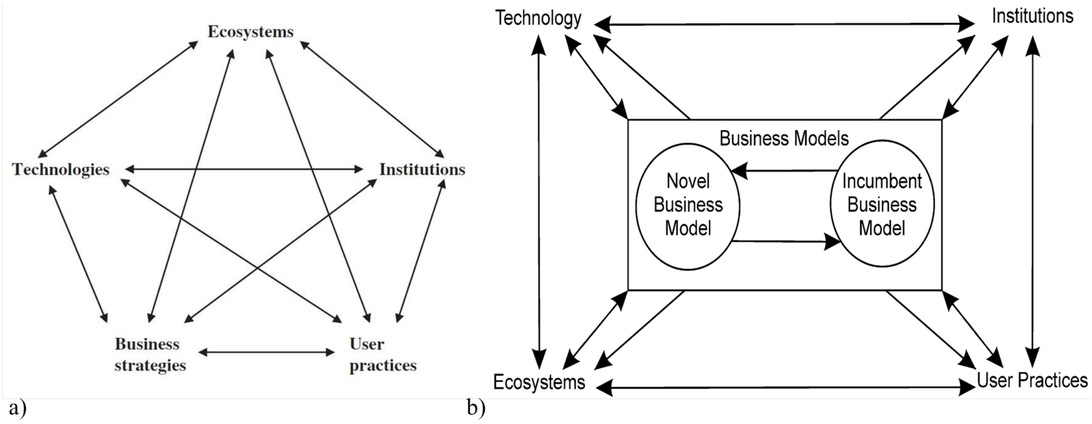

Figure 5.5: a) Coevolutionary framework [Foxon (2011)] b) Coevolutionary relationship between business models and the wider socio-technical system [Hannon *et al.* (2013)].

Responding to criticism over the limited evolutionary framing of the MLP, Geels (2013) also developed a co-evolutionary framework which conceptualises firms as embedded in two external environments (economic and socio-political) and in an industry regime which mediates strategic actions towards these environments (see Fig. 5.6). The bi-directional interactions within the Triple Embeddedness Framework (TEF) reflect *selection* (pressures from the environments) and *adaptation* (internally- and externally-oriented strategies) processes.

Other scholars have also attempted to consolidate insights across schools of thought. Winskel *et al.* (2014a) suggest a *learning pathways* typology, bringing together qualitative innovation analyses and quantitative learning-rate accounts. This intermediate approach provides a deeper understanding of learning processes within the energy sector.

Vantoch-Wood (2012) incorporates network analysis in the TIS in order to create more robust and transferable measures of emergent system functionality. Marigo (2009) suggests the merging of TIS with elements from the Technological Capability (TC) literature in order to better understand firm-level knowledge creation in developing

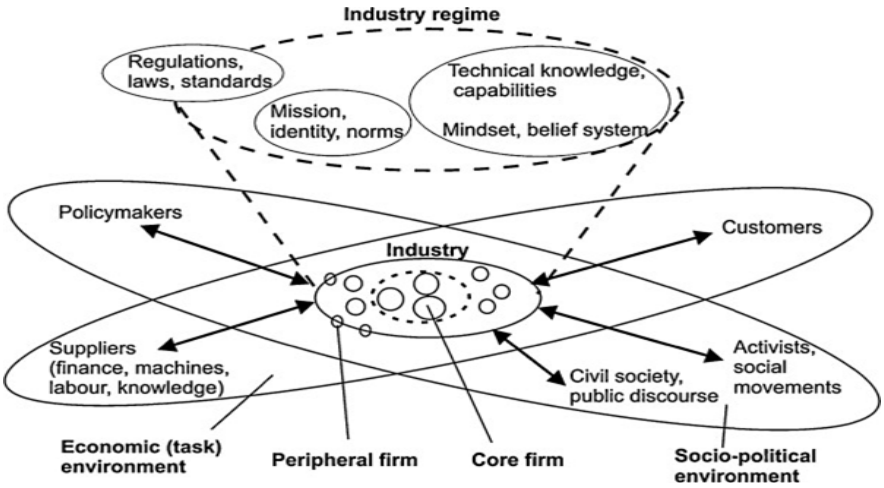

Figure 5.6: Triple Embeddedness Framework [Geels (2013)].

countries. Huijben and Verbong (2013) investigate the PV sector in the Netherlands by adopting a methodology that merges insights from SNM with business models. Nakamura *et al.* (2013) argue that technology in the MLP is regarded as static, and hence propose the integration of indicators from the TRL approach.

On the other hand, there has also been scepticism among academics whether elements of the various frameworks should form a unified transition theory, or they should be used separately to provide complementary insights. The development and usefulness of an overarching theoretical scheme has been discussed in the literature [Geels (2010); Stirling (2011); Markard *et al.* (2012)]. However, the rationale behind the synthesis of the adopted framework in this study is based on the assumption that common known weaknesses of the approaches can be overcome when they are combined and not used exclusively.

5.2.3 The analytical framework of functions

The aim of this analytical framework is not to develop a new grand theoretical approach for the study of sustainability transitions. It is rather an attempt to combine insights from literatures that were considered relevant to this research, in order to create a methodology appropriate for the assessment of the emerging, complex BIPV innovation system (see Table 5.1). This framework will provide the guidelines for the empirical data collection and the analysis of the findings.

The methodology proposed by the TIS approach for the structural and functional

Conceptual level	Descriptive methods	Analytical tools
Energy and Building Sectors	Industry and policy review Market assessment	MLP elements
BIPV innovation system	TIS structural elements Supply Chain	TIS functions
Firms	Business model Case studies	Business strategy

Table 5.1: Combination of concepts within the research process (author's compilation).

evaluation of the system is used as the starting point. However, it is extended in order to reflect dynamics and interactions among firms, niches, regimes and landscapes.

Following the MLP conceptual tradition and the scheme of analysis proposed by Markard and Truffer (2008a), the novel approach addresses innovation processes at various levels of aggregation. The innovation system in focus is conceptualised as a cluster of technological and market niches along with relevant institutions and resources. This representation encompasses a range of dynamics internal to the system, as well as interactions with its socio-economic environment. The framework of functions developed and adopted in this research uses heuristic indicators constructed using elements from several analytical approaches in order to identify and understand these dynamics.

Niche-internal and firm-level activities

The development of a knowledge base is a fundamental activity of innovation systems [Bergek *et al.* (2008a,b)] and initially occurs mainly within firms and protected market environments, or niches [Smith *et al.* (2014)]. Knowledge accumulates through several formal and tacit learning processes (see also Subsection 2.1.3). *Development of formal knowledge* {*F1*} is a function used to capture the level of formal scientific research and development activities resulting from targeted investment. Appropriate metrics for the current state and dynamics of knowledge development are learning curves and quantitative indicators including patents, bibliometrics (citations, publications), number of R&D projects, industrial assessments etc. [Bergek *et al.* (2008a)]. *Materialisation* {*F2*} is used to describe knowledge embodied in physical artefacts, including equipment, prototypes, production plants and infrastructure.

The third dimension of knowledge development relates to the learning-by-doing and learning-by-using processes that occur when new firms emerge, introduce new products to markets and initiate feedback loops with the users of the new technologies. *Entrepreneurial experimentation* {*F3*} measures the aggregate wisdom gained through these activities, as well as the resultant reduction of technological uncertainty by means of the process of trial and error. Quantitative indicators of experimentation include the number of new entrants, the number of different types of applications and the breadth of complementary technologies employed [Bergek *et al.* (2008a)]. *Business model innovation* {*F4*} on the other hand is a function that focuses on how existing firms gain competences by adapting to the changing socio-economic environment, and how their business strategies reflect this wisdom.

TIS-internal dynamics

Apart from the development of knowledge through various learning processes, its diffusion is a central function of the innovation system. The transmission and retention of knowledge is achieved through academic, professional, industrial and market networks [Hekkert *et al.* (2007b)]. *Knowledge diffusion through networks* {*F5*} is used to measure how advanced this transmission is, using both quantitative and qualitative metrics including the number and magnitude of sectoral associations, the cross-linking of experiments and platforms, the coordination of R&D activities and intellectual property rights, the issuing of best-practices etc.

Resource Mobilisation {*F6*} is an indicator that quantifies the resources that are allocated for the development of the innovation system in terms of human capital, financial assets, physical infrastructure etc. It can be measured using indicators including the volume of seed and venture capital, quality and volume of human resources (e.g. number of formal qualifications) and availability of complementary assets [Bergek *et al.* (2008b)].

New technologies either serve an original market segment where they have a competitive advantage, or they compete in established segments under normal market conditions. In the latter case, they usually lack the price structure that could make them competitive and hence, they need institutional protection by means of policy intervention. In either case, they are fostered within market niches, until they are ready to directly compete with incumbent technologies. *Market Formation* {*F7*} is used to reflect on the mechanisms behind the creation of such niches. In order to assess that function in a TIS it is important not only to identify and analyse current markets but also evaluate the processes that drive or hinder the formation of new ones [Bergek *et al.* (2008a)].

The integration of emerging technologies into the socio-technical configuration requires a critical mass and a certain level of momentum from their niches. *Niche cumulation and dominant designs* {*F8*} is a function that reflects this dynamic by measuring the level of niche cumulation and the emergence of certain technological trajectories, or 'dominant designs'. Other indicators of niche maturity include the involvement of powerful actors, the demonstration of promising learning curves and the capture of a significant market share [Geels and Schot (2007)].

TIS interaction with other innovation systems

Technological sectors that are proximal either geographically or with regards to their knowledge base interact with each other. This interaction may include the mutual benefit from knowledge spillovers, collective use of supply chain elements, increased recognition as well as exclusion from resources by competitive technologies. The BIPV sector in particular, is affected by developments in other sustainable energy systems, the power storage industry, distributed generation technologies etc. *Development of positive externalities* {*F9*} is used as an indicator of the aggregate effect of these interactions on the innovation system in focus and despite its name, it may also demonstrate a negative trend.

Interactions at the regime level

In order to achieve broad market deployment, a novel technology needs to comply with the existing configuration. *Legitimation* {*F10*} measures the social acceptance and the level of compatibility of the new technology with the current regulations and user routines. In order to assess legitimation in a TIS, both the existent levels and the activities related to legitimacy development need to be analysed. These activities include the formation of visions and expectations, market regulations and the direction of science and technology policy [Bergek *et al.* (2008a,b)].

According to the Multi-Level Perspective (see also Section 3.3), the second prerequisite for technological change apart from a certain level of niche maturity, is the destabilisation of the socio-technical structure. This misalignment of the incumbent norms is usually caused by pressures from the landscape level, internal tensions or changes in user preferences. *Tensions in the incumbent configuration* {*F11*} is a function that mirrors the collective effect of these pressures on the regime that make it more compliant with the novel technological options.

Interactions at the landscape level

As was explained in Subsection 3.1.5, landscapes represent the socio-technical background processes that provide the gradients for change. *Influence on the direction of search* {*F12*} refers to the combined effect of two different pressures: the direction of investment towards primary research in the TIS in focus and the guidance of the 'search heuristics' within the TIS along certain trajectories. This influence is measured using mainly qualitative metrics such as beliefs for growth potential, articulation of interest from customers, incentives and regulations [Bergek *et al.* (2008a)].

Table 5.2 provides an overview of the developed hybrid functional framework, an extended-TIS approach that was adopted throughout the empirical and analytical parts of this research.

Conceptual level	Function	Ref.
Contextual Dynamics		
Landscape	Influence on the direction of search	{F12}
Regime	Tensions in the incumbent configuration	{F11}
	Legitimation	{F10}
Other TISs	Development of positive externalities	{F9}
Sector level	Niche cumulation and dominant designs	{F8}
	Market Formation	{F7}
	Resource Mobilisation	{F6}
	Knowledge diffusion through networks	{F5}
Firm level	Business model innovation	{F4}
	Entrepreneurial experimentation	{F3}
	Materialisation	{F2}
	Development of formal knowledge	{F1}

Table 5.2: Hybrid (extended-TIS) functional framework (author's compilation).

Each function provides partial insights regarding the overall performance of the innovation system under investigation, indicating specific mechanisms that either induce or block the development of the system. Their cumulative assessment allows for an evaluation of the momentum of technological change and the potential for socio-technical transitions that will facilitate the integration of new technological applications in the dominant socio-technical configuration.

5.2.4 Process theory and Event history analysis

It is evident from the analysis up to now that innovation and technological change are complex systemic processes requiring not only the presence of certain structural elements, but also the fulfilment of certain functions. In order to understand such dynamic processes, a research methodology needs to be able to capture the level of fulfilment of these functions, as well as the ways they are interrelated [Hekkert *et al.* (2007b)].

The dominant research approach within social studies is the *variance theory* which explains changes in the outcomes (dependent variables) as the product of changes in the causal factors (independent variables), using mainly quantitative data to estimate the relative importance of these factors. However, by focusing on deterministic causation, this approach neglects qualitative evidence and fails to capture the underlying mechanisms that determine *how* technological change occurs [Hekkert *et al.* (2007b); Verbong *et al.* (2008)].

Process theory on the other hand, conceptualises change as the outcome of a temporal sequence of events [Pettigrew (1990); Van de Ven and Poole (2005)]. This approach uses qualitative and interpretive methods (e.g. empirical research and case studies) in order to reconstruct the event-chains and analyse how each function of the TIS affects the overall technological development and relates to other functions [Hekkert *et al.* (2007b); Verbong *et al.* (2008)]. Due to these strengths, this approach was chosen as the foundation for the development of the analytical methodology of this research.

The process approach uses an *event history analysis* as its operational instrument [Van de Ven *et al.* (1999); Poole *et al.* (2000)]. Events are instances of change with respect to the socio-technical system under investigation, enacted by actors who have preferences, interact and make decisions. They can be conferences, studies, policy measures, technological achievements, expressions of expectations etc. [Hekkert *et al.* (2007b); Suurs *et al.* (2009); Suurs and Hekkert (2009)]. A narrative is written with an explicit attempt to interpret and explain the event-chain, linking 'emerging conceptual and theoretical ideas inductively derived from the case to wider analytical themes' [Pettigrew (1990)].

In this research, a database was constructed based on various sources of published and empirical data. Narrative plots were then used to organise the evidence on the techno-economic context of the PV and BIPV sectors (Chapter 6) and the developments in the respective industrial, market and policy domains (Chapter 7). Separate narrative descriptions were then constructed based on evidence collected throughout two in-depth case studies (Chapter 8).

It should be clarified at this point that this approach does not directly follow the template of TIS event history analysis developed by innovation researchers in Utrecht University [inter alia Negro *et al.* (2007); Hekkert *et al.* (2007a); Negro *et al.* (2008)]. The multitude of empirical methods and the broad evidence base rendered a comprehensive analysis of the BIPV sector impractical.

The narrative descriptions in this research adopt a chronological order in a loose way, since the aim of the research is to provide selective analytical focus on the performance of the innovation system rather than a historical analysis of the sector. Throughout the narratives, events are linked to the framework of functions developed in Subsection 5.2.3. The allocated events can either positively or negatively contribute to the functioning of the system [Hekkert *et al.* (2007b)]. Finally, each function is assessed in terms of current status and contribution to the overall system performance (Chapter 9). The aim is to identify more general patterns as a first step towards the development of policy recommendations regarding the governance of the BIPV innovation system.

5.3 Methodology

Early on the designing of the research methodology, it was established that the complex nature of the cross-industry BIPV sector required a multi-layered approach for the collection of literature and empirical evidence. Therefore, a methodology of four distinct techniques was developed and employed in order to provide data at multiple levels and using different perspectives.

5.3.1 Desk-based research

Prior to the collection of empirical data, an extensive literature research was carried out in order to enhance the understanding of the technical and market characteristics of the PV sector, and establish the theoretical foundation of the research. This investigation of the international academic and industrial literature was sustained throughout the empirical research in order to inform the process with ongoing market developments.

Academic literature was the first source of evidence, providing an understanding of the broad context of the research and the principles for the development of the analytical framework. A review of similar studies on renewable energy technological innovation systems and sustainability transitions revealed the most relevant literary traditions and appropriate methods for the collection of empirical evidence. With regards to technological and market understanding, academic literature provided a strong yet limited background. Published research articles offer comprehensive reviews of the available technological options and historical overviews of markets and policy frameworks. However, they are not always able to capture the developments within the fast-changing PV industry.

The second major source of evidence was *industrial literature* including a range of PV specialist periodicals, newsletters and online resources that provided up-to-date information on industry and market conditions, cost and price dynamics, technological achievements and developments regarding regulations and policies. These also helped the identification of the main actors involved in the investigated sector and the construction of a preliminary database of potential interviewees for the empirical research. A list of the most referenced resources is provided in Table 5.3.

In addition to these resources, a series of webinars and podcasts organised by the International Solar Energy Society (ISES), Supergen Solar Hub, CSP Today, Solarbuzz and PennWell's Renewable Energy World contributed to the expansion of the knowledge base and provided insights from leading industry professionals.

Resource	Organisation	Type
Progress in Photovoltaics	Wiley	Journal
Photovoltaics International	Solar Media	Journal
Renewable Energy Focus	Elsevier	Periodical
Renewable Energy World	PennWell	Periodical
Solar Business Focus UK	www.solarpowerportal.co.uk	Periodical - Newsletter
PHOTON	www.photon.info	Periodical - Newsletter
PV-magazine	www.pv-magazine.com	Periodical
SWE	www.sunwindenergy.com	Periodical - Newsletter
SUN	Solarplaza	Newsletter and Web
PV-Insider	news.pv-insider.com	Newsletter and Web
REF	www.renewableenergyfocus.com	Newsletter and Web
GreentechSolar	www.greentechmedia.com	Web
PV-Tech	www.pv-tech.org	Newsletter and Web
Solar News	www.renewableenergyworld.com	Newsletter and Web
NBuzz	Solarbuzz	Newsletter
ISES SunBurst	International Solar Energy Society	Newsletter
SOLARIS	EPIA	Newsletter
BPVA weekly	BPVA	Newsletter
The Bulletin	roofing-today.co.uk	Newsletter

Table 5.3: PV specialist periodicals, newsletters and online resources (author's compilation).

5.3.2 Personal communications with academic, industry and policy experts

A series of *personal communications* complemented the desk-based research. The SUPERGEN PV21 consortium (of which this research project is part) provided access to a network of academics and industry actors who provided insights on technological specifications, manufacturing processes, system development issues and feedback from the end-market. Discussions with these experts were facilitated by 6-monthly conferences, and created a platform for the verification of information gained from other sources. Similar opportunities were offered by *networking* events organised by the Institute for Energy Systems (IES) of the University of Edinburgh, the Scottish Institute for Solar Energy Research (SISER) and the UK Energy Research Centre (UKERC).

A major source of interaction with academics and industry representatives was the European Photovoltaic Solar Energy Conference and Exhibition (PVSEC). The attendance of three consecutive events aided the development of a broad contact list and the establishment of personal relations with a range of actors across the supply chain. It also helped the development of the questionnaire which was used in the semi-structured interviews, and its testing through several short interviews.

National UK conferences and industry events facilitated further communications, especially with actors within the wider energy sector and policy representatives. These contacts were particularly important due to the innovation-systems approach adopted by this research. The initial communications were followed by emails in order to establish personal relations.

Table 5.4 provides a list of the main networking events that were attended, including conferences, workshops and seminars.

5.3.3 Semi-structured interviews with experts

In order to acquire a deeper understanding of the PV and BIPV technological and market domains, as well as their wider socio-technical environment, a series of *in-depth interviews* with key stakeholders were undertaken. The semi-structured technique was chosen as the most appropriate method for setting up the interviews. This technique uses open-ended questions that allow the respondent to provide narrative answers and the

Event	Location	Date	Type
Supergen PV21	Edinburgh	4/2011	Technical meeting
	Glyndŵr	9/2011	Technical meeting
	Bath	4/2012	Technical meeting
	Liverpool	9/2012	Technical meeting
EU - PVSEC	Hamburg	9/2011	Conference-exhibition
	Frankfurt	9/2012	Conference-exhibition
	Paris	10/2013	Conference-exhibition
PV SAT	Newcastle	4/2012	Conference-exhibition
Solar Power UK	Birmingham	10/2011	Exhibition
Solar UK	Watford	12/2013	Conference
BRE BIPV	Birmingham	10/2011	Conference
	London	10/2012	Conference
All Energy	Aberdeen	5/2010	Conference-exhibition
	Aberdeen	5/2011	Conference-exhibition
UK Energy System in Transition	Edinburgh	4/2014	Seminar
Commercialisation of Solar R&D	Loughborough	4/2012	Workshop
Transition Pathways	London	4/2012	Workshop
Solar Flair	Durham	11/2011	Conference
Transforming Scotland with Solar Energy	Glasgow	10/2013	Conference
Solar Energy Conference	Edinburgh	6/2014	Conference
Ecobuild	London	3/2011	Exhibition
	London	3/2012	Exhibition
	London	3/2013	Exhibition
	London	3/2014	Exhibition

Table 5.4: Attended conferences, workshops and seminars (author's compilation).

interviewer to guide the conversation and obtain qualitative data [Salant and Dillman (1994); Saunders *et al.* (2011)]. Additionally, asking the same questions to different actors aids the verification of information through the process of triangulation [Remenyi *et al.* (1998)].

The first step in the design of the interviews was the identification of the target population and the determination of the sample size. The sample was selected in order to represent most elements of the BIPV supply chain[3] including scientists, PV module manufacturers, system developers, project designers, EPCs (Engineering, Procurement and Construction) and users as is illustrated in Figure 5.7. The wider innovation system was represented by policy makers, regulatory organisations and industry associations, providing insights at different levels.

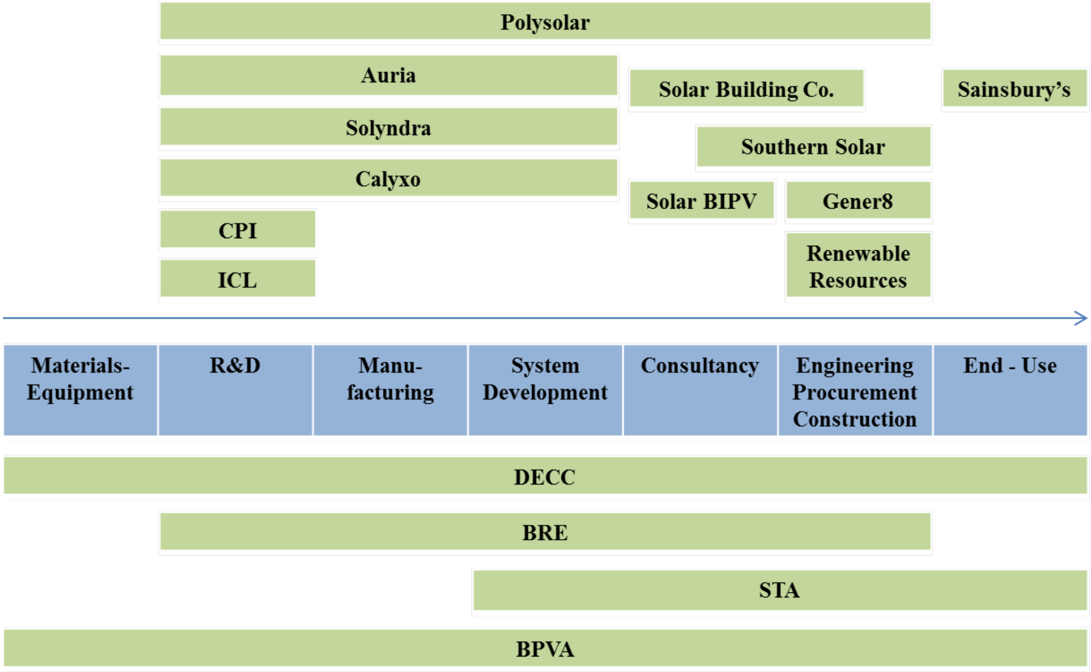

Figure 5.7: Distribution of interviewees along the BIPV supply chain (author's elaboration).

A crucial part of the preparation phase for the interviews was the development of the questionnaire. The selection and design of the questions directly affects the quality of the

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[3] Although upstream supply chain actors including material extractors and equipment providers play a role in the configuration of the cost structure of final products, their contribution to innovation processes was not considered to be crucial. Therefore, they were not included in the empirical research process. However, their role will still be discussed in the techno-economic review (see Chapter 6) and the analytical synthesis of the research (see Chapter 9).

acquired data [Lydeard (1991)]. This design was based on international guidelines for the conduct of surveys on innovation processes including the Oslo Manual [OECD (1997)], the Community Innovation Survey [DBIS (2011)] and previous empirical research on PV innovation [Marigo (2009); Candelise (2009)]. However, major adaptations were required in order to make it applicable to a range of actors within the technological domain relevant to this research.

The structure of the questionnaire consisted of two parts. The first part included questions regarding the background of the interviewee, the organisation, specifications of relevant products, processes and costs. The acquisition of quantitative data was facilitated by the use of a data-sheet that was handed in prior to the interview (see Appendix A.2). The second part referred to qualitative information regarding the wider socio-technical context, policy implications, current status of the domestic and international industry and the future development of the sector. Due to the diverse nature of the sample, not all questions applied to all interviewees. The generic questionnaire can be found in Appendix A.1.

The semi-structured interviews were conducted in person and over the phone throughout a period of two years (March 2011 to February 2013). They started with an introduction of the research background and objectives and typically lasted for 45-90 minutes. They were all audio-recorded with the consent of the interviewee, while notes were taken in order to help the transcription. Soon after the interview, respondents were contacted through email in order to verify the report and provide potential clarifications. A list of the interviewees is provided in Table 5.5. The codes in the first column will be used within brackets throughout the empirical research for referencing, in a similar style to bibliographical citations (i.e. [Ii]).

Despite its analytical strengths, the semi-structured interview technique also contained some limitations. Due to the time-consuming transcription process, the population had to be restricted to a small yet representative of the sector sample. Access to employees within organisations relevant to the study was difficult and often impeded by concerns regarding confidentiality and potential disclosure of sensitive data. Additionally, this difficulty in securing an interview implied an iterative process, resulting in long time lags.

However, the final sample of interviewees included professionals playing crucial roles

Ref.	Position	Organisation	Date	Type
I1	Professor	Imperial College London	11/2012	R&D
I2	Manager	CPI	2/2013	R&D
I3	Manager	Calyxo GmbH	5/2011	Manufacturer
I4	Deputy Manager	Auria	9/2011	Manufacturer
I5	Senior Director	Solyndra	3/2011	Manufacturer
I6	CEO	Polysolar	3/ 2012	System Developer
I7	Managing Director	Southern Solar	8/2012	EPC
I8	Technical Director	Renewable Resources	5/2012	EPC
I9	Technical Director	Gener8	3/2012	EPC
I10	Manager	Sainsbury's	2/2013	User
I11	CEO	Solar Building Company	9/2012	Consultancy
I12	Director	Solar BIPV	7/2012	Consultancy
I13	Director	STA	8/2012	Industry Association
I14	Chairman	BPVA	10/2011	Industry Association
I15	Principal Consultant	BRE	6/2012	Regulations
I16	Consultant	DECC	2/2013	Policy

Table 5.5: Semi-structured interviews (author's compilation).

across the innovation system and the supply chain. Additionally, the time frame of the interviews covered a critical period of the emerging PV and BIPV sectors, providing an ample empirical basis as the background for analysis.

5.3.4 Firm-level case studies

Semi-structured interviews not only helped throughout the exploratory phase of the investigation, but also provided a strong understanding of the dynamics within the socio-technical sector under analysis. In accordance with the research proposition that innovation is both a collective/systemic and an individual act, additional empirical evidence was required in order to focus on the intra-firm innovation processes. For that reason, the technique of *case-studies* was chosen as the most appropriate explanatory methodology to address the *how* and *why* questions of the research and establish causal relationships that could lead to a generalisable theory [Simons (1980); Stake (1995); Yin (2009)].

Case studies are empirical inquiries that investigate contemporary phenomena in depth and within their real-life context [Yin (2009)]. By analysing the dynamics present within single settings and using inductive (rather a statistical) generalisation, they can be useful in understanding complex phenomena in which there are many more variables of interest than data points [Eisenhardt (1989); Eisenhardt and Graebner (2007); Miles and Huberman (1984)].

Case studies rely on multiple sources of evidence, with data converging in a triangulation fashion. The research can be aided by the prior development of theoretical propositions that guide the data collection and analysis [Yin (2009)]. For this research these were facilitated through various empirical methods including literature reviews, online resources, interviews and field trips.

The designing of the case studies was based on methodologies that have been established and tested within the social studies literature [Stake (1995); Yin (2009)]. The technique for organising and conducting the research can be summarised in six steps:

1. Determine and define the research question.
2. Select the cases and determine the data gathering and analysis techniques.
3. Prepare to collect the data.
4. Collect data in the field.
5. Evaluate and analyse the data.
6. Prepare the report.

For the purposes of this research, two firm-level case studies were conducted, aiming to provide insights on how technical and wider socio-economic dynamics within the BIPV sector affect the strategic choices of companies within the sector, as well as on why certain choices have proven more successful in terms of market deployment.

Additionally, 40 firms active in the BIPV and the wider PV sector were preliminarily researched and monitored for a period of three and a half years from January 2011 to August 2014 in order to provide context for the corporate strategies analysis. Nine companies were further investigated and formed the basis for the comparative analysis (presented in Section 7.3).

The framing of the case studies follows the *two-level spatial perspective* (global and UK) of the research. This allows for a better understanding of the international scientific and manufacturing context, as well as the national market and policy characteristics of

BIPV, since both dimensions affect crucially the development and the dynamics within the sector.

Following this perspective and addressing the research questions outlined earlier in Section 5.1, two clusters of case studies were selected as the most appropriate, and are illustrated in Figure 5.8.

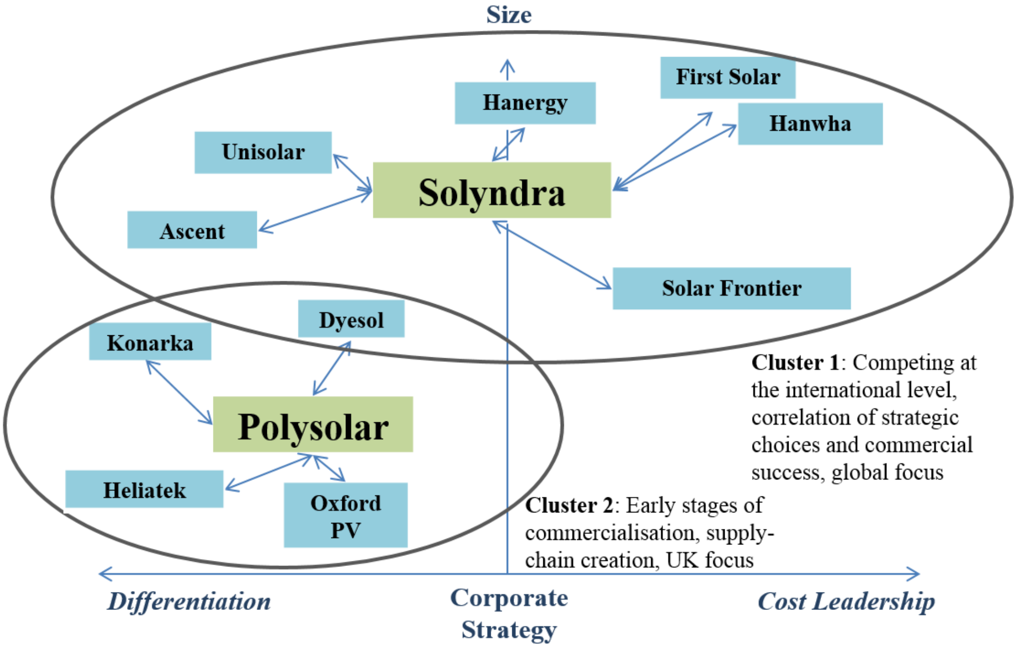

Figure 5.8: Mapping of the case study clusters according to size and corporate strategy (author's elaboration).

The *first case study* is structured around Solyndra, a USA-based firm that achieved international product commercialisation in 2008. Solyndra's tubular CIGS module is an innovative light-weight system that can be applied on industrial and commercial roofs. Despite the rapid market deployment and production scale-up, the company filed for bankruptcy in August 2011, raising questions related to the processes that affect the commercial success of premium PV products and the risks involved in diversifying activities into new products and markets.

This case was selected to provide an understanding of international pressures and drivers that affect the commercialisation potential of emerging PV products. The different phases in Solyndra's life cycle reflect not only firm-internal activities, but also processes in a rapidly changing socio-economic environment and a globalised supply chain. The analysis of these processes, and the comparison of the firm's strategic choices to those of successful competitors, allow for valuable observations regarding the adoption of either cost leadership or differentiation as a strategic model. Finally, the study provides insights for the BIPV sector in the UK, given the strong presence of the company in the early phases of the commercial-roof market segment.

The *second case study* focuses on an emerging UK-based manufacturer and system developer with strong R&D activity that is at the first steps of product commercialisation. Based in Cambridge, Polysolar Ltd was established in 2007 and specialises in opaque and semi-transparent glass PV modules that incorporate a-Si technology. These products are mainly used in building integrated systems (BIPV) such as facades, windows, roof tiles, canopies, car ports and greenhouses. The R&D department also focuses on organic polymer photovoltaics (OPV) and is currently in the manufacturing scale-up phase.

The aim of this case study is to assess the UK-specific characteristics of the BIPV sector. Integrating most of the supply chain with in-house research, system development and sales, the investigation of the firm provides insights regarding the performance of the BIPV innovation system in the UK. However, it does not neglect the international supply chain, looking into manufacturing activities and market deployment occurring overseas. A comparison to firms active in the same sector and in a similar commercialisation stage allows for broader observations and better assessment of corporate practices.

In the first stage of each case, a thorough literature review was carried out in order to collect all publicly available data related to the structural, operational and organisational history of each company. An initial techno-economic assessment of the products and a socio-techno-economic analysis of the respected market segments formed a basis for the next stages of the study.

During the second phase, a series of interviews (11 for the first case study, and 16 for the second) and surveys were carried out within each company. Target interviewees included executives, engineers, sales and marketing people, in order to get an understanding of corporate strategy of the firm, the relations with other industry actors and associations, the feedback from the market and the problems related to manufacturing, design and application of their systems. In order to have the whole supply chain perspective, interviews were also held with industrial and market partners of the companies both upstream (materials and equipment providers) and downstream (system developers, installers and users).

In the last phase, all data were combined and synthesised following the principles of process theory (see Subsection 5.2.4). For each case study an event history was constructed in order to set the background of the case. The business model of the focal firm was then described using the structure suggested by Chesbrough and Rosenbloom (2002) and addressing the main building blocks identified by Osterwalder and Pigneur (2010) (see Section 4.3). Finally, there was a firm-level analysis of all the collected data, as well as a cross-case analysis in order to recognise patterns and generalise the findings. The well-established relationships with firms' employees allowed for the reviewing of statements and first findings in order to ensure the validity and reliability of the research methods.

The empirical evidence collection methodology was adjusted and applied to the investigated clusters. The particularities of this methodology with regards to the techniques and time-frames, as well as the specific focus and aim of each case study will be further discussed in Sections 8.1, 8.2 and 8.3.

5.4 Summary and conclusions

This research is based on the proposition that innovation is both a systemic and an individual process. Therefore, in order to understand its dynamics and facilitate its governance, developments in both the firm level and the broader socio-technical configuration need to be looked into. BIPV in particular has the further characteristic of expanding over more than one industrial sectors, namely the PV power generation and the construction industries.

Various conceptual approaches have been developed for the analysis of innovation, and abundant implementations on real cases have provided a better understanding of technological change. However, they offer partial insights on the dynamics of complex innovation systems. Although the shortcomings of the various conceptual approaches and the potential for an integrated model has been discussed extensively in the literature, there has been limited work on the construction of an operational framework that can be readily implemented and used to facilitate the study of emerging cross-sectoral systems.

The analytical framework presented in this thesis combines elements from three different research strands, offering a structured methodology for the analysis of the BIPV sector at both an international and a national-UK level. This framework consists of twelve indicators or *functions* that identify and assess different innovation processes within the sector. Literature research findings and empirical evidence collected through personal contacts, interviews and two in-depth case studies will be presented in the form of narratives, where particular events are mapped to the functions according to the process theory methodology. The collective assessment of the functions will outline the performance of the innovation system, draw attention to potential weaknesses and link innovation dynamics to wider socio-technical transitions, providing insights for policy intervention.

Part II

Empirical Research

Introduction to the Empirical Research

Two particularities of the BIPV sector render it a notably complex technological domain. Firstly, it is an emerging sector lacking distinct dominant designs. On the contrary, the plethora of available PV technologies and the diversity of their applications have allowed for the development of numerous technological and market niches. Secondly, the development of BIPV applications involves the collaboration of professionals originating from two discrete industries: power and construction. This merging involves tensions with regards to the use of definitions, metrics and assessment criteria.

In order to identify and characterise innovation dynamics in this hybrid sector, the research adopts a multi-layered empirical methodology for the collection of evidence at different levels of aggregation. In the following chapters, a series of narratives will outline this empirical evidence, which will provide the basis for the analytical synthesis.

Chapter 6 provides an overview of the BIPV techno-economic domain, setting the context for the empirical research, and justifying the existence of multiple applications. It also aims to bridge the two discreet dimensions of the BIPV sector (energy and construction), by creating a common knowledge base regarding the technical and aesthetical characteristics of these applications.

Chapter 7 extends the analysis of the BIPV sector, addressing developments in the industry, market and policy configurations. A comparative firm-level assessment provides further insights regarding the correlation of business strategies and commercial success. By following a two-fold spatial perspective, the research investigates dynamics at both the global and the national-UK level.

Finally, Chapter 8 addresses dynamics within firms in order to provide a more micro-economic perspective. The analysis of two in-depth case studies highlights not only the significance of firm-level agency on the overall development of BIPV innovation, but also the effect of contextual processes on corporate strategies and the overall diversity of the sector.

Chapter 6

The Techno-Economic Domain of Photovoltaics in Buildings

Introduction

In contrast to other existing power technologies, most Building Integrated Photovoltaic (BIPV) applications are not just electricity generation devices, but rather multifunctional systems that also need to perform as traditional architectural elements. As such, BIPV systems may need to fulfil a range of tasks, depending on the level of building integration and the type of application. Some basic BIPV functions as building materials are illustrated in Fig. 6.1.

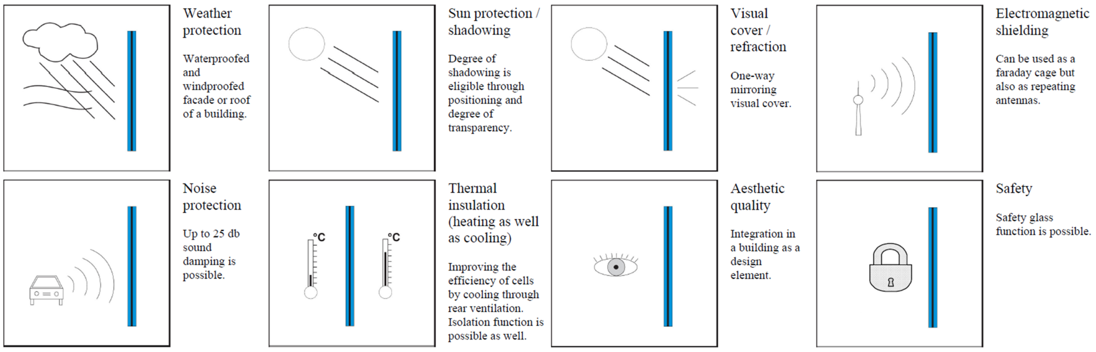

Figure 6.1: Basic functions of BIPV systems as architectural elements (adapted from Crassard and Rode (2007)).

Although in most energy technologies (including the utility-scale PV sector) *function* (in terms of power generation capability) is the primary concern and *form* (in terms of visual impact) comes after, in BIPV this paradigm is challenged. Architectural integration of BIPV requires the consideration of technical attributes at three levels [Hagemann (2004); SHC (2013a)]:

1. *Power generation:* This is the main utility of BIPV systems. The design of the

system is adjusted to the specific characteristics of the PV technology in order to optimise its performance and maximise its power yield.

2. *Functionality:* BIPV systems are components of the external envelope of the building and sometimes contribute to its structural framework. Therefore, they need to comply with building regulations and established practices.

3. *Aesthetics:* This is the dimension often disregarded by PV module manufacturers and system developers. However, 'integrability' of BIPV systems in terms of sizes, shapes, textures and colours is crucial for their wider adoption by the architectural community.

Additional contributing factors to the design and implementation of BIPV systems are user preferences, environmental concerns and financial constraints. The symbiosis of all these factors is illustrated in Fig. 6.2.

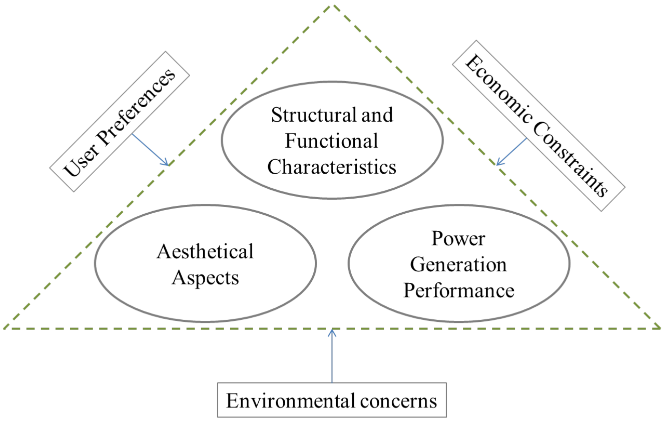

Figure 6.2: BIPV requirements for architectural integration (adapted from Hagemann (2004)).

The purpose of this chapter is to frame the techno-economic characteristics of BIPV systems, in order to facilitate the comprehension of the wide range of available applications and the justification of the segmentation of the market into multiple niches (see Chapter 7). As such, it relates to the second research question as it was formulated in Section 5.1. It also attempts to consolidate the two discreet dimensions of the sector (energy and construction), helping the reader understand the reasons behind the dissonance of perspectives among the involved actors and the struggle of niches to communicate and achieve collective legitimacy. Additionally, this hybrid energy- and building-oriented framing will create a knowledge base that will form the foundation of the analytical part of this research.

Section 6.1 focuses on the power generation capability of BIPV systems and their technical characteristics. The basic photovoltaic operation and available technologies are described, as well as the additional electrical and mechanical components needed for the operation of such systems.

Funtionality of PV systems is discussed in Section 6.2 where the main types of BIPV applications are outlined. The section also relates to aesthetics and user preferences regarding BIPV systems, taking into consideration the various levels of building integration and investigating the available and potential options.

Section 6.3 outlines the main performance aspects of BIPV systems, bringing together their power and aesthetical characteristics, while discussing the compromise that needs to be reached across these dimensions throughout the development of such systems.

Section 6.4 focuses on the economic characteristics and trends of BIPV systems and finally, Section 6.5 looks into environmental aspects of BIPV systems.

This chapter is based on review data and empirical evidence collected through personal communications and semi-structured interviews, and referenced in a similar style to bibliographical citations (i.e. [Ii]). Findings are linked to functions of the hybrid framework outlined in Section 5.2 using their reference codes presented in Table 5.2 within braces (i.e. {Fi}).

6.1 Power utility of BIPV systems

The power generation capability of BIPV systems arises from the operation of incorporated components known as *photovoltaic* (PV) *cells*. These consist of photo-active materials that convert sunlight into electric current. Depending on the PV technology, the type of application and the required power output, cells may be interconnected into *modules* [EUPVPlatform (2011); EPIA and GREENPEACE (2011)]. In many BIPV applications cells are directly integrated in architectural materials (e.g. glazing, tiles) without forming modules [Luque and Hegedus (2011)].

Although PV are autonomous power devices that can be connected directly to electric loads, in most applications they need to be configured in systems comprising of additional electrical and mechanical components. These *Balance of System* (BoS) components include cables, isolators, inverters (in the case of systems connected to the power grid), power storage units (e.g. batteries) and support structures. Two typical configurations of PV systems integrated in domestic buildings are illustrated in Fig. 6.3.

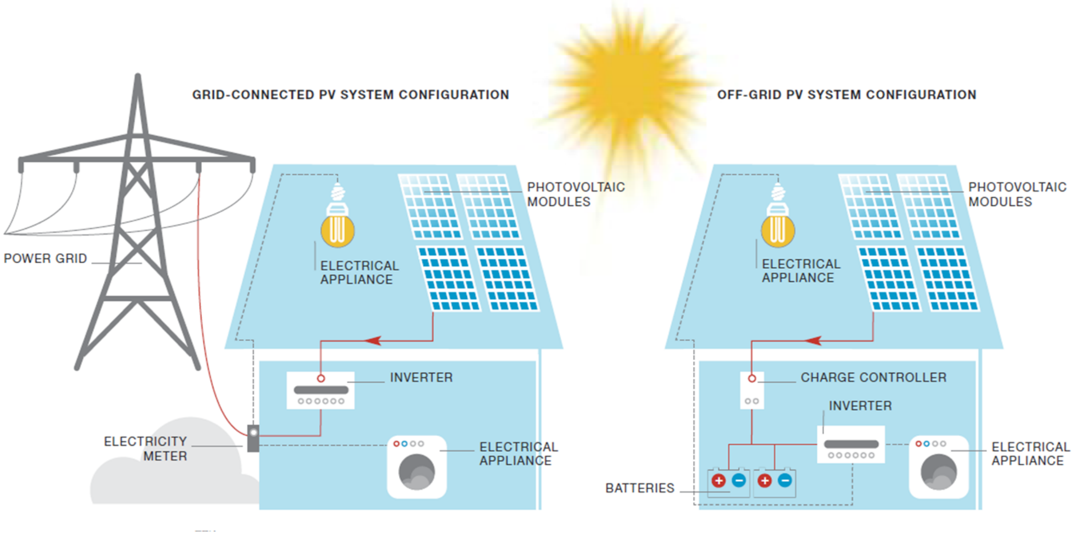

Figure 6.3: Configurations of PV Systems in Buildings [EPIA and GREENPEACE (2011)].

The following subsections will outline the basic technical features of PV devices and their BoS components.

6.1.1 Photovoltaic technologies

The term *photovoltaic* derives from the Greek word ‘phos’ ($\phi\varpi\varsigma$) meaning light and ‘volt’, the unit of electric potential, named after the Italian physicist Alessandro Volta who invented the first chemical battery [Oxford Dictionaries; Encyclopaedia Britannica]. PV technology involves the direct conversion of sunlight into electricity using semiconductor materials. Since the first discovery of the phenomenon by Edmond Becquerel in 1839 until the construction of efficient devices at Bell Labs in 1954 [Chapin *et al.* (1954)], the development of the technology involved significant scientific achievements and the combined work of leading physicists including Max Planck, Albert Einstein and Edwin Schrödinger [Green (2000); Luque and Hegedus (2011)].

Sunlight is composed by particles called *photons*, distributed over a wide energy spectrum. Semiconductors are materials with weakly bonded electrons, that may conduct electricity or not depending on certain conditions. When light is absorbed by a semiconducting material, photons with sufficient energy may break these bonds, releasing (or *exciting*) electrons and generating negative and positive charge carriers in the material [Boyle (1996); Luque and Hegedus (2011)].

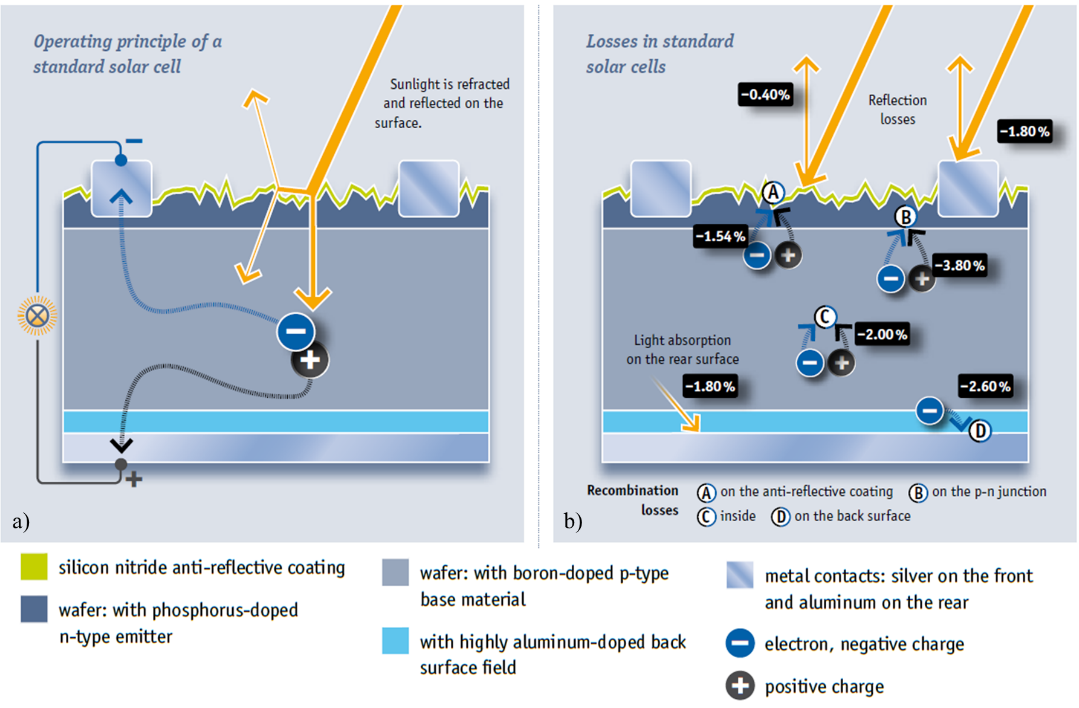

Figure 6.4: a) Photoelectric effect and b) Losses in PV cells [Solarpraxis (2012)].

PV cells consist of at least two layers of semiconducting materials that have been contaminated (or *doped*) with chemical elements in order to create a surplus of either positive (p-type) or negative (n-type) charge carriers [Boyle (1996)]. At the interface of these layers (p-n junction), an electric field is formed that ensures the coordinated move of excited electrons towards a specific direction. If an electric load is connected to the opposite sides of the cell, electrons will flow through the formed circuit, constituting an electric current [Green (2000)]. This simplified process is illustrated in Fig. 6.4a.

The minimum amount of energy necessary to excite an electron is called *band-gap energy* and is specific to the semiconductor. Photons with energy lower than that threshold will be absorbed by the back material of the cell increasing its temperature. The ones with more energy will create pairs of charge carriers, while the excess energy will be again dissipated as heat in the cell. These ‘spectrum losses’ pose an upper limit in the proportion of incident light power that can be converted into electricity, which is 48%. Taking into account the process of recombination of charged particles before they reach the electrodes, the highest theoretical conversion rate (*cell efficiency*) that can be achieved by a single pn-junction semiconductor is limited to 33.7%. This efficiency is further reduced in practice mainly by reflection of photons at the front materials and impurities in the semiconductor crystal structure. Therefore, the maximum efficiency of single-junction PV cells achieved in laboratories reaches 28.8%. Higher conversion efficiencies can be achieved in multi-juction cells, or by increasing the incedent sunlight using optics [Green (2000); Luque and Hegedus (2011); Solarpraxis (2012); NREL (2014)]. A synopsis of these losses (disregarding spectrum losses) is provided graphically in Fig. 6.4b.

A variety of semiconductors with different properties have been considered for the production of PV cells {F1}. The most common categorisation of cell technologies was introduced by Martin Green, and is based not only on the semiconductor materials and inner structure, but also on the level of commercial development [Green (2001); Candelise (2009); EUPVPlatform (2011); EPIA and GREENPEACE (2011); Solarpraxis (2012)]:

- *First Generation* cells are made from thin slices (*wafers*) of crystalline silicon cut from either a single crystal or a block of silicon. They have dominated the PV industry since its very beginning and are considered to be the maistream PV technology {F8}.

- *Second Generation* technologies are based on thin films (TF) of inorganic semiconductor materials including silicon (amorphous silicon or micro-crystalline), cadmium-telluride (CdTe) and copper-indium-gallium-selenide (CIGS). Although they offer the potential of lower manufacturing costs and more versatile application, they have not yet achieved broad market penetration.

- *Third Generation* technologies include PV cells made from organic materials, concentrator devices and multi-junction semiconductors. Most technologies in this category have not reached commercialisation, and are being developed with the prospect of either reducing the manufacturing costs drastically or achieving ultra high efficiencies.

Fig. 6.5 provides an illustration of these technological families.

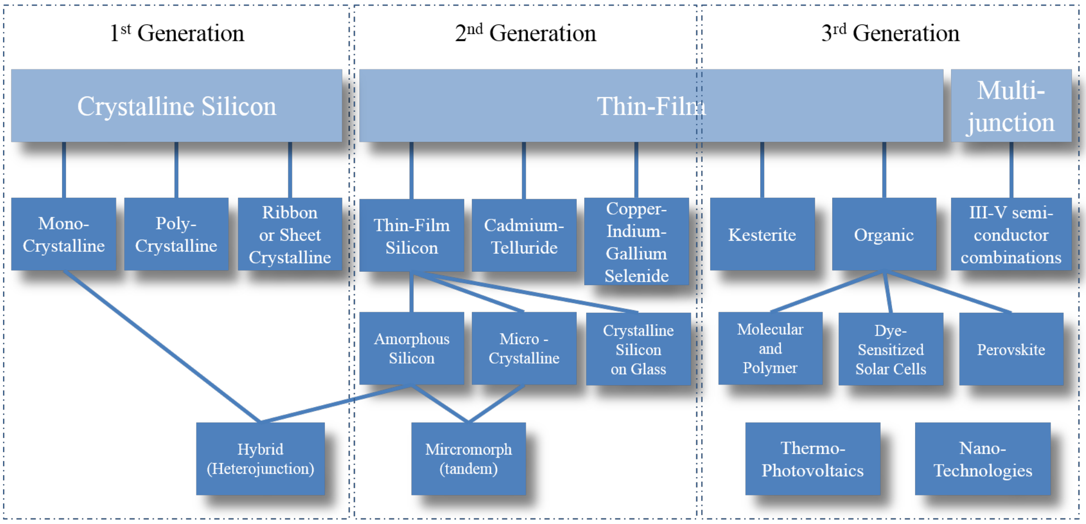

Figure 6.5: Categorisation of solar cells (author's elaboration).

First generation: Crystalline silicon technologies

Wafer-based crystalline silicon (c-Si) is the most prevalent PV material, with 91% of module capacity sold in 2013 based on this technology {F8} [Mints (2014a)]. This market domination may be attributed to the wide availability of silicon[1] and its well-balanced set of electronic, physical and chemical properties as a semiconductor. Additionally, the first-generation PV industry has been benefiting from its symbiosis with the well-established Integrated Circuit (IC) industry, that has provided a knowledge base for materials, processes and manufacturing tools, as well as a production mass capable of reducing costs through economies of scale {F1 and F2} [Green (2000); Bagnall and Boreland (2008)]. These knowledge and learning spillovers are missing from other more radical technological niches within the PV sector, and are considered to be a common factor behind the market prominence of c-Si materials {F8} [I1; I6].

There are two main types of crystalline silicon cells: *monocrystalline* (monoc-Si) and *polycrystalline* (polyc-Si) cells[2]. Both types use polysilicon feedstock produced by the high purification and processing of silica. Ingots are then created by melting doped

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[1] Silicon is the second most abundant element in the earth's crust after oxygen and is commonly found in quartz and sand [Green (2000); Marigo (2009)].

[2] The terms *single-crystal silicon* and *multi-crystalline silicon* are also used to name the two types of cells. Although there is no consensus in the literature, this study will adopt the *mono-* and *poly-* denomination.

polysilicon into a single crystal using the Czochraski process or polycrystalline blocks using casting processes[3]. Wafers are then sawn from the ingots (see Figure 6.6a), and finally cells are constructed through processing (etching and doping) and the addition of elements including anti-reflective coating and electrodes [Green (2000); Luque and Hegedus (2011); Solarpraxis (2012)]. The final structure of a c-Si cell is illustrated in Fig. 6.6b.

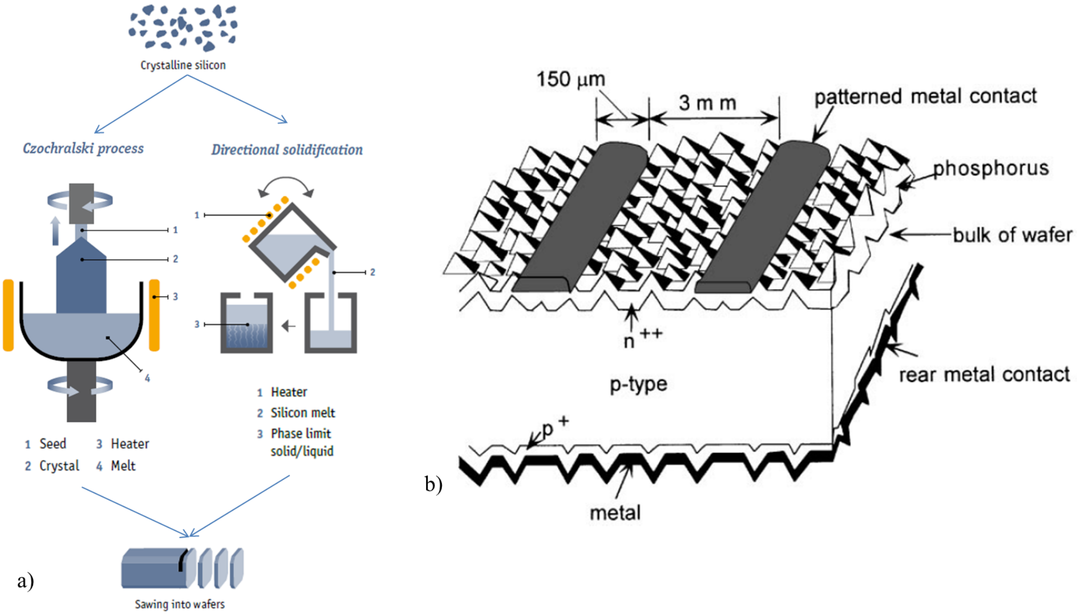

Figure 6.6: a) Manufacturing process of c-Si [Solarpraxis (2012)] and b) Structure of a typical c-Si PV cell [Green (2000)].

Other crystalline silicon technologies have been developed in order to either bypass energy- and material-intensive processes including crystal growth and ingot sawing, or increase cell efficiency. *Ribbon and sheet-defined film growth* is a technique that eliminates the sawing step requiring 30% less silicon feedstock than wafer methods [Solarpraxis (2012)]. Although the technology was commercialised in 2006 by Evergreen Solar, production diminished after the company filed for bankruptcy in 2011 within a wider consolidating industry (see also Section 7.1) [Church (2011)].

The *Heterojunction with Intrinsic Thin layer* (HIT$^{\mathrm{TM}}$) is a PV technology that combines crystalline silicon with amorphous silicon layers (see Subsection 6.1.1) in order

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[3] Other ingot manufacturing processes have also been developed; however, they are not included in this review due to space limitations.

to increase cell efficiency. HIT cells are bifacial, able to convert light hitting either surface of the module, making use of reflected and indirect illumination. The technology was commercialised by Sanyo and is currently owned by Panasonic [Green (2000); EPIA and GREENPEACE (2011); Stuart (2011)].

PV cells are interconnected into strings and encapsulated into layers of plastic films and glass. These layers offer electrical isolation and protection from corrosion, mechanical damage and thermal shocks. The durability of this structure is crucial for the operating lifetime of the module, an important design factor in BIPV applications [I2; I4; I6]. The entire cradle-to-grave life-cycle of a c-Si module is summarised in Fig. 6.7a.

Second generation: Thin-film technologies

The development of Thin-Film (TF) semiconductors and their use as PV materials instead of silicon wafers is based on the proposition that reduced use of active materials and alternative manufacturing processes can lead to significantly lower production costs [Green (2000)]. In contrast to silicon, these materials have direct band-gap energies, resulting in very high absorption coefficients. TF require layers of less than 1 micrometer (μm) in order to form efficient PV devices [EUPVPlatform (2011)]. These layers are deposited on inexpensive substrates including glass and flexible foils allowing for roll-to-roll production [Solarpraxis (2012)]. Flexibility in terms of substrate materials and module shapes due to deposition manufacturing processes allow for a wide range of applications and renders TF PV technology particularly suitable for integration in building elements {F7} [I15].

Amorphous-Silicon (a-Si) is the primary material used in TF silicon (TF-Si) devices. Although a-Si demonstrates much better absorption characteristics than c-Si resulting in thinner active layers, the amount of generated charge carriers is rather low. Additionally, a-Si cells degrade significantly during their first hundreds of hours of operation under sunlight due to a phenomenon known as Staebler-Wronki effect [Miles *et al.* (2005); Kazmerski (2006)]. Therefore, stabilised efficiency of single-junction a-Si cells does not exceed 10% in commercial applications [Kho (2010)]. Configurations of multiple junctions or combinations of a-Si with micro-crystalline silicon (*micromorph*) have demonstrated better efficiencies [Solarpraxis (2012)]. Another way to reduce silicon

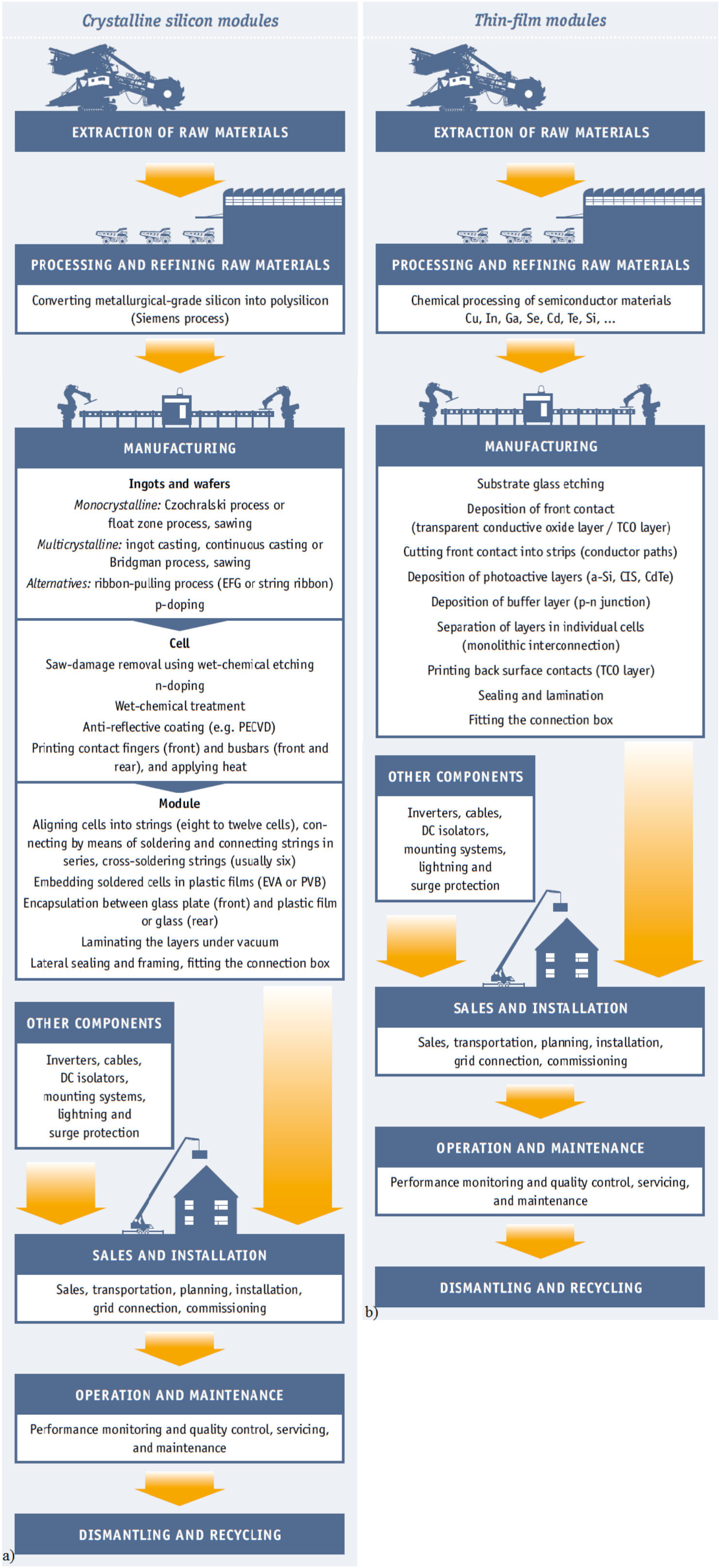

Figure 6.7: Life Cycle of a) c-Si and b) TF PV modules [Solarpraxis (2012)].

usage in PV cells is by depositing thin layers of polyc-Si on glass (Crystalline Silicon on Glass - CSG) in a structure similar to the one illustrated in Fig. 6.8 [Green *et al.* (2004)].

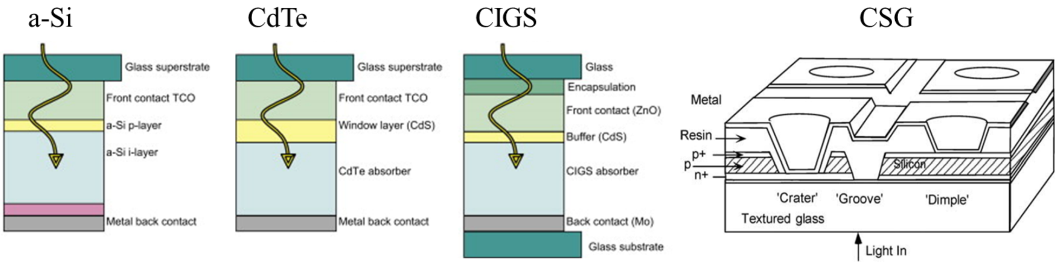

Figure 6.8: Schematics of TF PV devices [Bagnall and Boreland (2008); Green *et al.* (2004)].

Cadmium Telluride (CdTe) is a near-optimum semiconductor that can absorb most of the incident light in layers just a few microns thick [Miles *et al.* (2005)]. Despite initial health and safety concerns and potential environmental hazards from incorporating cadmium in power devices, extensive studies show that such issues can be easily resolved through thorough tracking of deployed products and recycling regimes [Kazmerski (2006)]. Solar modules were exempted from pre-existing bans against the use of hazardous substances in electrical and electronic devices in both the EU and Japan [I3; Osborne (2011a); Gifford (2013a)]. First Solar is the only Gigawatt-scale manufacturer of CdTe modules, capturing 5% of the global PV market in 2013 and having demonstrated significant improvements in both lowering manufacturing costs and increasing efficiency, recently surpassing that of polyc-Si cells {F2, F7, F8} [Mints (2014a); NREL (2014)].

Chalcopyrite compounds are a family of semiconductors including copper-indium-diselenide, copper-indium-gallium-diselenide and copper-indium-disulphide, usually referred to using the generic abbreviation CIGS. Due to their high tolerance towards crystal defects and impurities, CIGS materials have lower requirements on raw materials and processes than other semiconductors, resulting in a greater scope for cost reduction [Solarpraxis (2012)]. The record efficiency of CIGS modules in laboratories has surpassed that of both polyc-Si and CdTe ones, and manufacturing processes have been developed for the deposition of films on a range of rigid and flexible substrates [NREL (2014);

Cheyney (2010)]. In spite of these advantages, manufacturing of the technology has been rather slow to scale up, mainly due to slow transfer of scientific achievements to the production lines and the lack of standardised equipment, with total CIGS sales capturing 2% of the global PV market in 2012 and 2013 {F2, F7, F8} [Mints (2014a); Bagnall and Boreland (2008)].

TF modules can be assembled by singulated cell processes similar to the ones followed by the c-Si industry. Thin layers of semiconductor are deposited on a substrate, cut into cells and interconnected into strings and modules. However, the true potential of TF for cost reduction and high throughput rates can be achieved by eliminating manufacturing processes using *monolithic integration*. In this technique, the semiconductor material is deposited on the substrate or superstrate and all the electrical connections are created in situ. The final module is created by laminating the single cell into a weather-proof encapsulant [Solarpraxis (2012); Cheyney (2010)].

TF technologies offer the potential of versatile, efficient modules at low production costs. Their life-cycle contains less steps than that of c-Si as shown in Fig. 6.7b. Photo-active layers can be deposited on substrates of various shapes and materials, using low-cost techniques (e.g. printing) {F7}. However, this potential has not been realised in practice yet [I8; I9; I15]. Efficiencies of modules in production lines are significantly lower than those of c-Si, and the manufacturing cost is not low enough to compensate for the consequent additional cost of BoS. This is partly due to the gap between lab and production efficiencies, resulting from stability issues, poor material reproducibility and uniformity over large areas. Additionally, the TF industry has not benefited from knowledge spillovers from a mature sector, as was the case of c-Si and the IC industries. TF manufacturers follow proprietary procedures and utilise bespoke production lines and equipment, not allowing for economies of scales and fast learning rates {F1 and F2} [Bagnall and Boreland (2008); Gazis *et al.* (2013)].

Third generation: Emerging technologies

The so-called *third PV generation* refers to technologies that are not widely commercialised. These emerging technologies have the potential of either increasing drastically the power output of the cells through higher conversion efficiencies and concentrator devices, or decreasing the manufacturing cost by utilising abundant or organic materials and cost-effective processes.

Multi-junction Cells (MJC) use several alloyed semiconductors stacked on layers. By using materials with varying band-gap energies, MJC reduce spectrum losses and increase significantly the theoretical limit of conversion efficiency, with record efficiencies currently reaching up to 44.4% [Miles *et al.* (2005); NREL (2014)]. In order to compensate for their high manufacturing cost, these cells are used in conjunction with optic devices that focus sunlight (up to a 1000 times) onto small collection areas (Concentrator Photovoltaics - CPV) and tracking systems that align them towards the sun. The high power-to-weight ratio of these devices make them attractive for space applications; however, there is also potential for commercial and utility-scale terrestrial applications at regions with high solar radiation {F7} (see Fig. 6.9) [Karam *et al.* (1999); Kazmerski (2006); EPIA and GREENPEACE (2011)].

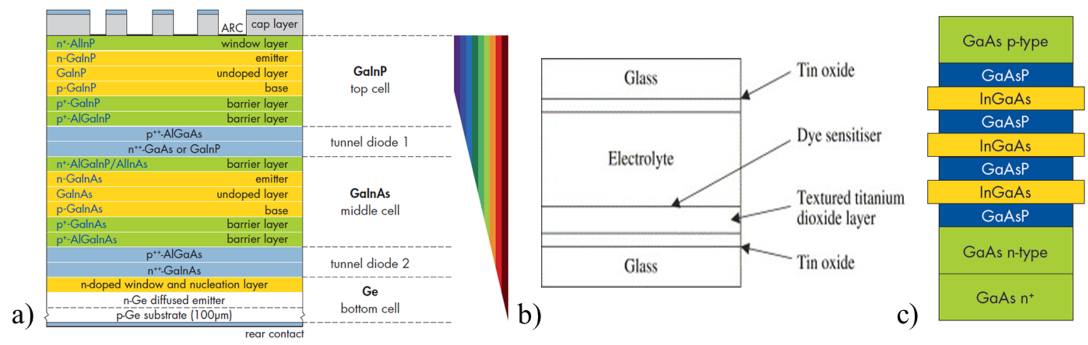

Figure 6.9: Schematics of a) a GaInP/GaInAs/Ge triple-junction cell [EUPVPlatform (2011)] b) a Grätzel DSSC [Miles *et al.* (2005)] and c) a QW-based approach.

Kesterite (CZTS) solar cells are thin films with similar characteristics to CIGS. However, in this technology rare elements such as indium and gallium are replaced by zinc and tin, making it less susceptible to potential issues regarding availability and increasing costs of materials [Mitzi *et al.* (2011)]. The emerging technology has attracted significant research and commercial interest from leading materials and electronics firms including IBM, DuPont and Solar Frontier {F1} [Deign (2012); Gupta (2014)].

Organic Photovoltaics (OPV) use molecular and polymeric semiconductors along with fullerene in order to generate charge carriers in a process similar to photosynthesis. This technology has been used in Organic Light-Emitting Diode (OLED) and thin-film transistors in consumer electronics [Miles *et al.* (2005); Solarpraxis (2012)]. Simplicity of deposition processes, flexibility of layers and the prospect of very low cost of materials is currently driving an increased interest in OPV, especially in BIPV {F7} [Nelson (2002); EPIA and GREENPEACE (2011)]. However, low conversion efficiencies and unresolved stability issues impede the diffusion of applications in the market [Miles *et al.* (2005); Kazmerski (2006)].

Dye-sensitised solar cells (DSSC) also use organic materials to construct photo-electrochemical devices known also as *Grätzel cells* (see Fig. 6.9b) [Miles *et al.* (2005)]. *Perovskite*-structured semiconductors are based on inexpensive organic materials that can be easily deposited on large surfaces. In less than five years of development, this technology has demonstrated substantial efficiency improvements, rendering it one of the most promising options for BIPV applications [Hodes (2013); Gifford (2013b)].

Other emerging PV technologies include power generation from heated bodies using *thermophotovoltaics* and *nanotechnologies* that have the potential to create layers of high conversion efficiency (e.g. *quantum wells* (QW) - see Fig. 6.9c). Most approaches are at the demonstration stage and are expected to achieve commercialisation as additive technologies, increasing the output of conventional PV systems [Green (2001); Kazmerski (2006); EPIA and GREENPEACE (2011)].

6.1.2 Electrical BoS components

In order for the photo-active components of a PV system to be able to provide useful electric power to a load or the grid, they need to be connected to a range of electronic devices.

Inverters are the second most important component of PV systems after PV generators [Luque and Hegedus (2011)]. These devices convert Direct Current (DC) provided by modules into Alternating Current (AC). This is essential in grid-connected applications where synchronisation of generated power with the electricity distribution network is required, but also in off-grid applications in order to supply AC-compatible appliances. Since all of the solar power flows through the inverter, its properties fundamentally affect the overall performance of the PV system. Modern inverters are equipped with a range of features including control (e.g. Maximum Power Point tracking), protection and data recording devices for the analysis and monitoring of the system [EPIA and GREENPEACE (2011); Sonnenenergie (2007)].

Power storage devices are mainly used in applications that are not connected to the power grid in order to store excess electricity produced throughout the day and supply it to the load when PV modules do not generate (e.g. at night or when cloudy) [EPIA and GREENPEACE (2011)]. They can also be used in grid-connected systems in order to control when generated power is exported to the grid, and hence maximise the benefits from either self-consumption or selling power at peak times [I12; I15]. Despite the wide range of available technologies that span from thermal storage to mechanical devices (including flywheels, pumped hydro-power, compressed air), chemical storage in the form of batteries is the most appropriate technology for the distributed character of PV systems [Kogiou (2010); Barker (2014a)].

Limited life expectancy and high cost are two characteristics that render batteries the weakest among BoS components [Luque and Hegedus (2011)]. However, the rapid expansion of the electric-vehicles (EV) industry will provide a considerable distributed storage capacity, since the batteries of these vehicles can be used in smart-grid configurations through charging and discharging cycles {F9}. Moreover, the consequent expansion of the Lithium Ion (Li-ion) battery manufacturing capacity is expected to lower their cost, and also facilitate the development of domestic power storage systems [Montgomery (2014a)].

Charge controllers are used in PV systems with power storage in order to prevent overcharging and deep discharging of the batteries. It is the link between the solar generator, the storage units and the load. Since battery lifetime highly depends on the way it is managed, this is a crucial device affecting the overall operational cost of the PV system [EPIA and GREENPEACE (2011); Luque and Hegedus (2011)].

Other electrical components of PV systems include DC and AC cables and connectors for the linking of the system to the storage device and the grid, combiners and junction boxes for the interconnection of modules and inverters, isolators and power meters for the measurement of the generated electricity [Sonnenenergie (2007); Luque and Hegedus

(2011)].

6.1.3 Mechanical BoS components

Apart from electrical components that are crucial for the safe and efficient use of the generated solar electricity, certain mechanical BoS elements are also needed for the structural support of the system and the maximisation of its energy yield.

Mounting systems are devices designed to physically support the solar modules. Depending on the type and position of the installation, the mounting system may need to tilt the modules towards a direction that is optimal for sunlight absorption, weatherproof and ballast them against high winds, or integrate them into the building envelope [Luque and Hegedus (2011); Zeeuw (2011); Sonnenenergie (2007)].

In PV systems where power output maximisation is required, *tracking devices* may be used in order to follow the sun and reposition the modules accordingly[4]. In other applications where limited space is available, *optics* may be used in order to increase the solar output of high efficiency modules. Refractive lenses or reflectors can increase the sunlight that reaches the photo-active materials, increasing significantly their power output [Luque and Hegedus (2011)].

Other BoS devices that might be included in PV systems are monitoring devices with internal memory or data transmission capabilities, security systems including closed-circuit television (CCTV), lightning and surge protection, building materials that facilitate a smoother integration of PV modules in buildings (e.g. inactive 'dummy' modules of certain sizes and shapes) etc.

6.2 Functionality of PV and BIPV systems

Photovoltaics are versatile power generation devices, with applications ranging over a wide power output spectrum. PV systems are used in consumer electronics to provide a power supply of milliwatts to a few watts, in remote dwelling electrification at a kilowatt-scale and in utility-scale solar farms (hundreds of kWp to GWp), supplying electricity to the distribution network. They are also highly modular and scalable, with

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[4] PV power output varies like the cosine of the angle formed by incident solar radiation and the perpendicular to the module. Therefore, output is minimal when the sun is at an oblique shallow angle relative to the module.

applications of all sizes comprising configurations of the same power units (modules) {F7} [Luque and Hegedus (2011)].

Although PV systems have been used in aerospace applications since as early as 1958, the first commercial modules became available in the mid 1970s [Solarpraxis (2012)]. PV applications are usually categorised based on whether they are connected to the power grid or not, as illustrated in Fig. 6.10 [Sonnenenergie (2007); EPIA and GREENPEACE (2011)].

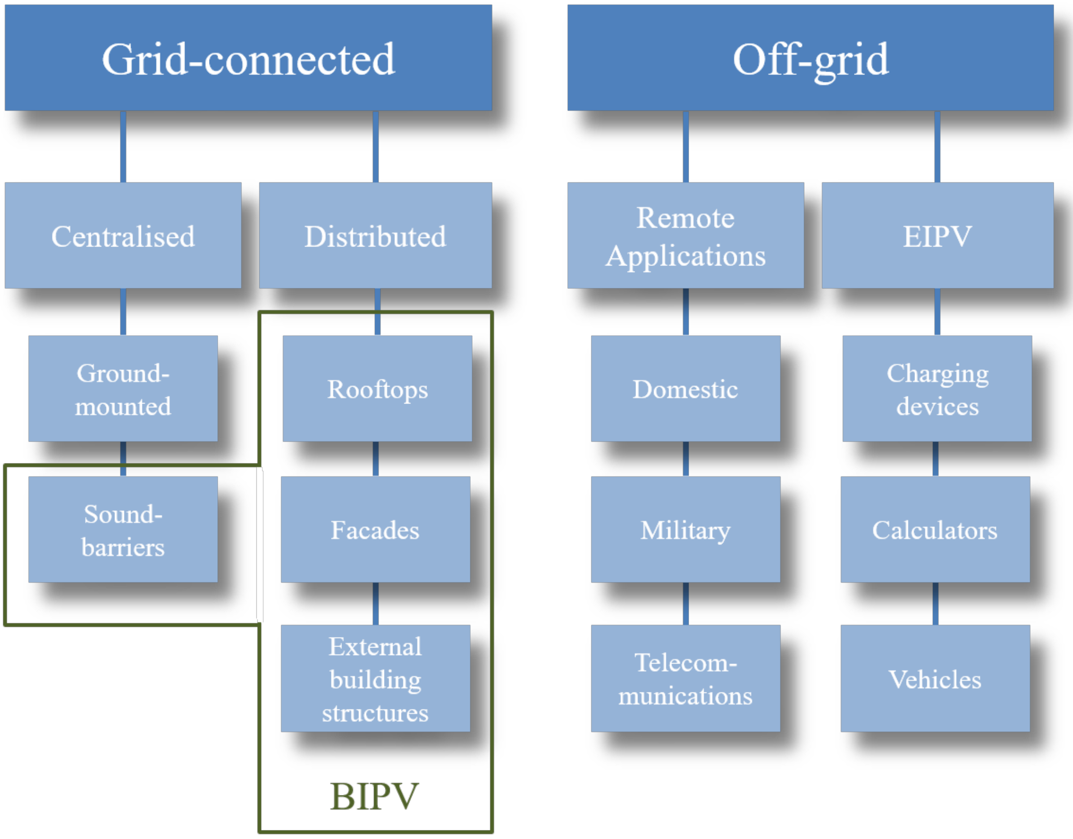

Figure 6.10: Categorisation of PV system applications (author's elaboration).

A significant amount of *off-grid* or *stand-alone* systems is used in remote regions with no access to centrally generated electricity. Applications include domestic use in rural areas of developing countries or islands, telecommunication systems, military camps, water pumps and traffic lights (see Fig. 6.11). Due to the intermittent nature of the solar resource, off-grid systems are often used along with power storage devices or in hybrid configurations with other renewable and fossil-fuel power systems [Sonnenenergie (2007); Luque and Hegedus (2011)].

Figure 6.11: Examples of off-grid applications (various sources).

Another family of off-grid applications involves consumer applications and Electronics-Integrated Photovoltaics (EIPV). The increasing amount of portable electronic devices has driven the demand for mobile power supply and storage. Many firms have responded to that demand by integrating PV cells in such devices or by developing products that can be used for battery charging (see Fig. 6.12) [Sonnenenergie (2007); Luque and Hegedus (2011)].

Figure 6.12: Examples of EIPV devices (various sources).

Grid-connected PV installations are differentiated according to whether they provide their generated power to a particular load (decentralised) or feed bulk electricity to the network similarly to centralised power stations (see Fig. 6.13). The former are mainly installed on commercial and domestic buildings, and form the technological domain of this research (see Subsection 6.2.1). The latter are usually ground-mounted systems installed in farms (*greenfield* land) or land occupied previously by industrial or commercial facilities (*brownfield* land). In both cases, installations are associated with a range of power electronics that establish the compliance of the installation with the grid [EPIA and GREENPEACE (2011); Luque and Hegedus (2011)].

Figure 6.13: Examples of utility-scale solar projects in the UK (photos by Lightsource Renewable Energy Ltd).

6.2.1 Building-Integrated PV

Residential and commercial buildings contribute about 40% of the energy consumption in developed countries, more than both the industrial and transportation sectors [Pérez-Lombard *et al.* (2008); EC (2013)]. Consequently, reduction of their energy requirements through increased efficiency and in situ production is a crucial component of a sustainability strategy [EU (2010); EC (2013)]. BIPV systems address the growing need for active technologies that maximise energy-efficiency of buildings, and in particular for distributed power generation devices {F9} [I12; I15].

Integration is defined as the combination of parts in order to form a whole and is therefore closely associated with the concepts of interdependence and interaction [Oxford Dictionaries; Prasad and Snow (2005)]. According to the architectural community, *building integration* refers to the functional and structural combination of materials, while *architectural integration* adds the highly subjective criterion of aesthetic incorporation [SHC (2013a,b)]. However, the term has been used loosely within the PV and construction industries to characterise various configurations of PV systems installed in buildings without particular consistency [Crassard and Rode (2007)].

In this work, the term BIPV has been broadened to include PV systems installed in existing and new buildings, as well as multifunctional systems incorporated in urban infrastructure and developed not with the sole purpose of power generation. According to this definition, PV devices used to power urban equipment including parking meters, street lights, waste bins and information boards are excluded from this analysis, although sheltering structures, carports and noise barriers are included.

Three levels of integration are identified, as illustrated in Fig. 6.14 [Crassard and Rode (2007); SHC (2013b)]:

- *Application* (Building Applied PV - BAPV) refers to systems that are added over the actual envelope of the building. There is controversy regarding the classification of these applications as BIPV, due to their lack of multi-functionality.

- *Constructive addition* includes conventional building materials that have been manufactured with inherent PV capability and systems where PV modules partially replace elements of the actual envelope.

- *Constructive integration* refers to systems that fully replace conventional building materials and therefore, need to fulfil all of their functions.

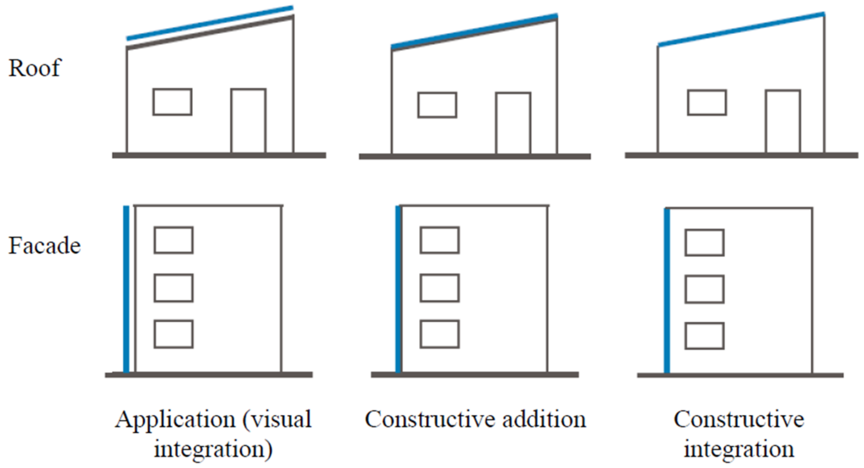

Figure 6.14: Levels of integration [Crassard and Rode (2007)].

Although the technical differentiation among these levels is certain, the socio-economic drivers and barriers to their diffusion are also different to some extent [I1; I6; I12; I15]. Different levels of integration imply different levels of disruption with regards to established practices in the construction sector, and different potential for replication of the systems, leading to different potential for scaled deployment {F8}. Therefore a granular approach to PV in buildings was considered as the most appropriate approach in this analysis.

Under this framing, a typology of BIPV applications can be defined according to their position within the building: systems on roofs, facades and external structures [SHC (2013b)].

Roofs

Roofs have been the obvious solution for PV installations in buildings due to their pertinent location with respect to the solar resource. A great range of products has been developed spanning all levels of integration {F7}.

Sloped roofs offer an ideal platform for PV systems that require a tilted position for optimal performance (see Section 6.3). BAPV devices consist of a mounting system that retains the modules against gravitational and weather-related loads. Although the increased profile of these systems offers ventilation to the modules leading to increased energy yields, they are usually considered aesthetically unappealing (see Fig. 6.15) [Prasad and Snow (2005)].

Figure 6.15: Examples of BIPV on sloped roofs (photos courtesy of Hanergy, Systaic, Unisolar and Solon).

More aesthetically pleasing systems have been developed that fall into the category of constructive addition (see Fig. 6.16). These products include either mounting systems and laminates that replace part of the roofing material or prefabricated PV tiles, shingles and slates that formally match with common building components. These systems are generally more expensive than BAPV and need to comply with several weather-proofing requirements [SHC (2013b)].

Figure 6.16: Examples of BIPV slates and tiles (photos courtesy of Solar Slate, Tegola Solare, SRS Energy and Solaire France).

Flat roofs are common in commercial and industrial buildings, offering a high potential for BIPV diffusion. Although they usually require mounting systems that increase the BoS cost, modules can be potentially positioned towards any direction, maximising their energy yield (see Fig. 6.17). Depending on the type of the roof material these racking systems can be bolted or weight-ballasted to the roof [Prasad and Snow (2005)]. TF PV technologies allow for the manufacturing of flexible laminates that can be directly attached to the roof using adhesives. Although these lightweight stainless steel foils or plastic membranes can be easily installed and offer seamless integration on flat or corrugated roofs with low load-bearing capability, they are often more vulnerable to weather conditions [I8; I9; SHC (2013b)].

Figure 6.17: Examples of BIPV on flat roof (photos courtesy of Lumeta, Solyndra, Sunpower and Solopower).

Glazed roofs including skylights and atria are examples of fully integrated systems, providing all structural, sound- and weather-proofing functions of conventional glass materials (see Fig. 6.18). Early consideration of the BIPV devices is essential, along with the active involvement of both the architect and the engineering team, requiring a high level of communication and collaboration [I1; I6; I12; Zeeuw (2011)]. A sparse distribution of c-Si cells within sheets of glass can produce an aggregate effect of semi-transparency, while translucent and laser-etched TF modules may provide a more uniform result [SHC (2013b)].

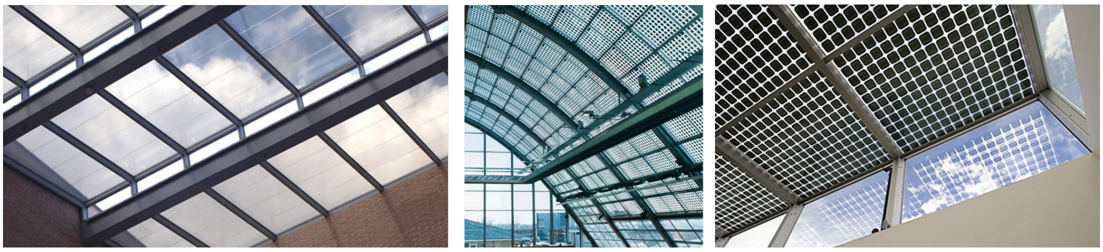

Figure 6.18: Examples of BIPV glazing (photos courtesy of Schüco, Onyx and Philadelpia Solar).

Facades

BIPV modules can be installed in building facades adding an external cladding element, replacing an external layer or substituting the entire facade system (see Fig. 6.19). In the first case, modules are mounted on an insulated load-bearing wall, allowing for back-ventilation of the installation, an ideal configuration for c-Si modules that are particularly sensitive to high temperatures [Prasad and Snow (2005)].

Curtain wall systems and glazing offer additional opportunities for PV integration of opaque or semi-transparent modules. Potential applications include the external layer of double-skin facades or structural glass of commercial buildings, residential windows, architectural glass for textured and decorative interior glass walls and dividers, and flexible membranes that can be applied on existing glass surfaces. In all cases, a range of mechanical and thermal requirements need to be taken into consideration [Polysolar (2012d); SHC (2013b); Johnson (2014)].

Figure 6.19: Examples of BIPV facades and windows (photos courtesy of Soltecture, Onyx, Oskomera and Polysolar).

External structures

The third category of BIPV applications includes external building elements and systems integrated in urban infrastructure. PV may be incorporated in vertical building fixtures including balustrades, handrails and ornamental facade components, as well as shading devices including eaves, louvres and canopies. In addition to the logical combination of providing shade in sunny days and generating electricity at the same time, these external structures are generally well ventilated, providing optimal energy performance conditions for the PV cells [Prasad and Snow (2005); SHC (2013b)]. Semi-transparent modules can also be incorporated in domestic greenhouses offering ultra-violet (UV) light protection and better temperature regulation than conventional glazing [Polysolar (2014b)].

Carports with integrated PV systems are a fast growing market segment, correlated with the wide diffusion of plug-in hybrid (PHEV) and electric vehicles (EV). These structures may incorporate charging stations, as well as provide weather protection [Beadle (2012)]. Other urban BIPV applications include shelters, bus stops, kiosks and noise barriers alongside roads (see Fig. 6.20) [Prasad and Snow (2005); Luque and Hegedus (2011)].

Figure 6.20: Examples of BIPV balustrades, louvres, canopies and carports (photos courtesy of Green Coast Solar, Colt, Solartec and Skyshades).

6.3 Power and aesthetical performance aspects of BIPV

When designing a BIPV installation a compromise must be reached between energy yield optimisation and aesthetical integration. Although maximisation of the generated electricity is usually the aspiration for the user, this has to be achieved in a way that complies with the demands for formal integration into the urban environment of the building. PV technological options play a crucial role on these considerations.

Performance of BIPV systems is mainly assessed using metrics borrowed from the PV sector. However, this structured assessment is often inappropriate for the characterisation of disruptive technologies such as BIPV. Conventional metrics offer partial insights that do not internalise the multi-level factors contributing to design considerations. This observation complies with the recurring theme of complex methods required for the assessment of the BIPV sector.

6.3.1 Power aspects

Although power generation is not the sole function of BIPV applications, it is a significant factor affecting the BIPV design choices for both product developers and users. Consumption and trading of the generated electricity offer financial returns that compensate for the premium price of BIPV systems compared to conventional building materials. Therefore, maximisation of the power output results in higher returns and shorter amortisation periods of the initial investment. Additionally, the total amount of electricity generated by a BIPV system determines to a great extent its life-cycle environmental impact.

Power performance metrics

A range of metrics and indicators are commonly used for the evaluation of the power performance of a PV system.

Peak power of a PV system (P_p in Wp) is the maximum power output measured at Standard Test Conditions (STC)[5] [Luque and Hegedus (2011)]. In real conditions, modules may generate momentarily a higher or lower output than this *rated* or *nominal* value provided by the manufacturer, depending on the intensity of incident solar radiation and the temperature of the module. However, since the solar radiation resource is intermittent due to Earth's rotation and weather variability, the average power output of a PV system throughout a period of time is considerably lower than the peak power. The ratio of actual to peak output over a period of time (usually a year) is defined as the *capacity* or *load factor* of a power device. This factor is less than 25% for PV systems in most regions, considerably lower than that of most other power plants[6] [Jungbluth *et al.* (2005); DECC (2013c)].

Although P_p is the metric most frequently used in the PV industry for system sizing and pricing, it provides no indication of either the covered area or the electricity output, factors crucial to the building designer and the user respectively. Low-efficiency modules (e.g. TF or OPV) require more area in order to provide the same power output to more

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[5] STC specifies a temperature of 25°C for the PV cells, irradiance of 1000 W/m^2 and an air mass of 1.5 (AM1.5).

[6] Indicative 5-year average capacity factors for power plants in the UK are 62.3% for nuclear, 55% for CCGT, 27.4% for wind, 34.8% for hydro, 5.2% for wave and tidal, 51.4% for bioenergy and 8.3% for PV [DECC (2013c)].

efficient ones, resulting in higher BoS costs (e.g. cabling, mounting systems etc.). This misalignment in the methods and criteria used by actors involved in a BIPV project to characterise and assess systems is often quoted as one of the most important barriers to the wider adoption of BIPV by the construction industry [I6; I12; I15; I16]. Additionally, due to the low capacity factor of PV, the economic efficiency of a system is not reflected properly on a per Wp basis alone, and hence it cannot be directly compared to that of other power systems without considering the electricity output over a period of time.

Conversion efficiency (η in %) of a power device is the percentage of the respective primary resource converted into useful energy. In the case of solar PV it can be calculated by dividing the peak power output (P_p in Wp) of a PV system by the power of solar radiation, or *irradiance* (Ir in W/m^2) striking the area (A in m^2) of the system, defined as *in-plane irradiance* (Ir_i in W), as measured in STC [Marion *et al.* (2005); Luque and Hegedus (2011)]:

$$\eta = \frac{P_p}{Ir_i} = \frac{P_p}{Ir \times A} \tag{6.1}$$

Cell efficiency depends on the type and quality of the active materials and the manufacturing processes. It is often used by the PV sector to refer to scientific advancements, potential improvements and comparative analyses of the various technologies (see Fig. 6.21) of solar cells. Module efficiency on the other hand takes into consideration losses that stem from the electrical interconnections and the geometry of the cells within the modules [Luque and Hegedus (2011)].

TF and OPV technologies have traditionally demonstrated lower efficiencies than first generation PV technologies {F1}. This trend is notably apparent in commercial modules, where there seems to be a difficulty in transferring scientific advancements into manufacturing lines [Bagnall and Boreland (2008)]. However, this trend is now been challenged through up-scaling of production and recent developments in manufacturing processes and materials {F2}. CdTe manufacturer First Solar in particular is expected to surpass average efficiency of polyc-Si modules and reach that of monoc-Si ones by 2017, while emerging firms aim to transfer the significant success of perovskite materials in laboratory conditions into commercial BIPV products [Hodes (2013); Gifford (2013b); Munsell (2014); Scanlon (2014)]

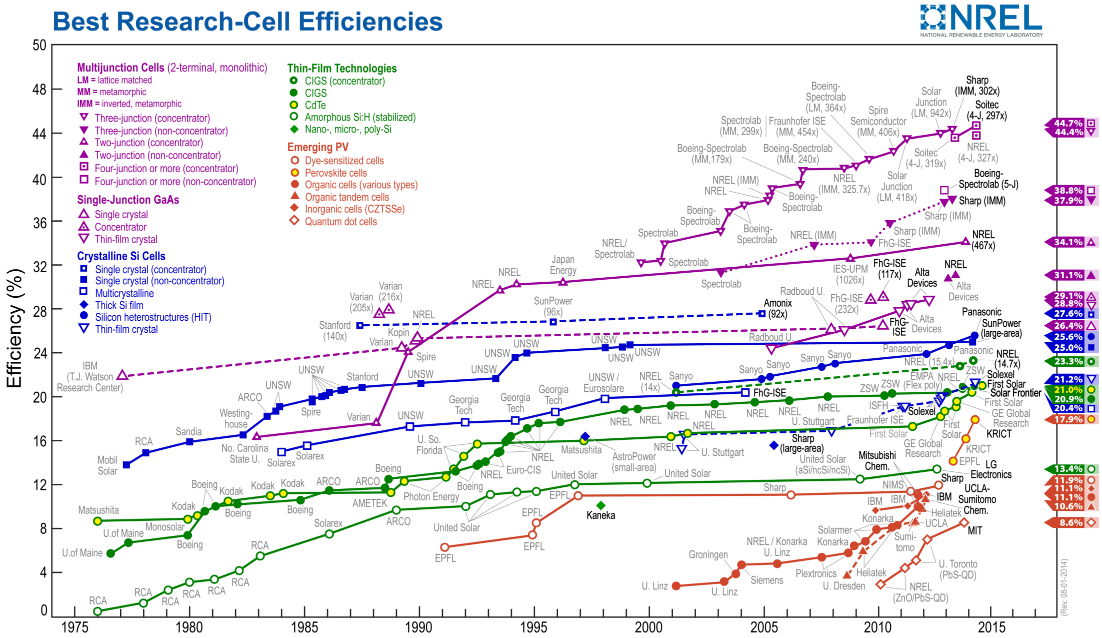


Figure 6.21: Record efficiencies of PV cells [NREL (2014)].

Photovoltaic Technology	Efficiency (%)	Power Output Density (Wp/m^2)	Required Area (m^2/kWp)
monoc-SI	15-20	150-200	5-6.7
polyc-Si	13-17	130-170	5.9-7.7
TF-Si	6-10	60-100	10-16.7
CdTe	14	140	7.1
CIGS	10-13	100-130	7.7-10
OPV	5-7	50-70	14.3-20

Table 6.1: Effect of efficiency on PV system area (author's compilation).

Compared to peak power, efficiency is a better power performance metric for a module, taking into consideration its area and providing an indication of the power output density (see Table 6.1). This is particularly relevant in the case of BIPV where area is a crucial parameter in the choice of the system. However, it still gives limited insight with regards to the energetic output and the associated manufacturing and installation costs.

The performance of PV devices in real conditions is affected not only by the components and configuration of the system, but also by environmental factors, including the annual amount of solar radiation energy or *insolation* (In in Wh/m^2), temperature and soiling of the modules. The effect of these factors on the overall performance of different PV technologies has been researched extensively by research institutes including the Fraunhofer TestLab in Germany, the National Renewable Energy Laboratory (NREL) in the USA and the recently founded National Solar Centre (NSC) in the UK {F1} [I12; I16]. Although comparative studies indicate that TF technologies are less susceptible to output reduction due to temperature increase and better performance under diffuse light, generalisation of these location- and system-specific studies is not achievable, since the combined effect of the factors is not yet entirely understood [I3; inter alia Makrides *et al.* (2008); Colli *et al.* (2010); Woyte *et al.* (2013)].

The overall PV system performance in real conditions can be assessed by using the total generated electricity output of the system measured over a period of time, or **energy yield** (Y in Wh). Energy yield depends on PV technology, irradiance and environmental conditions. It is often presented normalised over the installed capacity of the system (Wh/Wp) or over the system area (Wh/m^2) reflecting energetic performance and area-utilisation. The latter is useful in BIPV applications, providing an indication of the potential electricity generation from a designated area, as well as the financial returns since both electricity trading and financial incentives for renewable energy generation are mostly calculated on a per kWh basis.

Performance ratio (PR in %) is the ratio of the actual energy yield of a PV system over a period of time to the *nominal* or *reference yield*, which is the expected electricity that would be generated by the system considering the local resource and efficiency of the system [IEC (1998); Marion *et al.* (2005)]:

$$PR = \frac{Y}{In \times A \times \eta} = \frac{Y}{In \times A \times \frac{P_p}{Ir \times A}} = \frac{Y/P_p}{In/Ir} \tag{6.2}$$

PR takes into consideration most sources of module and system losses and therefore, it is a useful metric for the comparison of different systems, often quoted as the *quality factor* of an installation [Pless *et al.* (2005); SMA (2010)]. The statistical average of PR of new PV installations has improved over the last 20 years from 65% to 85% due to more precise module rating, better design and installation and more reliable components with shorter repair times {F2} [Woyte *et al.* (2013)].

Factors that influence the power performance of BIPV

Annual energy yield highly depends on the **orientation** and **inclination** of the active BIPV surface. Due to the varying position of the sun throughout the day and year, static PV collectors are rarely perpendicular to solar radiation. Output is maximum when modules face towards the direction of the 'average' position of the sun. Optimal tilt orientation is towards the equator, while tilt depends on the latitude of the installation [Luque and Hegedus (2011); Zeeuw (2011)]. The combined effect of orientation and inclination on the insolation levels of a building located at the northern hemisphere is illustrated in Fig. 6.22.

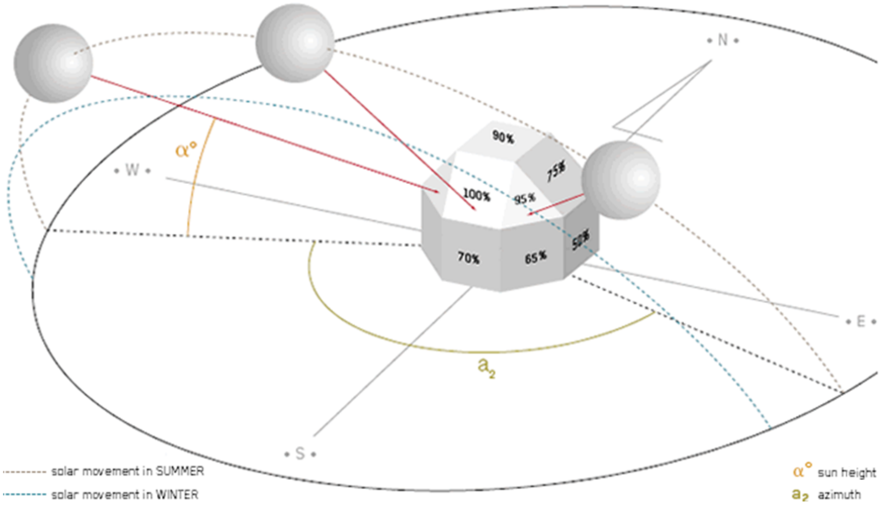
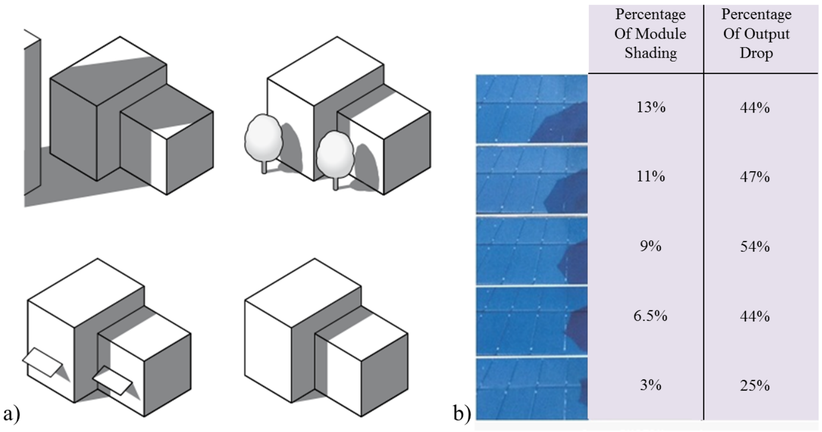


Figure 6.22: Insolation levels at various orientation and inclination angles within a building [Sapa (2014)].

Although direct light is ideal for solar power generation, PV cells are also able to capture indirect or diffuse light. TF and OPV technologies have demonstrated better performance in low-light conditions (e.g. cloudy weather and times of low sun height) due to their wider spectrum sensitivity than c-Si technologies. This characteristic renders them a better option for BIPV systems with sub-optimal orientation [Luque and Hegedus (2011); Zeeuw (2011)].

Shading is another factor affecting significantly the power output of PV modules and consequently, the energy yield of a BIPV system. Shading may be due to vegetation, adjacent buildings, soiling of the modules and construction elements of the building or the BIPV system itself [SHC (2013b)].

Obscured cells become heat sinks and create 'hot spots' within a module, causing a power drop in the PV array that is disproportionally higher than the area of partial shading (see Fig. 6.23) [SUPSI (2014)]. This can be prevented by connecting high-voltage module in parallel or by using micro-inverters for each module [Polysolar (2012d)].



Percentage Of Module Shading	Percentage Of Output Drop
13%	44%
11%	47%
9%	54%
6.5%	44%
3%	25%

Figure 6.23: a)Examples of shading in buildings [Zeeuw (2011)] and b)Effect of partial shading on a PV array power output [SUPSI (2014)].

The operational **temperature** of a BIPV system plays a decisive role on its energetic performance. Power output declines at high temperature by 0.1-0.2%/^{o}C in a-Si, 0.3-0.4%/^{o}C in CIGS up to 0.4-0.5%/^{o}C in c-Si modules [Luque and Hegedus (2011); Onyx (2012); SUPSI (2014)]. Therefore, passive ventilation of the system is beneficial, although not always possible in integrated systems.

An additional factor that affects the energy yield of a BIPV system is the quality of the electrical components of the BoS. The contribution of the various causes of system losses is reflected on the final Performance Ratio (PR) of the installation as summarised in Table 6.2.

Common losses	Absolute PR reduction
Glass Reflection	2 - 4%
Deviation from STC	2 - 4 %
Temperature effect	3 - 6 %
Snow, dust, soiling on the modules	1 - 2 %
Shadows	≥ 0 %
Tolerance and mismatching	2 %
Inverter losses	≥ 5 %
Cables and line losses	1 - 2 %

Table 6.2: Contribution of various factors to PR reduction [SHC (2013b)].

6.3.2 Visual aspects

Architects and building developers require a high degree of flexibility with respect to the materials they incorporate in their buildings. One of the most prominent demands of the architectural community is the greater availability of products with a wide range of visual and formal characteristics {F7, F8} [SHC (2013b); Hardy *et al.* (2012)]. Manufacturing of bespoke products usually comes with an extra cost due to small quantities produced and also requires consideration of provision of spare units for future maintenance [SHC (2013a)].

Shape and **size** are the paramount considerations for integrated PV systems. Manufacturing and cost limitations regarding the production of modules allow for certain types, which are usually optimised for ground-mounted installations, rather than BIPV. This issue is more profound in c-Si technologies where cells are restricted to quadratic grid configurations. In certain applications where the required shapes and sizes are not feasible from a manufacturing or economical point of view (e.g. edges, corners, shaded areas) there is the possibility of fake elements (*dummies*) that have similar formal characteristics with BIPV but no power generation capability [I6; I11; SHC (2013b)].

Thin film PV technologies offer a much wider flexibility of shapes due to the utilised deposition manufacturing processes (see Fig. 6.24) [Luque and Hegedus (2011)]. Bendable products can be incorporated in non-flat surfaces, while roll-to-roll production techniques allow for easier customisation [Zeeuw (2011)]. However, such systems are usually less durable than glass modules, and are often excluded from systems requiring long-term integration [I8; I9].

Figure 6.24: Examples of flexible PV modules (photos courtesy of Unisolar, Global Solar, Konarka and Flexcell).

Colour is a primary concern for architects, especially regarding materials incorporated in visually prominent parts of the building, including facades and glazing. The colour of PV collectors is also crucial for the performance of the PV elements, since it is related to the light-spectrum absorbed by collectors. Although conventional c-Si cells are manufactured in dark and cold colours (blue, dark blue, black) in contrast to the usually light and warm shades of building surfaces, bespoke modules may be produced in a wide range of colours, using different anti-reflective coatings (see Fig. 6.25. Pigmentation of TF and OPV cells is generally easier [Luque and Hegedus (2011); SHC (2013b); SUPSI (2014)]. Depending on the shade of the coating, the conversion efficiency of the module may drop by 13% to 25% [Hardy *et al.* (2012)].

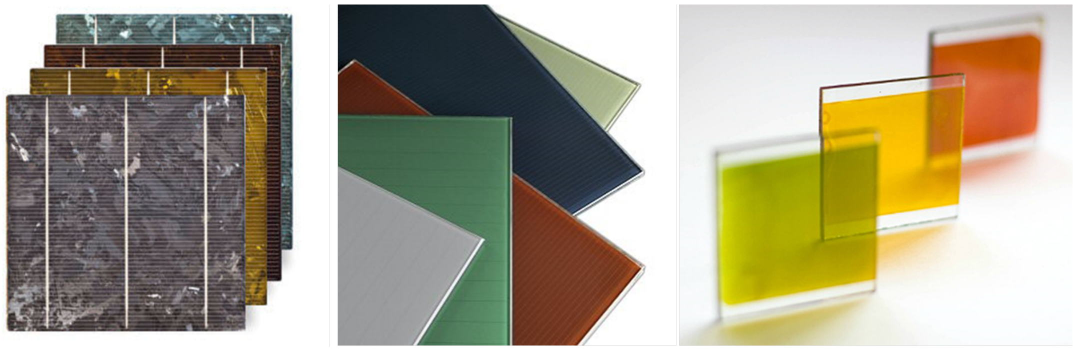


Figure 6.25: Examples of coloured c-Si, TF and OPV modules (photos courtesy of Sunways, Solar Tiles and Oxford PV).

In addition to PV cells, other visible parts of the BIPV system that can be coloured are module background sheets and frames. Matching colours may provide a uniform result, while contrasting colours can be used to attract attention and focus on the BIPV installation [Luque and Hegedus (2011)].

Transparency of the BIPV system is also a substantial factor in cases where they substitute glass elements. BIPV systems utilising c-Si PV technologies can achieve various levels of light transmittance by leaving gaps among the interconnected cells. Although different configurations may achieve a range of patterns, certain requirements regarding the electrical interconnection of the cells raise considerations for the visual outcome of the installation [SHC (2013b)]. Laser etching techniques used in TF technologies allow for more homogeneous results similar to that of coloured glass, while OPV have the potential of truly transparent and colourless PV through the utilisation of the non-visible light spectrum (see Fig. 6.26 [Polysolar (2012d); SUPSI (2014)].

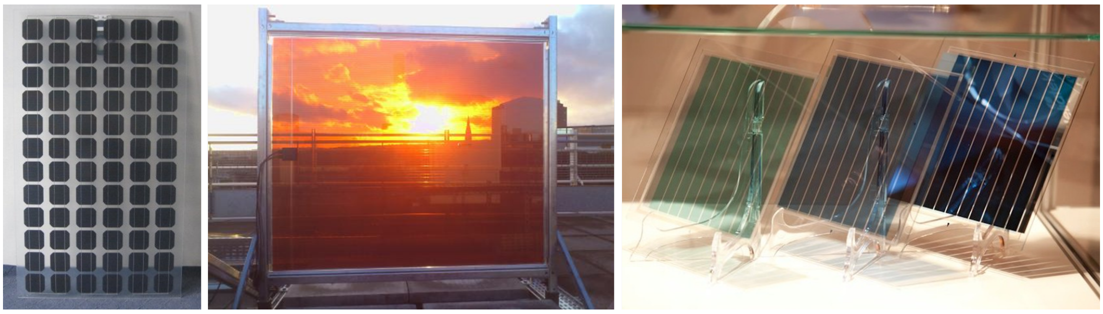


Figure 6.26: Examples of semi-transparent c-Si, TF and OPV modules (photos courtesy of Solar Constructions, Polysolar and Heliatek).

Grain size variation and **texture** are additional visual factors involved in BIPV system design. The former refers to the perceptual effect generated by silicon crystals and is not an issue in TF and OPV technologies, which produce uniform cells [SUPSI (2014)]. The latter relates to the reflectivity and roughness of the products that need to be compatible with the rest of the building surfaces [SHC (2013a)]. Variation can be achieved through several processes and coatings, affecting the conversion efficiency of the system [Hardy *et al.* (2012)].

6.4 BIPV economics

Despite the manifold environmental and power generation utilities of BIPV systems, the empirical research has revealed that economic considerations are usually the most prominent factor affecting their implementation and design. Applications are often assessed based on investment criteria, including initial and operational costs, annual returns and payback periods [I6, I10, I12, I15, I16].

Investment cost is dictated by the prices of PV materials and BoS components (see also Section 6.1). Revenues on the other hand arise from the use and sale of the generated electricity, as well as incentives for the production of distributed renewable power. These financial benefits constitute the main value proposition of BIPV against conventional building materials [I6, I15].

There exists a variety of indicators used for the economic appraisal of BIPV systems and their combined use is required to provide a transparent and objective representation [Bazilian *et al.* (2013)]. It needs to be highlighted again that such conventional metrics offer a limited representation of the overall value of disruptive BIPV systems. Different framing and more complex assessment methods are required for the internalisation of additional socio-economic benefits. Responding to this requirement, this research adopts the multi-level approach introduced in Section 5.2 and further implemented in the empirical and analytical parts of this thesis.

6.4.1 Manufacturing cost and market price of PV modules

A significant cost component of all BIPV applications is attributed to the integrated PV modules. Although historically this has been the main system cost element, its contribution has demonstrated a declining trend, which is expected to continue in the near future [OECD/IEA (2011)].

Despite the growing attention drawn by the developments within the PV sector, the quality of information on the industry economics can vary widely and it remains challenging to gain a coherent picture of the underlying production costs and market prices. This can be attributed to the complexity of the PV value chain and distribution channels, the volatility of costs and prices, as well as the regional characteristics of the markets within which systems are deployed [Bazilian *et al.* (2013)].

Additionally, there is confusion within the literature regarding the terms *cost* and *price*, which are often used interchangeably, despite the different dynamics that drive them. Production costs are affected by manufacturing-specific trends including feedstock costs, capital and operational expenditure, efficiency of processes and capacity utilisation rate. Commercial prices on the other hand result from a combination of production costs and profit margins and are affected by market forces, including supply-demand dynamics, competition and corporate strategy [Candelise *et al.* (2013)].

The historical trend of production costs and the aggregate effect of learning processes on their evolution can be illustrated using *experience curves*, which describe the quantitative relationship between cumulative production and unit cost [Supergen (2009)]. The percentage change in cost for every doubling of the cumulative production is expressed by the *learning rate*, an indicator often used to describe the performance of energy technologies and predict future cost reductions[7] [Van Sark (2010); Sandén (2005); IEA (2000)].

Experience curves have many analytical limitations, especially when used on emerging technologies with narrow time series data. They offer very limited understanding of the complex drivers of cost reductions, and often use prices as a proxy for production costs. However, they have been widely used to describe the significant drop in PV module costs and prices [Candelise *et al.* (2013)]. The learning rate most commonly quoted in the PV literature is 20% (see Fig. 6.27) {F1} [EPIA (2011a); Jäger-Waldau (2013); IEA (2014a)].

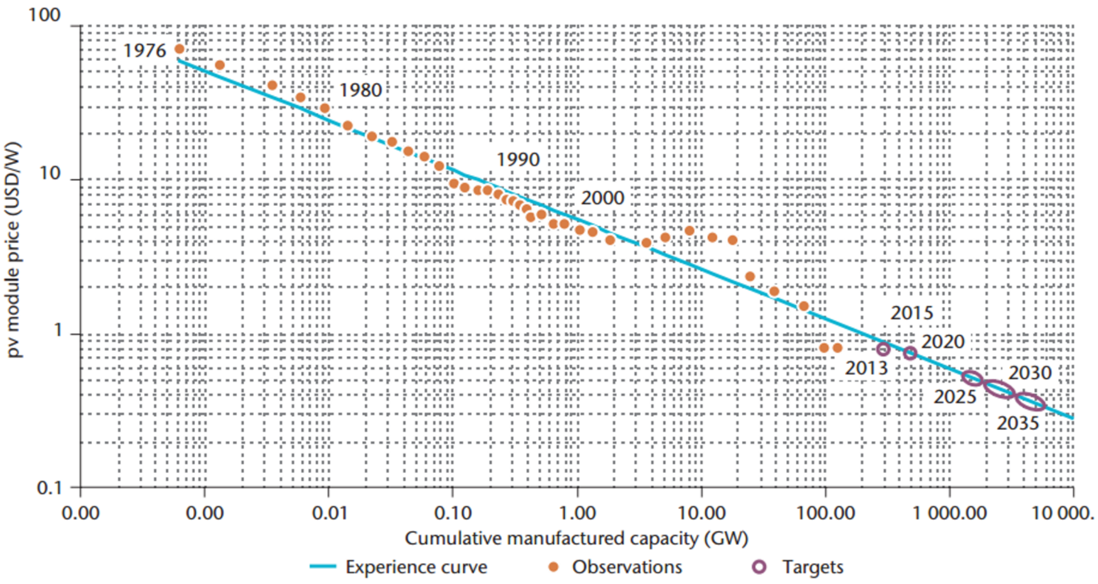


Figure 6.27: Historical and projected PV experience curve [IEA (2014a)].

The temporary polysilicon feedstock shortage in the mid 2000s caused a bottleneck in silicon production and prevented effective competition, reversing the downward trend in module prices despite ongoing technological advancements {F9} [Candelise *et al.* (2013)]. High deployment volumes during this period were sustained by generous

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[7] *Progress ratio*, the complement to the learning rate, is another indicator often used in the literature.

incentive schemes in Europe that enabled profit margins for manufacturers and system developers {F7} [Jäger-Waldau (2013)]. However, the subsequent steep decline in polysilicon feedstock prices along with the increased manufacturing capacity and the resulting oversupply of modules created a highly antagonistic market environment. These developments drove aggressive price reductions that occurred at a higher rate than manufacturing cost reductions due to scale and incremental innovation in materials and processes (see Fig. 6.28) [EPIA and GREENPEACE (2011); Bazilian *et al.* (2013)]. The historical development of the PV industry and market will be further discussed in Chapter 7.

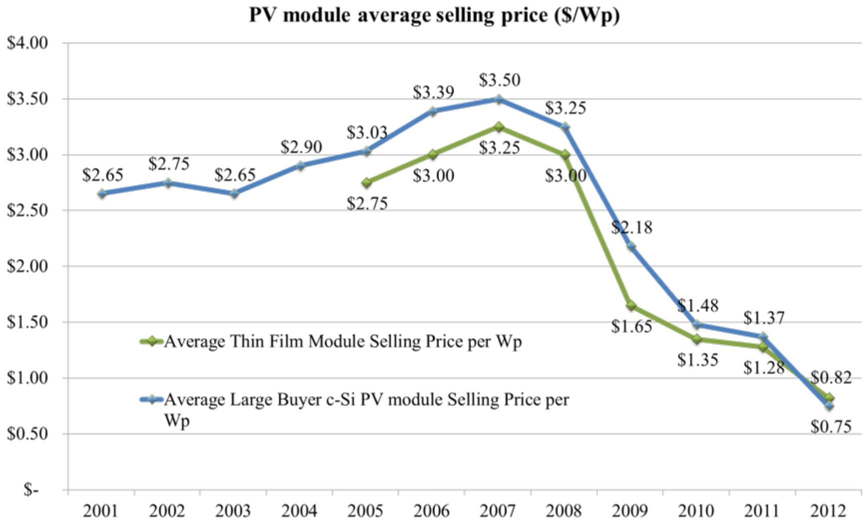

Figure 6.28: Price trends for PV modules for the period 2001-2012 (author's elaboration using year-average data from Mints (2012a,b) and Photon (2014)).

Module prices for all commercial PV technologies fell below the $1/Wp threshold during 2011 [Photon (2014)]. These prices did not reflect respective production costs and drove many manufacturers out of the industry. During the following consolidation era prices stabilised and even slightly increased, while cost reductions due to technological and process advancements created sustainable profit margins for stakeholders across the supply chain [Mints (2012c); Bazilian *et al.* (2013)]. Current spot prices for PV modules in Europe have demonstrated a stable trend since early 2013, averaging at €0.6-0.68/Wp ($0.75-0.85/Wp) as illustrated in Fig. 6.29 [Photon (2014)].

Thin-film PV technologies that are more suitable for BIPV applications have the potential for significantly lower manufacturing costs than c-Si modules, due to low active

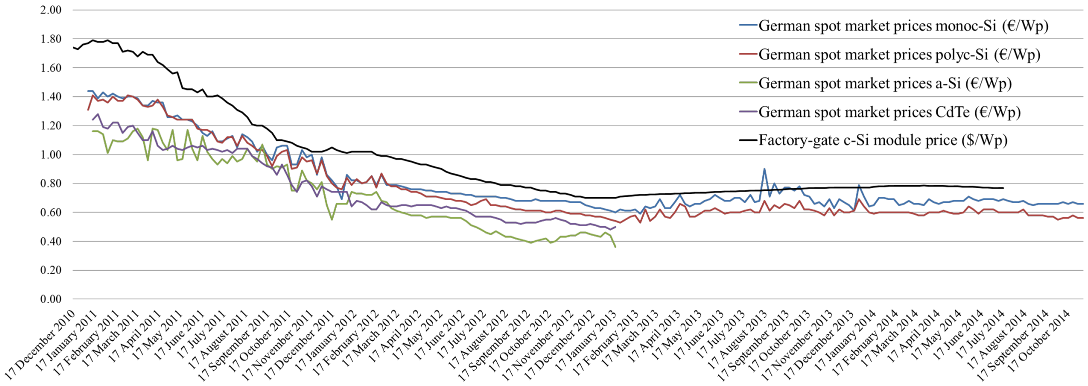

Figure 6.29: Price trends for PV modules for the period 2010-2014 (author's elaboration using weekly spot-price data from Photon (2014)).

material utilisation and more efficient manufacturing processes that do not rely on silicon ingot cutting into wafers, such as roll-to-roll deposition (see Subsection 6.1.1). However, the average selling price of TF modules per unit power has not yet demonstrated that potential, remaining at par with average polyc-Si prices [Photon (2014)].

The relatively high production cost can be partly attributed to the high capital expenditure involved in the construction of a TF manufacturing plant which may be up to six times higher than that of a c-Si plant of the same size [Luck (2014a)]. The use of expensive custom-made equipment has a profound impact on the cost structure of TF products, and imposes a very effective barrier to market-entry. It also restricts the size of most manufacturing lines, not allowing the benefit of economies of scale {F2, F3} [I6; Mints (2011b)].

Potential improvements that can render production cost savings include better material utilization, thinner absorber layers, lower capital investment from the use of standardised equipment, low-cost production sites, higher device efficiencies and an overall change in the PV industry and supply chain [Bagnall and Boreland (2008); Bazilian *et al.* (2013); Luck (2014b)].

6.4.2 Economics at the system level

Although PV modules are a significant part of the overall BIPV system cost structure, there are other elements that affect its overall price, namely electrical and mechanical BoS components as well as installation costs (see Section 6.1). Depending on the application type, the contribution of these cost elements accounts for around 45-65% of total system cost [Ernst & Young (2011); PB (2012); Candelise *et al.* (2013)].

BoS costs follow the downward trend of PV modules due to various learning processes and scale, but at a slower rate. Consequently, the contribution of the module to the final system price is declining and is expected to become less than 30% of the total system cost by 2020 (see Fig. 6.30) [OECD/IEA (2011); Jäger-Waldau (2013)].

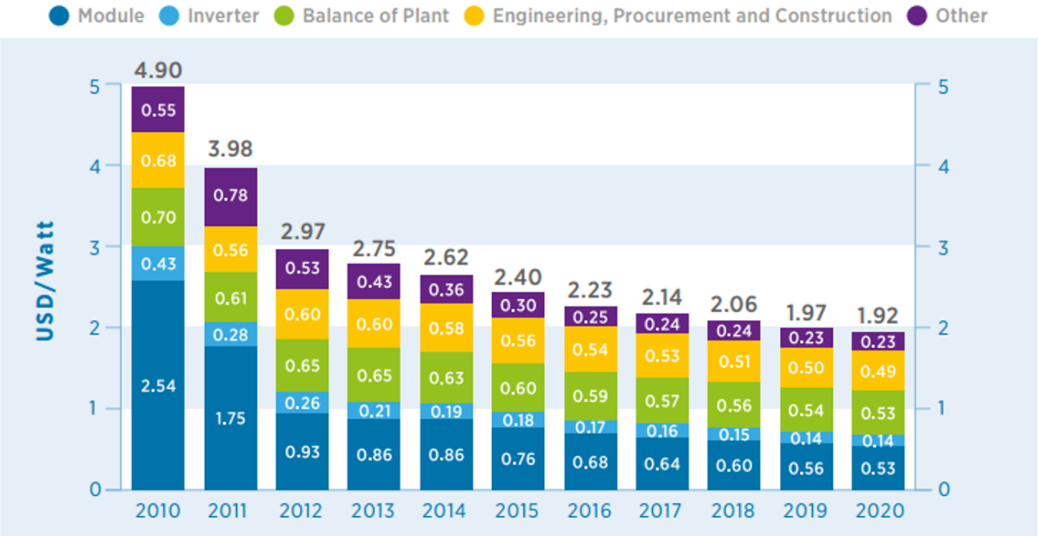

Figure 6.30: Projected PV system price breakdown [IRENA (2014a)].

A factor that is becoming increasingly important in the shaping of prices of installed PV systems is the contribution of *soft costs* which relate to customer acquisition, permitting, inspection and interconnection, installation labour, financing costs and overheads [Bony *et al.* (2010); Friedman *et al.* (2013)]. These non-hardware costs vary significantly among countries due to different legal requirements and maturity of the market that directly impacts local competition downstream the supply chain [Jäger-Waldau (2013); IEA (2014a)]. They also depend highly on the size of the installed system, adding considerable complexity to the economic analysis [Barbose *et al.* (20013)]. The impact of these variations on PV system prices are illustrated in Fig. 6.31. A survey conducted for the USA Department of Energy in 2012 revealed that these costs constitute 64% of the total residential system price, 57% of the small (less than 250 kW) commercial system price, and 52% of the large (250 kW or larger) commercial system price [Friedman *et al.* (2013)].

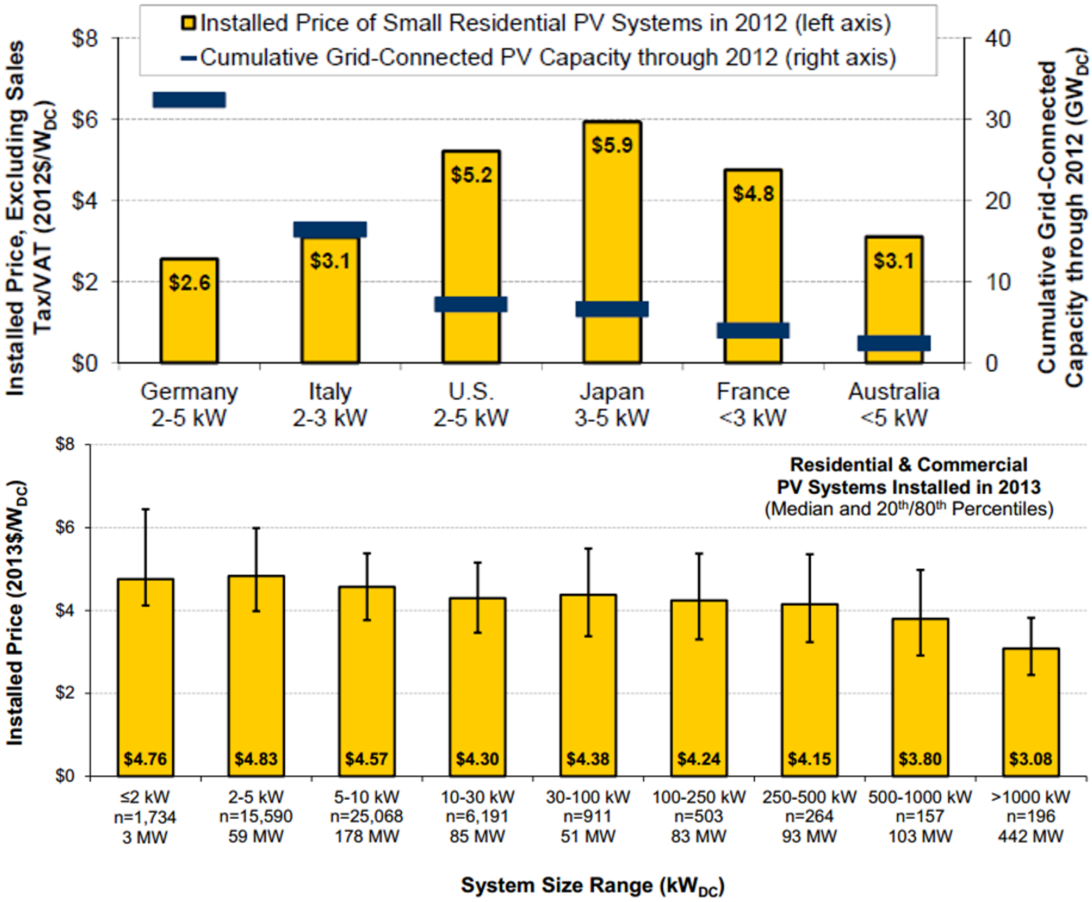

Figure 6.31: PV system price variation for different countries and system sizes [Barbose *et al.* (20013); Feldman *et al.* (2014)].

Although system prices are useful for the evaluation of the economic feasibility of a BIPV project, a more accurate indicator for the long-term system performance is the Levelised Cost of Energy (LCOE) [Bazilian *et al.* (2013)]. This cost corresponds to the average value of the generated electricity that would render the net present value (NPV) of the sum of the discounted revenues equivalent to the NPV of the sum of the costs during the economic lifetime of the system [Yuan *et al.* (2014)]. Therefore, the metric can be calculated by dividing the NPV of all capital and operational expenditures associated with the system by the discounted power generated over its life-cycle:

$$\sum_{N}^{t=0} \frac{LCOE \times E_t}{(1+r)^t} = \sum_{N}^{t=0} \frac{I_t + M_t + F_t}{(1+r)^t}, \quad or \tag{6.3}$$

$$LCOE = \frac{\sum_{N}^{t=0} \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{N}^{t=0} \frac{E_t}{(1+r)^t}} \tag{6.4}$$

where I_t is the investment expenditures in year t, M_t is the operations and maintenance expenditures in year t, F_t is the fuel expenditures in year t (zero for PV systems), E_t is the power generation in year t, N is the system's life expectancy in years and r the discount rate [EPIA (2011a); Jäger-Waldau (2013)]. It should be noted that the summation calculation starts at $t = 0$ to include initial expenditures, which are a significant cost component in BIPV systems [Yuan *et al.* (2014)].

LCOE is highly dependant on the location and the configuration of the system. It internalises all hardware and soft costs and therefore, allows the comparison of electricity prices from different power technologies (see Fig. 6.32). The significant variation in the methodologies used to calculate the LCOE of power systems indicates that comparisons should be made with caution and based on a range of cost figures rather than an absolute value [Szabó *et al.* (2010)]. Additionally, the environmental cost of CO_2 is usually not included in the calculation of the LCOE for fossil-fuel based power systems and therefore, a direct comparison to renewable systems is further hindered [EPIA and GREENPEACE (2011)].

Closely related to the LCOE is the concept of *grid parity*, the point in time when LCOE of a particular power technology in a particular market segment and location is equal to the long term cost of grid-supplied electricity [EPIA (2011a)]. Fig. 6.33 illustrates the difference of a typical BAPV system LCOE from retail electricity prices in Europe. As is evident, in many regions grid parity has been reached, and it is currently economically advantageous to procure electricity to a building using integrated PV systems rather than the grid [Ossenbrink *et al.* (2013)]. However, this conclusion can only provide partial insights, since there are additional grid reliability, infrastructure and power storage requirements that are not accounted for [I7; I15].

With regards to different PV technologies, thin-films suffer from lower conversion efficiencies compared to c-Si technologies. At the system level, this implies a cost penalty as more area and BoS components are required for a system of the same capacity [I3; I4;

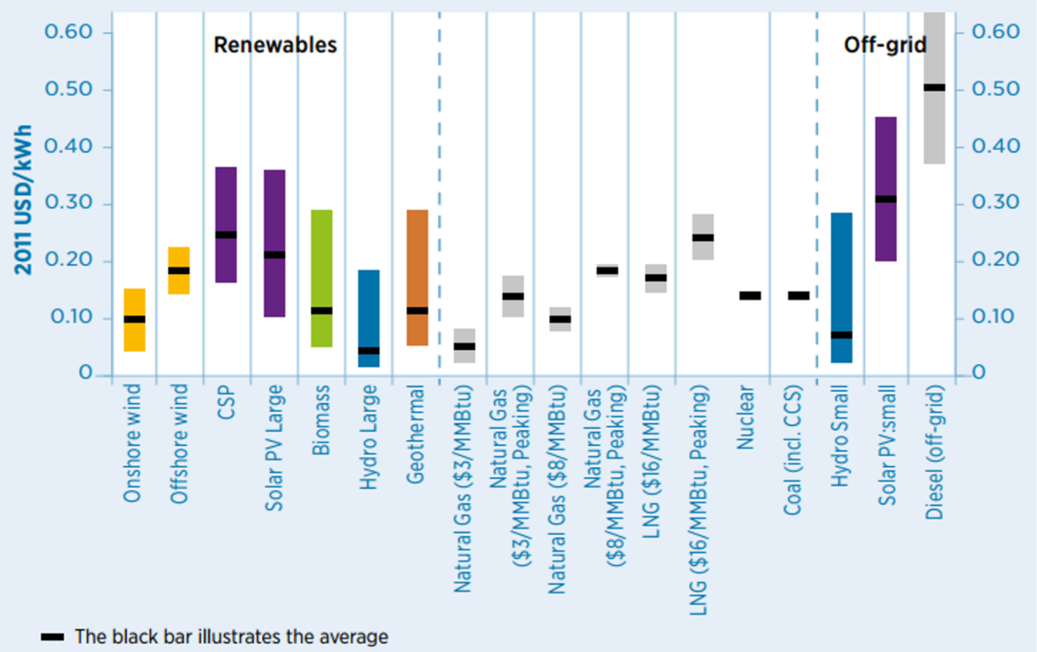

Figure 6.32: LCOE of power systems [IRENA (2014b)].

I6; Luck (2014a)]. On the other hand, in many cases certain thin-film technologies have demonstrated higher energy yields (kWh/kWp) than cSi, offering a potential advantage when comparing their respective LCOE [I3; I5; Hegedus (2006)].

6.4.3 Further economic considerations

In addition to system prices and revenues from their use, there are other economic considerations particular to BIPV systems. Due to their distributed nature and spatial proximity to the point of power use, BIPV challenge the incumbent electricity generation infrastructure that is based on centralised production and distant transmission to users {F11}. The potential high uptake of such systems would have a significant impact on grid-related costs due to the required reconfiguration of the network [EPIA (2011a)].

Additionally, the intermittent nature of the solar resource raises further discussions regarding the variation of the actual value of PV electricity throughout the day. This value could be maximised through the use of power storage (e.g. electric vehicles) and smart demand-side management systems that could temporally regulate power consumption in order to increase the benefits of self-consumption {F9} [EPIA and GREENPEACE (2011)].

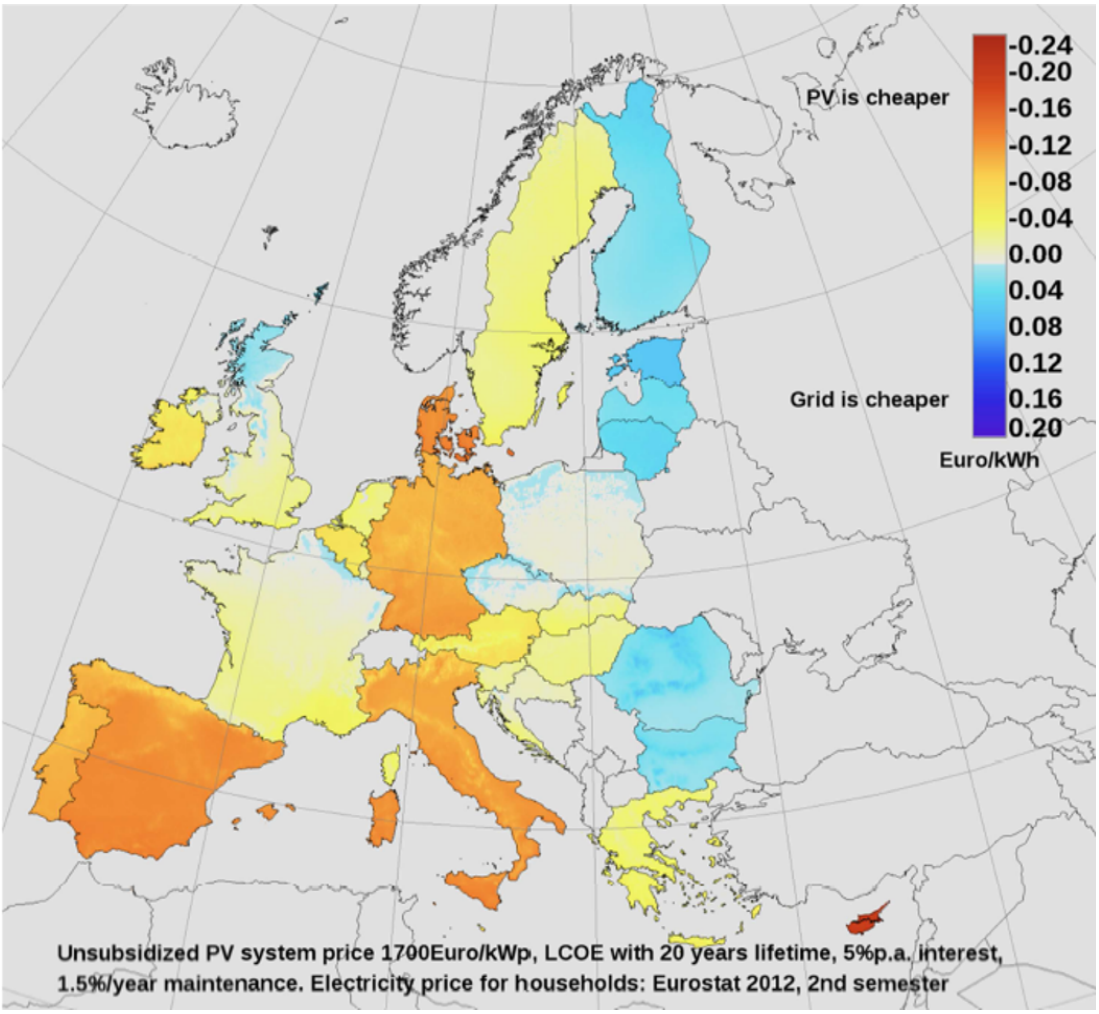

Figure 6.33: Difference between the LCOE of a domestic BAPV system and household retail electricity prices in Europe [Ossenbrink *et al.* (2013)].

6.5 Environmental aspects

An additional factor that is increasingly affecting PV system design is its overall environmental impact. Increasing environmental awareness is driving the adoption of products and processes that are less energy and carbon-intensive. This is particularly relevant to the construction and energy sectors, due to their profound environmental impact [PVPS (2014); SUPSI (2014)]. In order to assess this impact and facilitate the regulatory frameworks designing, standardised methodologies have been developed including the Life Cycle Assessment (LCA) [ISO14040 (2006); ISO14044 (2006)].

The LCA framework evaluates the overall environmental burdens associated with a product, adopting a *cradle to cradle* (or grave) approach that includes all materials and processes involved in resource extraction, manufacturing, transportation, use, recycling and material recovery (or disposal) [PVPS (2014)]. Therefore, it provides an holistic view of the environmental impact across the supply chain that is not specific to a geographic location or impact category. The indicators used more often in LCA are the Global Warming Potential (GWP in g CO_2-eq/kWh) and the Energy Pay-Back Time (EPBT in years) referring to the time needed by an energy system to generate an amount of energy equal to the one consumed throughout its life-cycle [JRC (2014); Fthenakis *et al.* (2011)]. Despite the holistic approach of LCA, there are still limitations in its applicability to BIPV systems, since there is ambiguity regarding the appreciation of the savings associated with the substitution of conventional building materials.

Multiple LCA studies have been conducted for the comparative evaluation of the various PV technologies, assessing a GWP of 25 to 35 g CO_2-eq/kWh and a EPBT of 0.7 to 2.2 years, significantly lower than those of fossil-fuel technologies and similar to other renewable systems. CdTe has been indicated as the best performing PV technology [I3; PVPS (2014); Fthenakis *et al.* (2011); Karaiskakis *et al.* (2013)]. However, the research on BIPV system is significantly more limited. GWP of BIPV systems is generally superior compared to conventional PV systems, since it is mitigated by the avoided environmental impact of substituted building materials. Consequently, the environmental impact declines with increasing integration of the systems [Jungbluth (2005)]. EPBT on the other hand is a much more case-specific metric, since it is highly associated with the energy yield of the systems. Indicative results include a GWP of

-10 to 30 g CO_2-eq/kWh and a EPBT of 0.8 to 3.8 years [Perez and Fthenakis (2011); Perez *et al.* (2012); Karaiskakis *et al.* (2013); Cucchiella *et al.* (2013)].

Recycling is a crucial factor in the estimation of the life-cycle environmental impact of products. BIPV systems comprise mainly of glass, aluminium, plastics and semiconductor materials that can be easily recovered and reused after their end-of-life achieving rates of more than 90% [Larsen (2009); SUPSI (2014)]. The BIPV recycling industry is currently negligible in terms of size due to the long operational lives of PV devices (25-30 years) and the longer lifetimes of buildings. However, several manufacturers have developed and pre-financed recycling operations, while a comprehensive network of partners for the collection and end-of-life handling of PV products (PV CYCLE) has been established in Europe since 2007 {F4 and F6} [I12; Larsen (2009); PVCYCLE (2014)].

6.6 Summary and conclusions

Integration of PV materials in buildings requires the merging of power generation and architectural elements. The development and design of a BIPV system involves a range of considerations regarding the power performance, functionality, appearance, environmental impact and economic characteristics of the system. Its long-term performance depends on the compromise reached along these elements.

The BIPV sector is characterised by a fragmented technological domain that spans two industries and a wide range of materials and applications. The structured knowledge bases and benchmarking methods developed for each industry are often not compatible with each other and therefore, not always appropriate for the overall assessment of radical BIPV systems.

Empirical evidence suggests that complex approaches are required to fully appreciate the technical and socio-economic characteristics of the sector. This finding is consistent with the wider methodological premise of this thesis that adopts a multi-level perspective for the characterisation of its disruptive nature.

Chapter 7

BIPV Industry, Market and Policy Assessment

Introduction

One of the main aims of this research (formulated into the second research question in Section 5.1) is to understand the various processes that enable or hinder innovation and affect the commercialisation potential of the multiple BIPV applications. The methodological approach is based on a multi-level perspective that assesses dynamics within firms, involved industries and the wider socio-economic environment.

The purpose of this chapter is to continue the analysis of the technical and socio-economic context started in Chapter 6, addressing developments at the two higher levels. It merges data collected through primary and secondary research in order to create narratives regarding the evolution of the industry, the market and the regulatory frameworks affecting the BIPV sector. In the absence of a fully developed and delineated BIPV industry with increased visibility among stakeholders, these data often relate to the wider PV sector rather than just the focal segment.

Section 7.1 provides a historical overview of the overall PV industry and market, as well as an analysis of the sector according to several criteria.

Section 7.2 outlines the particular characteristics of the BIPV sector, highlighting empirical findings regarding drivers and barriers to its growth.

Section 7.3 provides a firm-level comparative assessment that analyses the different strategies adopted by BIPV firms and investigates a potential correlation of business models and commercial success.

Section 7.4 outlines policies and regulations affecting the development of the BIPV sector, while Section 7.5 focuses on the regulatory framework in the UK.

This chapter contains a high amount of review data as well as empirical evidence collected through personal communications and semi-structured interviews. Findings are linked to functions of the hybrid framework outlined in Section 5.2 using their reference codes presented in Table 5.2 within braces (i.e. {Fi}).

7.1 The global PV sector

Although the BIPV sector can be classified as a segment of the wider PV industry, it is rarely included as such in market assessments by analysts. Market data are usually classified according to technological, geographical or the most prominent market categories of ground- and rooftop-mounted applications. Inevitably this industry and market assessment relies heavily on market data referring to the overall PV industry.

7.1.1 A brief history of the PV sector

The history of commercial PV applications is characterised by intermittent phases of strong growth. Throughout its 60 years of existence, the PV market has expanded by a Compound Annual Growth Rate (CAGR[1]) of 36.5%, among the highest rates demonstrated by a technological sector {F8} [REN21 and ISEP (2013); OECD/IEA (2011); Masson *et al.* (2014)].

The evolution of the PV market can be described in terms of five chronological periods (see Fig. 7.1). After the invention of the 'Bell Solar Battery' in 1954 [Chapin *et al.* (1954)] and a few pioneering applications, the first real commercial opportunity for PV devices appeared in 1958 and their introduction as power sources in satellites. The market was restricted in space applications for almost fifteen years. In the wake of the two oil crises in the 1970s and in a time of increasing environmental awareness, the sector grew significantly until it stagnated following the discontinuance of R&D support schemes in the USA. For more than a decade, the market was dominated by consumer electronic and off-grid applications. The real take-off occurred after the introduction of R&D programmes that stimulated market formation processes {F7}, as well as capacity- and electricity output-based financial incentives that have been the main driver for

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[1] CAGR provides a constant rate of growth over a time period. It can be calculated using the formula $CAGR = (\frac{FinalValue}{InitialValue})^{(1/T)} - 1$, where T is the time in years.

growth in the sector over the last fifteen years [Surek (2003); Jacobsson *et al.* (2004); Candelise (2009); Mints (2011a)]. These incentives facilitated the direction of resources towards the PV sector {F6}, stimulated research activities {F12} and increased the overall visibility of the sector among sustainable energy technologies {F10}.

Since 2010, the PV sector has been attracting the largest amount of new investments among renewable energy technologies and was the power technology that added the highest new generation capacity in Europe in 2012 {F6} [Jäger-Waldau (2013); Masson *et al.* (2013)]. According to the European PV Industry Association (EPIA), global installed PV power capacity reached 138.9 GWp in 2013. However, despite its substantial expansion, the PV sector remains a niche market in absolute terms, with PV systems contributing a small fraction of electricity needs {F8}. In 2012, this contribution was limited to 0.6% and 2.6% of global and European demand respectively, while in regions with high PV penetration it reached 5% (Germany) and 7% (Italy) [Masson *et al.* (2013, 2014); EurObserv'ER (2014)].

PV production capacity and market demand

Adhering to moderate growth rates of the PV sector in the last two decades of the 20^{th} century, investment in solar industry and expansion of production capacity was limited {F6}. This led to a severe manufacturing bottleneck after the introduction of financial incentives for the installation of PV systems in the mid 2000s. The sharp increase in demand caused a significant shortage of silicon feedstock, the material used for the production of the bulk of PV modules {F9} [Candelise *et al.* (2013)].

The main consequences of this bottleneck were the brief inversion of the PV cost reduction trend and the substantial investments on the expansion of silicon ingot production {F2}. The time-lag between investment and completion of these facilities {F11} allowed for the development of novel technologies and market segments {F7} that were previously not as cost-effective as the mainstream c-Si technologies [Van Sark *et al.* (2007)]. Research on TF and OPV technologies attracted significant resources {F6}, while multiple manufacturers invested on the commercialisation of new materials and product applications {F3}. Existing companies either focused on the improvement of manufacturing processes that increased average module efficiency and material utilisation, or the upstream supply-chain integration in order to decrease their dependency on

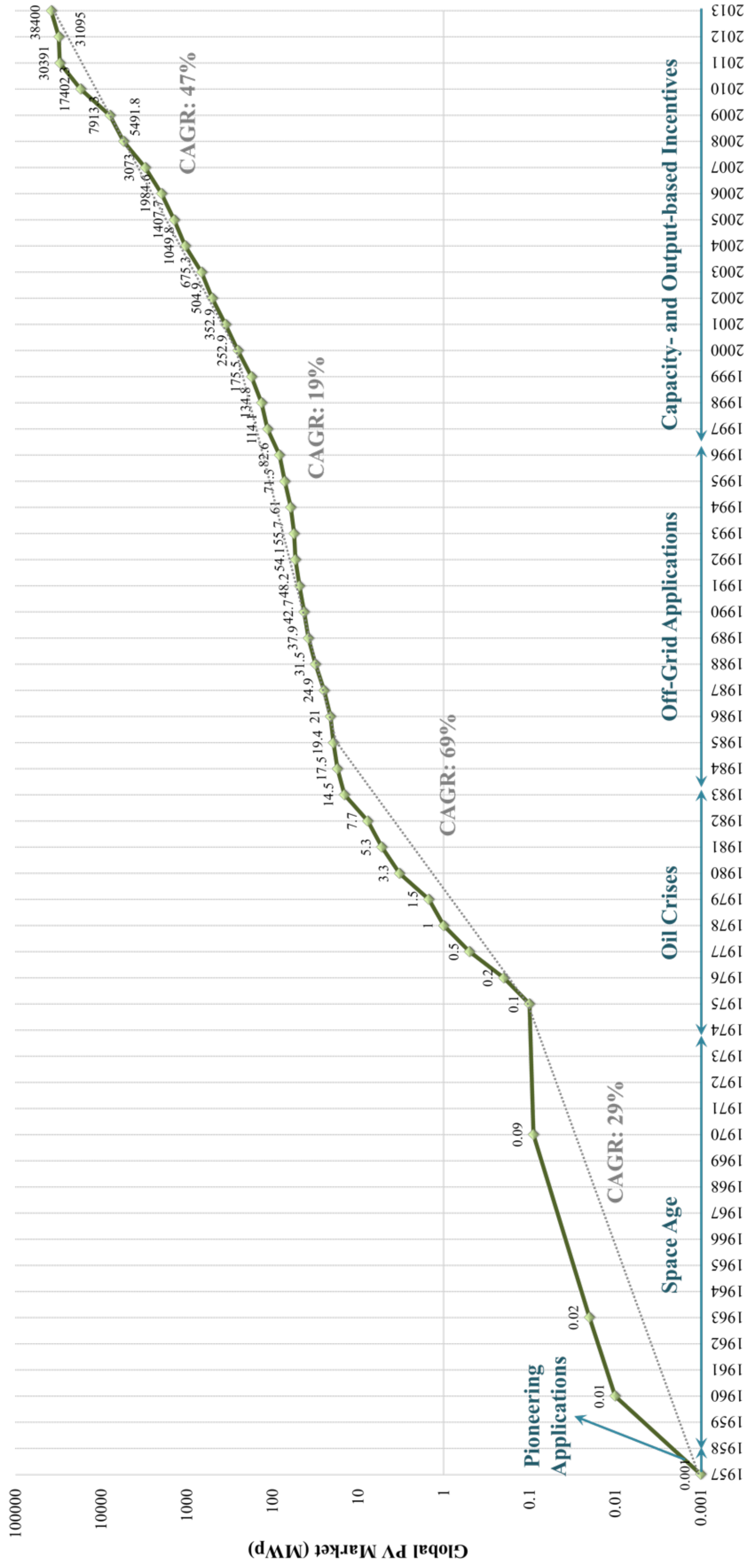

Figure 7.1: The five phases of historical PV market development (author's elaboration using data from Navigant Consulting, EPIA, IEA, JRC and Jacobsson *et al.* (2004)).

feedstock price volatility {F4} [Kazmerski (2006); Van Sark *et al.* (2007); EUPVPlatform (2011); Grau *et al.* (2012)].

Additional silicon production facilities came online in late 2000s, coinciding with a recessing economical environment that caused the retraction of financial aids among other austerity measures in leading markets {F9}. Overall manufacturing capacity, driven by optimistic market growth forecasts, significantly outpaced demand, leading to accumulation of PV product inventories and under-utilisation of production lines. It also led to diminishing profit margins for manufacturers, driving many of them out of the solar sector. More resilient firms reorganised their business model by integrating downstream components of the supply-chain and taking advantage of higher margins within engineering, procurement and construction (EPC) activities {F4} [Mints (2011a); Jäger-Waldau (2013); Gazis *et al.* (2013)].

The supply-demand asymmetry of the PV sector can be better illustrated and assessed using historical figures on production capacity and market size provided by industry associations and market analysts (see Fig. 7.2). At this point, it needs to be stressed that there is high uncertainty and significant discrepancies in the literature regarding production and market data. This is due to the very competitive nature of the market environment, the lack of common practices in the measurement of the various metrics, manufacturing outsourcing and the multitude of intermediate parties within the globalised PV supply chain that hamper objective and reliable enumeration of products {F5} [Jäger-Waldau (2013)].

As is evident in Fig. 7.2, the discrepancy between supply and demand has recently declined, with 7% of the manufactured products in 2013 remaining in inventories compared to more than a third in 2009 and 2010. However, a more thorough analysis reveals that this market rationalisation is due to a significant consolidation of the industry, leading to multiple un-utilised facilities and minimal capital expenditure on equipment {F2}. A recovery is expected by 2015, when the manufacturing surplus minimisation is forecast to trigger a new investment cycle [Jäger-Waldau (2013); Osborne (2014c)].

More specifically, market demand is predicted to grow from 46 to 50 GWp in 2014 and exceed 60 GWp in 2015. Production capacity on the other hand is not predicted to exceed 65 GWp by 2015 [Masson *et al.* (2013); Wolfgram (2014); Sharma (2014)].

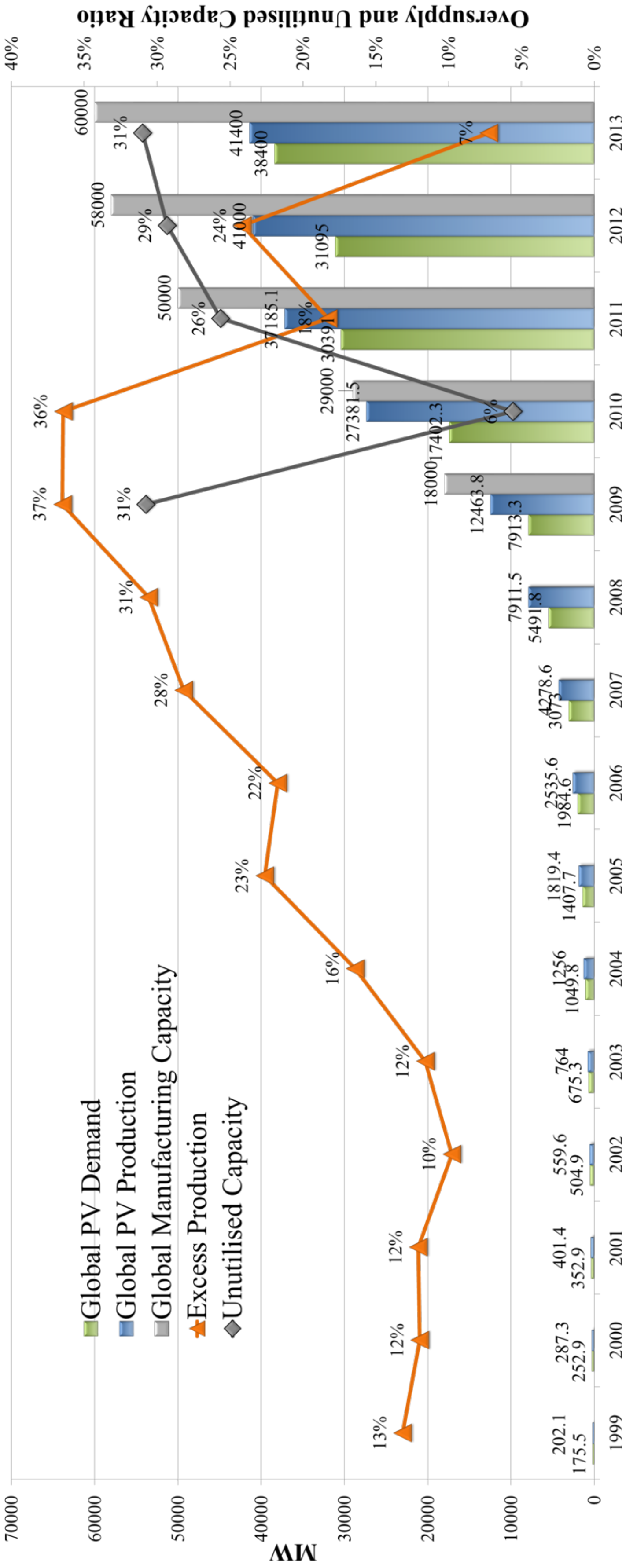

Figure 7.2: Global PV production and demand trends (author's elaboration using data from Navigant Consulting, EPIA, IEA and NPD Solarbuzz).

This convergence of market volume and production capacity is expected to provide an industry-market rationalisation, which will then drive the better correlation of selling prices to manufacturing costs, as well as a more stable environment for entrepreneurial activities and innovation {F3}.

Further forecasts of the PV sector have been developed by multiple organisations including the International Energy Agency (IEA) and Greenpeace International. Some indicative scenarios for the growth of the cumulative global installed PV capacity are presented in Figure 7.3. According to IEA, the combination of PV, concentrated solar thermal and storage will be the dominant source of electricity by 2050, accounting for up to 27% of global production [Parkinson (2014)].

7.1.2 Analysis of the PV sector

PV industry is characterised by a high level of segmentation, which is not limited to a geographical fragmentation of the globalised supply chain [I1; I11; I16]. As was discussed in Chapter 6, PV systems are versatile and modular devices allowing for a wide range of applications at different scales {F7}. Additionally, research experimentation has generated a multitude of economically feasible technologies with different characteristics {F3}.

Despite the significant commercial opportunities arising from this variety of options, highly antagonistic market dynamics combined with a recessing global economy have led to a turbulent industrial environment. More than 100 companies have experienced some form of restructure, bankruptcy or acquisition since 2009, with 44 and 36 reported procedures occurring in 2012 and 2013 respectively [Wesoff (2013); Parnell (2013b); Osborne (2014d); Parnell (2014c)]. The turbulent environment within the PV sector has also affected wider industry participants, including Photon Holding GmbH, the leading solar PV trade publisher for the last two decades {F5} [Willis (2014d)].

The characteristics of the ongoing consolidation in the PV industry are considerably different from those of other technological sectors, such as telecommunications and consumer electronics. The market share of the 10 leading firms has not increased throughout this process, but rather dropped from 88% in 2000 to 54% in 2012 [Mints (2014c)]. The opposite trend appears in the increasing market share of the top 50 and top 100 companies. The multitude of bankruptcies, mergers and acquisitions of firms

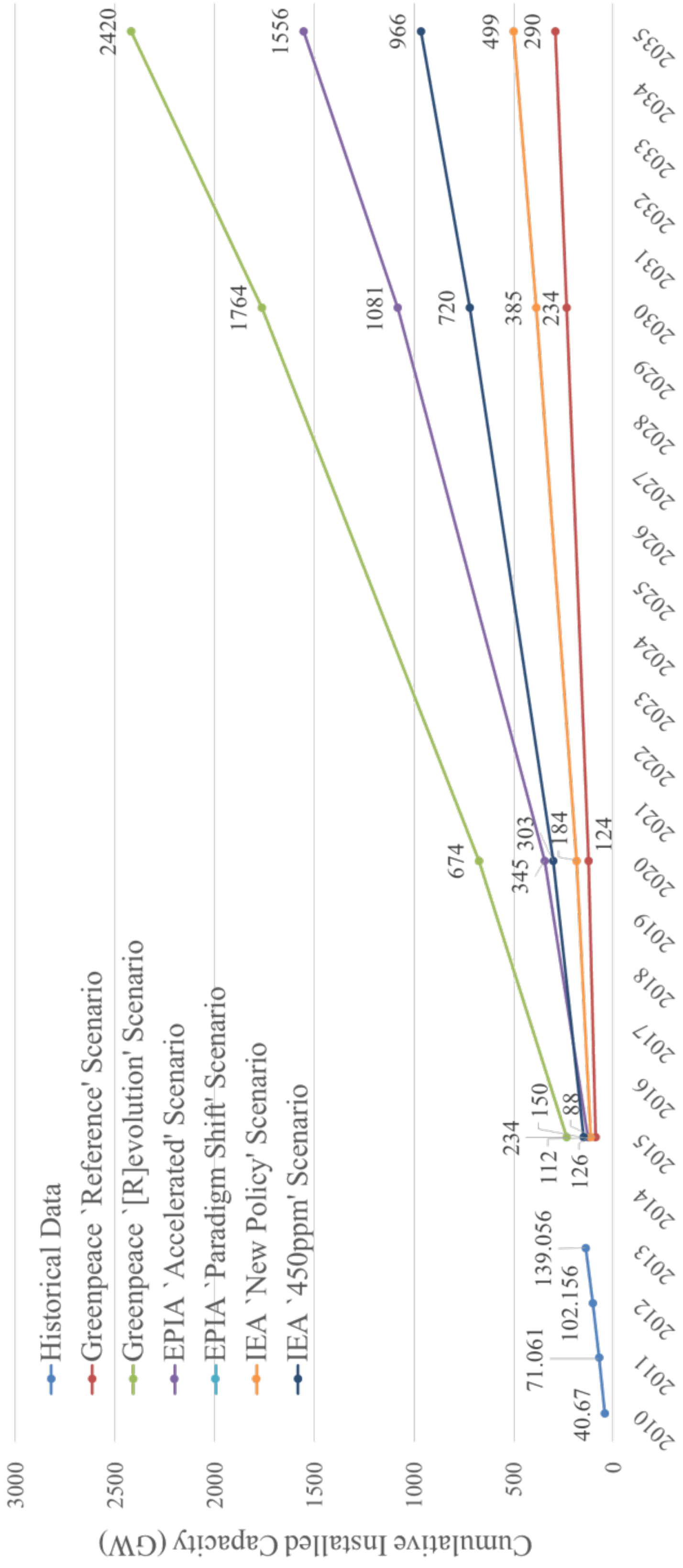

Figure 7.3: Global cumulative installed PV capacity scenarios (author's elaboration using data from REN21 and ISEP (2013); Jäger-Waldau (2013); EPIA and GREENPEACE (2011); IEA (2012); Greanpeace *et al.* (2012)).

with pilot production lines has been overcompensated by the entrance of major firms from adjacent industries including semiconductors and energy {F3, F4} [Jäger-Waldau (2013); Colville (2014a)].

One implication of this observation is that no clearly defined business models have emerged as dominant paradigms within the entrepreneurial world {F4} [Colville (2013)]. That said, most of the affected companies are manufacturers with technologically diversified production based mainly on TF PV technologies. The disintegration of these firms highlights the dangers involved in experimentation with novel technologies, differentiation into radical applications and the overall propensity to innovate {F3} [I2; I15; REN21 and ISEP (2013)].

Geographical distribution

Ever since the introduction of subsidies based on either installed capacity or power output, the PV market has been significantly policy-driven. This is particularly reflected in the geographical distribution of the sector, where major markets are located not in regions with a large solar resource but rather in countries with high governmental subsidies [Candelise (2009); Masson *et al.* (2013)]. The geographical distribution of industries and markets is important for this research as it outlines the globalised supply chain, incorporates regional dynamics in the analysis, justifies developments in business strategies within firms and provides insights regarding changes of the public image of the sector.

Although Europe has been the dominant PV market for the last decade, this trend is likely to change, with its contribution to global demand declining from 85% in 2008 to just 22% in 2014. Apart from Germany that has demonstrated a steady growth, European markets are characterised by short periods of overheated development due to the implementation of favourable policy followed by sharp declines after its retraction. Characteristic examples include Spain in 2008, the Czech Republic in 2010, Italy and France in 2011 and the UK in 2013 and 2014 [Masson *et al.* (2013); Willis (2014b)]. These fluctuations have resulted in the contraction of confidence among investors {F3, F6} and the significant damage of the image of the sector as a sustainable technological domain {F10} [I12; I13; I14].

In contrast to Europe where new investments in renewable energy technologies are declining, an increasing number of countries in Asia and Oceania are actively supporting solar power as part of their sustainable energy agenda {F6}. Although the Japanese government was among the first to provide incentives for the deployment of PV systems, market growth was rather moderate until the reformation of the country's energy market after the Fukushima nuclear accident in 2011 {F9}. China has also demonstrated strong growth recently and is expected to become the largest market in 2014 due to ambitious revisions of renewable energy targets [Sharma (2014)]. PV demand has also been booming in the USA driven by declining module prices that have rendered solar electricity competitive to grid power, especially in states with expensive power supply {F9} (See Fig. 7.4) [Lacey (2013)].

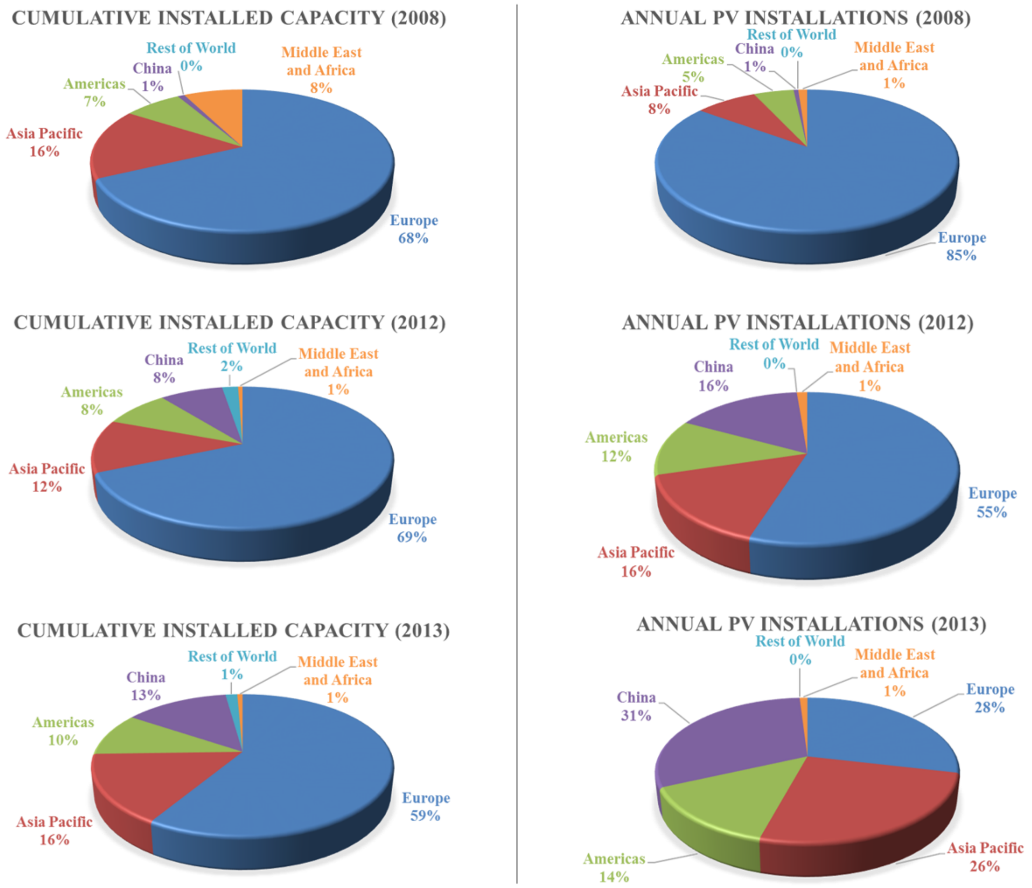

Figure 7.4: Geographical distribution of the PV market in 2008, 2012 and 2013 (author's elaboration using data from Masson *et al.* (2014)).

On the supply side, PV industry has been characterised by the shift of the bulk of manufacturing to the Asia-Pacific region. Production in China, Taiwan and Malaysia grew from a negligible size in 2005 to a 79% global share in 2012 driven mainly by vertically integrated firms focusing on cost leadership using economies of scale {F4, F8} (see Fig. 7.5). Nine out of ten major PV manufacturers are based in this region, when all top ten manufacturers were located in Japan and Europe in 2004 [Mints (2014c)]. This dramatic capacity expansion has caused significant manufacturing cost reductions, which in addition to the market oversupply have in turn reduced module prices by 80% from 2008 to 2012 [Jäger-Waldau (2013); Candelise *et al.* (2013)].

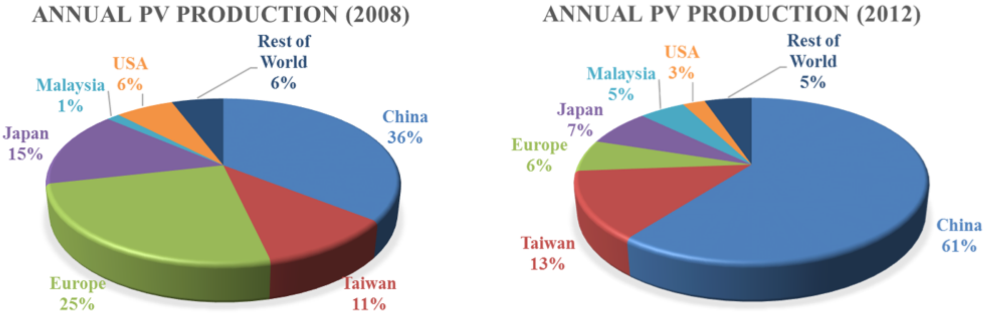

Figure 7.5: Geographical distribution of the PV manufacturing industry in 2008 and 2012 (author's elaboration using data from Jäger-Waldau (2013)).

Furthermore, this reformation of the manufacturing geography has triggered a series of bilateral trade disputes, based on allegations regarding production dumping strategies and subsidisation procedures that damage international competition. Both the EU and the USA have imposed tariffs on modules imported from China in an attempt to protect domestic industry and secure jobs upstream the supply chain, while investigations have also been initiated by India and Australia [Barker (2012); Parnell (2013a); Stearns (2013); Montgomery (2014b)]. Responding to these actions, the Chinese Ministry of Commerce imposed tariffs on polysilicon feedstock imported from the EU, the USA and South Korea, while manufacturers have restructured their business model, outsourcing part of their cell production to Taiwan and Malaysia {F4}. These reciprocal litigations are often considered by industry actors to be harmful to the overall industry, increasing uncertainty and reducing confidence among stakeholders {F3, F10} [I13; Barker (2014b); Martina (2014); Clifford (2014)]. Manufacturing outsourcing on the other hand complicates the backward tracing of PV modules, raising concerns regarding the quality of products with considerably long life expectancies [Mints (2014b)].

Technological differentiation

The broad PV technology mix provides a solid foundation for future growth of the sector as a whole. Applications spanning from consumer electronics to utility-scale power stations require systems with a range of technical characteristics {F7} [Jäger-Waldau (2013)]. The extensive variety of options is particularly relevant to the BIPV sector, which is very demanding with regards to the availability of products with a range of visual and formal characteristics {F8} [SHC (2013b); Hardy *et al.* (2012)].

Wafer-based silicon technologies (c-Si) have dominated the PV market throughout its 60-year history. In spite of not being the optimal semiconductor material for solar energy conversion, a well-established knowledge base borrowed from the electronics industry facilitated the fast deployment of reliable, durable devices with relatively high efficiencies and low manufacturing costs {F1} [I6]. The accumulation of experience over the years has allowed for the development of a mature sector and a comprehensive supply chain with vested interests in the sustainability of the c-Si manufacturing base {F8} [Green (2006); Van Sark *et al.* (2007)]. Additionally, it provides a low-risk investment environment for investors who can acquire equipment and expand their facilities at short time frames {F3} [Candelise (2009)].

TF technologies have always drawn significant interest within the research and entrepreneurial communities due to their reported advantages compared to c-Si {F3, F6}. These include better suitability of semi-conductor materials for sunlight absorption, reduced demand for active materials, higher energy yield due to lower temperature coefficient for power loss and the ability to manufacture monolithic-integrated, semi-transparent and flexible modules. These characteristics provided the potential for the deployment of a wide range of PV products at low manufacturing costs, making TF technology the most suitable for both the BIPV and the utility-scale power sectors [Hegedus (2006); Green (2006)]. Based on this potential Andersson and Jacobsson (2000) predicted their eventual market domination.

Two spikes in the historical market share trend notwithstanding, this market domination of TF technologies has not been realised (see Fig. 7.6). The first spike occurred in late 1980s, with the expansion of PV applications integrated in consumer electronics and off-grid devices {F8}. A-Si has traditionally been the most suitable technology for such systems due to low manufacturing cost and flexibility with regards to shapes and materials [EPIA and GREENPEACE (2011)].

The second spike occurred when the bottleneck of silicon feedstock raised concerns regarding the adequacy of c-Si production capacity to cover increasing demand in mid 2000s. Many observers at the time recognised the opportunity of TF to establish their potential and achieve accelerated market penetration {F11} [Swanson (2006); Hegedus (2006); Green (2006); Van Sark *et al.* (2007)], while Rogol and Fisher (2005) predicted the reversing of the trend after the expansion of silicon feedstock production.

Total market share of TF technologies has been declining for the last three years, due to the dramatic price reduction of c-Si modules {F9}. Average TF modules remain less efficient than c-Si, while the price difference required to compensate for that lower efficiency has been diminished [Parnell (2014d)]. Most TF companies could not follow the explosive growth rates of the c-Si industry, and have not yet developed products that can offer a competitive value proposition. The TF PV industry has not developed dominant designs and remains fragmented in terms of technologies, processes and business strategies {F8} [Van Sark *et al.* (2007); Bagnall and Boreland (2008); Gazis *et al.* (2013)].

As of 2014, three are the main TF manufacturers with viable production lines, one from each major technological sub-sector. First Solar achieved significant production scaling and cost reduction, and managed to be one of the top 10 PV manufacturers throughout the last decade [Mints (2014c)]. Solar Frontier produced in 2013 75% of all CIGS products, and is the only TF company with planned capacity expansion in 2014, while 3Sun is the only a-Si manufacturer with a capacity over 100MWp. Hanergy has announced a very optimistic capacity expansion plan after acquiring three CIGS companies, but its success is yet to be seen. The successful business models are based on comprehensive in-house supply options and strong operations downstream the supply chain including project acquisition and EPC activities {F4} [Colville (2014a)].

This experience of market repression has been viewed by some researchers as an example of technological lock-in. In spite of being arguably inferior in the long term, c-Si technology excludes other technologies due to early dominant market position {F8} [Unruh (2000); Green (2006)]. However, analysts expect that TF technologies will eventually realise their potential, with EPIA predicting 33% global market share by

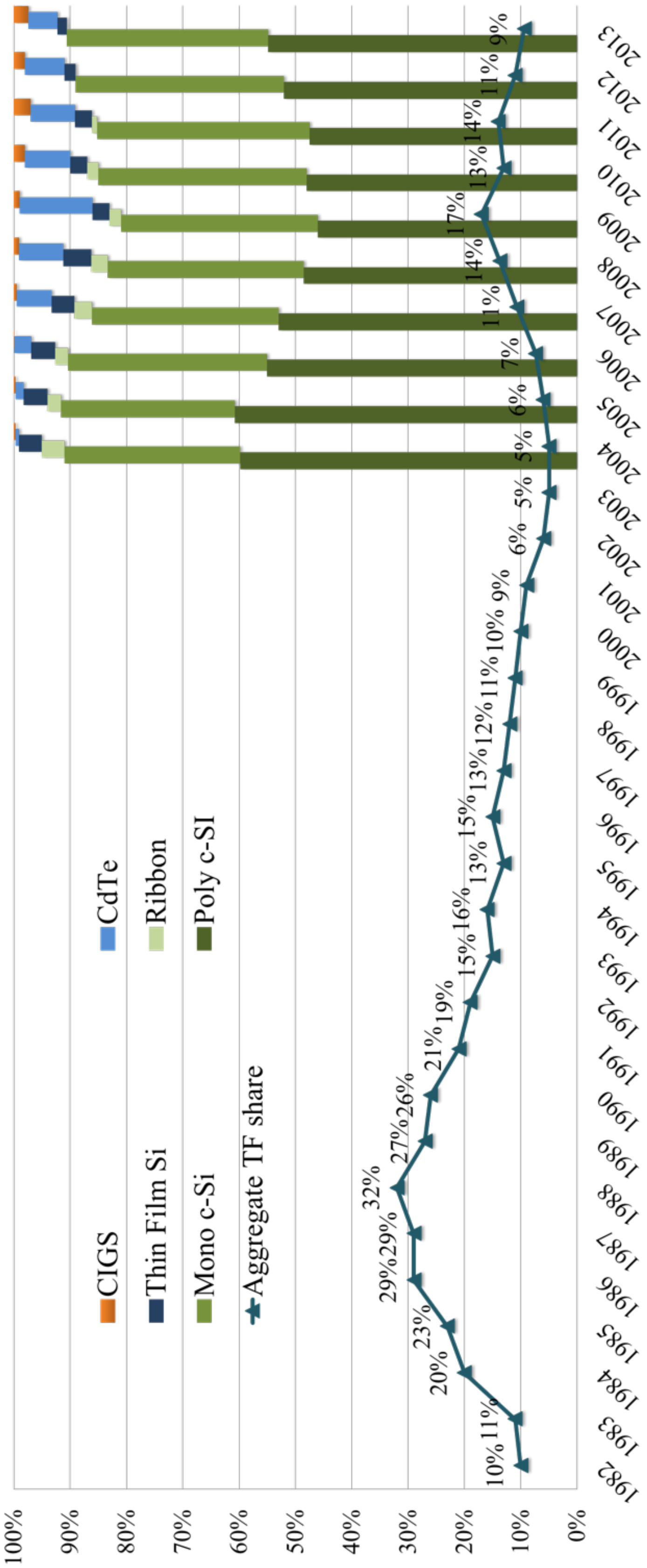

Figure 7.6: Market share of PV technologies (author's elaboration using data from Mints (2010, 2012a, 2014b)).

2020 [EPIA and GREENPEACE (2011)].

Third-generation PV technologies are still at the first stages of commercialisation, with no significant market share until this moment. Simplicity of manufacturing, flexibility of layers and the potential for very low production cost are expected to drive the broad deployment of these technologies, especially in the BIPV sector {F8} [I1; I15; Nelson (2002)]. According to EPIA, emerging CPV and OPV will capture 6% of the global market by 2020 [EPIA and GREENPEACE (2011)].

Market segments

PV applications vary widely in terms of scale and technology. Therefore, the PV market is constituted of a multitude of segments, or clusters of technological and market niches, each one with particular characteristics regarding potential growth, support and level of disruptiveness {F7}.

In industry reviews, PV systems are often differentiated according to their size, application type and whether they are connected to the central power grid or not. This research adopts the methodology followed by EPIA that takes into account not only the installed capacity of the system, but also the nature of the investor (private or public) and the regime of the respective retail electricity prices [Masson *et al.* (2014)]. The consideration of these parameters allows for the internalisation of social and economic processes and is hence more appropriate for multi-level analysis.

According to this methodology, the PV market can be divided into five segments [Masson *et al.* (2014)]:

- **Ground-mounted** installations are centralised utility-scale power plants. Although this market segment experienced high growth when capacity-based financial incentives were introduced, it is expected to decline after the revision of the regulatory frameworks in many countries that focus on supporting smaller distributed systems. Construction costs per unit power are relatively low due to scale economies, as is the wholesale value of the generated electricity.

- **Industrial** roof-mounted applications are also utility-scale plants; however, most of the generated power is consumed locally, providing a higher value rate compared to ground-mounted systems. Additionally, these systems benefit from existing electro-mechanical infrastructure.

- **Commercial** systems are medium-scale installations applied or integrated in urban buildings and infrastructure. The value proposition of these systems includes not only the use and sale of retail-price electricity, but also the marketing benefits for the owning company from making a 'green statement' of covering part of their power needs from renewable resources {F9} [Hegedus (2006)]. Commercial carports with integrated charging facilities are a market segment with particular growth potential, considering the significant expansion of the sector of electric vehicles {F9} [Beadle (2012)].

- **Residential** applications are small systems integrated in domestic buildings. The financial benefits for home-owners include self-consumption of the generated power, sale of excess power at high retail prices to the grid and, if there is relevant regulation, the additional incentive provided by local authorities based (usually) on the amount of units of generated electricity. System costs are relatively high due to the small scale of the installation and the quality of the components which is usually high in order to maximise the output from the limited space. The deployment of power storage systems in the form of electric vehicles or battery units is expected to increase the benefits from residential applications through smart supply-demand coordination {F9} [Willis (2014c)].

- **Off-grid** applications include systems of small to medium scale, ranging from consumer electronics to rural electrification installations. Although this segment was the dominant PV market until 2000, it is currently limited to less than 1% of global demand, with limited regulatory support. However, the sector is expected to experience accelerated growth since sharp cost reductions are making PV systems affordable in many regions of developing countries where grid-power is either non-accessible or unreliable {F7} [Mints (2013); Moore (2014)].

Market segmentation is geographically heterogeneous and highly depends on the local regulatory frameworks {F12} [Masson *et al.* (2014)]. This is particularly evident in Europe, as illustrated in Fig. 7.7.

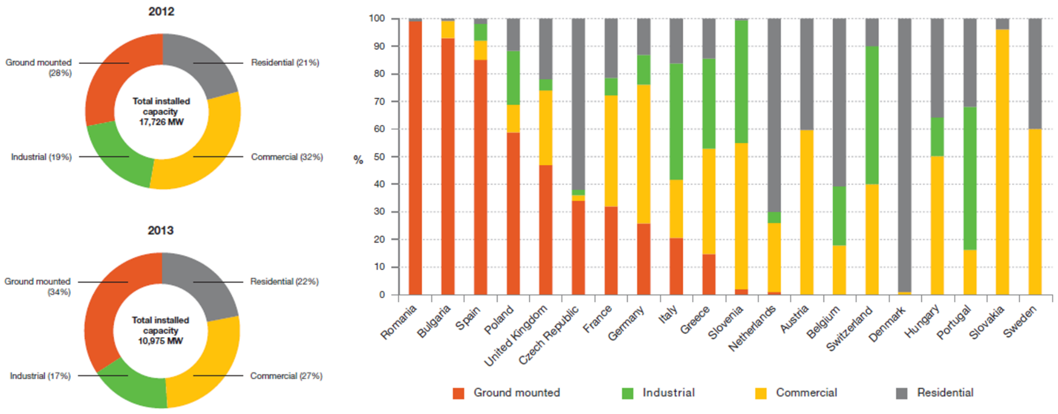

Figure 7.7: Market segmentation of grid-connected PV systems in Europe [Masson *et al.* (2014)].

7.2 The BIPV sector

According to the broadened definition of BIPV introduced in Subsection 6.2.1[2] and the mainstream market segmentation discussed earlier, the BIPV sector spans four of the main PV market categories: residential, commercial, industrial and off-grid systems.

Despite the socio-economic and technical characteristics of BIPV systems that fundamentally differentiate them from other PV applications, there is empirical evidence that the sector is not recognised as a separate entity {F10}. This is evident throughout the PV industry, with BIPV receiving arguably limited visibility within trade associations {F5}, market analyses and most importantly policy design {F7, F12} [I1; I6; I11; I12].

Immediately correlated to this lack of a well-defined and recognised BIPV sector is the absence of historical market data regarding PV installations in buildings. One estimation of the market size was 1201 MWp in 2010, representing 7% of total PV installation on that year; however, it is not made clear which BIPV systems are included in this calculation [REN21 and ISEP (2013)]. Using a different approach, Pike Research estimates global BIPV and BAPV market at just over 400MWp in 2012, expecting a growth to 4.6 GWp of installations by 2017 [Chan (2013)]. Following an econometric methodology NanoMarkets estimated the market at US\$2.1 billion in 2012 and predicted an increase to US\$7.5 billion by 2015, driven mainly by new buildings [Gasman (2011);

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[2] It is reminded that in this research the term BIPV addresses PV systems installed in existing and new buildings, as well as multifunctional systems incorporated in urban infrastructure and developed not with the sole purpose of power generation.

Chan (2012)]. The significant discrepancy in the figures and metrics demonstrates the lack of an established knowledge base, definitions and perspectives, impeding the development of a common vision for the sector {F10} [I12; I15].

The current economical downturn has impacted the BIPV sector to a considerable level. The overall dampening of the construction sector resulted in the very restricted development of new buildings {F9} [I12, I15]. BIPV applications are premium-priced products with long-term cost effectiveness due to power generation, and are therefore not easily considered in the initial design of a building [I6]. Furthermore, the ongoing consolidation of the PV industry has mainly affected firms with diversified manufacturing lines, limiting the range of commercially available products {F3} (see also Subsection 7.1.2). The engagement of major construction companies including panel and glass manufacturers and the incorporation of PV elements in the existing production lines as an additional process will potentially allow not only the reduction of capital expenditure, but also the access to comprehensive supply chains and marketing channels {F4} [I6; [Gasman (2011)].

The majority of BIPV products are designed and manufactured based on experience gained by the development of devices targeted to other PV market segments {F1, F2} [I6; I12]. Therefore, they are not always compatible with building specifications and regulations, which often require complex planning permissions and bureaucratic processes [I4]. Further barriers to the deployment of BIPV and other microgeneration technologies include grid balancing issues, which can be aided by better temporal supply-demand matching in order to maximise in situ power consumption, as well as the adoption of storage technologies {F9} [I3; I16; PVPS (2012)].

According to industry actors, the involvement of the architectural community has been limited due to aesthetical and functional reasons {F10} [I3; I5; I6; I15]. The market dominance of c-Si modules has eclipsed other technological options that are potentially better suited for building integration. As discussed in Subsection 6.3.2, new PV materials offer the possibility for a range of colours, shapes, textures and levels of transparency, providing architects with the required visual and formal flexibility. Better communication of these options to the architectural community could be achieved by trade associations, targeted workshops and other types of knowledge diffusion and education networks {F5} [I12; I16].

At the residential sector, the value proposition of BIPV lies in the increasing retail prices of electricity that make the idea of generation and self-consumption appealing to home-owners {F9}. Initial cost of PV systems remains the main limiting reason for further adoption; however, higher availability of loans due to the increasing bankability of devices and expansion of leasing programmes could make them accessible to a larger population {F6} [I12; Goosens (2014)]. Moreover, a potential growth of the EV and power storage sectors is expected to strengthen local electricity grids and facilitate future growth of distributed energy systems, including BIPV {F9} [I12; I16].

At the commercial and industrial segment, BIPV offers the opportunity to companies of using solar systems as a marketing device, as well as increasing the share of renewable electricity within their energy mix [I12]. Considering that cost of investment and payback periods are the major influencing factors in this segment, optimal system design is crucial [I6; I10]. Additionally, if PV integration is adopted at an early stage of the building development, the avoided cost of conventional materials being replaced by BIPV products can be estimated and included in the cost analysis [I3].

Major BIPV markets in Europe include Germany, France and Italy. Growth in these countries was driven mainly by policy instruments focused explicitly on the development of the BIPV sector (see also Section 7.4) {F7, F12}. Early support facilitated the development of significant expertise along the BIPV supply chain, a wide knowledge network and a high level of awareness among end-users {F10} [Carella (2009)]. In countries with no targeted incentives, market expansion has been slow, despite the success of the wider PV sector (e.g. Spain).

With 82% public support, solar PV in the UK has a significant role in connecting individuals, communities and businesses with future deployment of renewable technologies and the transition to the low-carbon economy {F10} [PVPS (2012)]. Empirical evidence shows that adoption of BIPV systems has stimulated positive changes in consumer behaviours, including increased energy use awareness and electricity savings [Keirstead (2007)]. These potential benefits have been recognised and addressed in the Solar PV Strategy developed by the UK government in 2013 which focuses on small- and medium-scale roof-top PV systems {F12} [I16; DECC (2013b, 2014a)].

The UK has developed a strong body of organisations at the basic and applied R&D stages and is recognised as being a leader in the development of 3^{rd} generation PV technology worldwide {F1} [PVPS (2011)]. Nevertheless, R&D activity is often viewed by involved actors as being disjointed and poorly coordinated [I12; I16].

The significant growth of the PV market that surpassed 5GWp of installed capacity in 2014 has also created a comprehensive network of installers, especially within the ground-mounted and BAPV market segments {F8} [Clover (2014)]. However, industry actors argue that it has not yet realised a network of manufacturers and system developers that would complete an efficient supply chain able to accelerate growth within the sector [I1; I6; I7; I12; I13; I15].

7.3 Cross-firm assessment

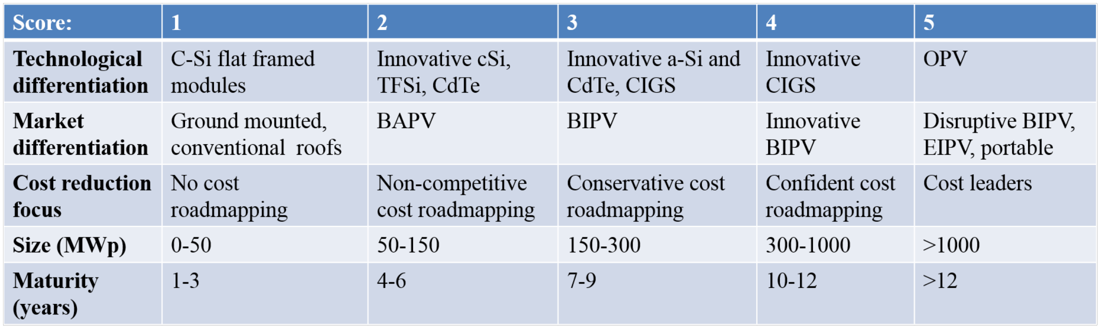
The previous sections provided an outline of the global BIPV sector investigating industry-wide characteristics and developments. This section focuses on the firm level in order to provide a better understanding of the impact of these developments on strategic choices of individual companies, and highlight the correlation of specific strategies and commercial success within the BIPV market.

The comparative assessment in this research is based on a framework of indicators, that was developed to facilitate the evaluation of strategic choices. The framework consists of three metrics that are used to quantify relative strategic orientation and two contextual metrics regarding the background of the researched firms:

- **Technological differentiation** is used to measure the efforts of a firm for the development of novel technologies and processes.
- **Market differentiation** is a metric that assesses the diversification of production into niche applications and markets.
- **Cost reduction focus** evaluates the strategic focus of a firm on becoming the cost leader in their respective market segment.
- **Size** reflects the manufacturing capacity of the firm.
- **Maturity** is used to measure the longevity of the firm within the sector.

A preliminary market research revealed over 110 firms with technological and market relevance to this research. A data-base was built for each company using publicly available data, announcements and information collected during personal communications. All data were collected from January 2011 to August 2014, a period of over three and a half years that was characterised by a substantial reconfiguration of the PV sector with numerous new entries, mergers, acquisitions and corporate exits.

Based on data availability and relevance to the aims of this study, 40 firms were selected to be further investigated. Focal firms included companies active not only in the BIPV sector, but also in other segments of the PV industry, to provide a wider perspective. A scoring methodology was implemented for the comparative analysis of their strategic characteristics using the framework of five indicators. Each firm was attributed a score from 1 to 5 against each metric, following a comparative scale outlined in Fig. 7.8.

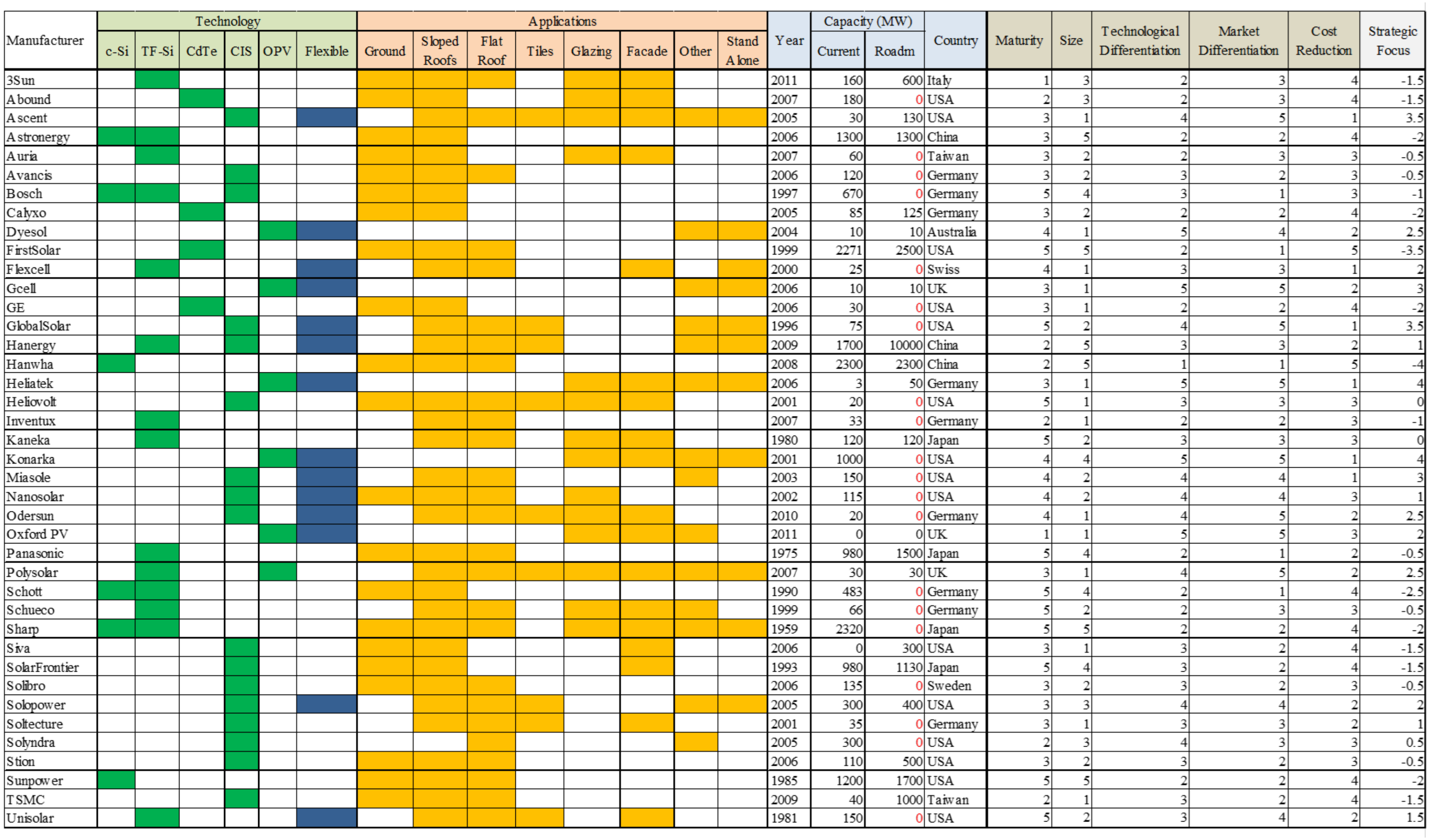


Score:	1	2	3	4	5
Technological differentiation	C-Si flat framed modules	Innovative cSi, TFSi, CdTe	Innovative a-Si and CdTe, CIGS	Innovative CIGS	OPV
Market differentiation	Ground mounted, conventional roofs	BAPV	BIPV	Innovative BIPV	Disruptive BIPV, EIPV, portable
Cost reduction focus	No cost roadmapping	Non-competitive cost roadmapping	Conservative cost roadmapping	Confident cost roadmapping	Cost leaders
Size (MWp)	0-50	50-150	150-300	300-1000	>1000
Maturity (years)	1-3	4-6	7-9	10-12	>12

Figure 7.8: Framework for comparative analysis (author's elaboration).

Manufacturing capacity data were collected from corporate announcements and secondary reports by market research analysts, while market activities were assessed based on commercial products and published R&D projects. Many figures provide just a trend rather than final numbers, since not all companies announce their capacity expansions or reductions in advance, and information about ongoing R&D projects is very limited. A summarising table of the findings is presented in Fig. 7.9.

Finally, nine of the most relevant firms were selected to provide more detailed stories and highlight a potential correlation between business models and commercial status in the PV sector.



Manufacturer	Technology						Applications								Year	Capacity (MW)		Country	Maturity	Size	Technological Differentiation	Market Differentiation	Cost Reduction	Strategic Focus
	c-Si	TF-Si	CdTe	CIS	OPV	Flexible	Ground	Sloped Roofs	Flat Roof	Tiles	Glazing	Facade	Other	Stand Alone		Current	Roadm							
3Sun		🟩					🟨	🟨	🟨		🟨	🟨			2011	160	600	Italy	1	3	2	3	4	-1.5
Abound			🟩				🟨	🟨			🟨	🟨			2007	180	0	USA	2	3	2	3	4	-1.5
Ascent				🟩		🟦		🟨	🟨	🟨	🟨	🟨	🟨	🟨	2005	30	130	USA	3	1	4	5	1	3.5
Astronergy	🟩	🟩					🟨	🟨							2006	1300	1300	China	3	5	2	2	4	-2
Auria		🟩					🟨	🟨			🟨	🟨			2007	60	0	Taiwan	3	2	2	3	3	-0.5
Avancis				🟩			🟨	🟨	🟨						2006	120	0	Germany	3	2	3	2	3	-0.5
Bosch	🟩	🟩		🟩			🟨	🟨							1997	670	0	Germany	5	4	3	1	3	-1
Calyxo			🟩				🟨	🟨							2005	85	125	Germany	3	2	2	2	4	-2
Dyesol					🟩	🟦							🟨	🟨	2004	10	10	Australia	4	1	5	4	2	2.5
FirstSolar			🟩				🟨	🟨	🟨						1999	2271	2500	USA	5	5	2	1	5	-3.5
Flexcell		🟩				🟦		🟨	🟨			🟨		🟨	2000	25	0	Swiss	4	1	3	3	1	2
Gcell					🟩	🟦							🟨	🟨	2006	10	10	UK	3	1	5	5	2	3
GE			🟩				🟨	🟨							2006	30	0	USA	3	1	2	2	4	-2
GlobalSolar				🟩		🟦		🟨	🟨	🟨			🟨	🟨	1996	75	0	USA	5	2	4	5	1	3.5
Hanergy		🟩		🟩		🟦		🟨	🟨	🟨			🟨	🟨	2009	1700	10000	China	2	5	3	3	2	1
Hanwha	🟩						🟨	🟨	🟨						2008	2300	2300	China	2	5	1	1	5	-4
Heliatek					🟩	🟦					🟨	🟨	🟨	🟨	2006	3	50	Germany	3	1	5	5	1	4
Heliovolt				🟩			🟨	🟨	🟨	🟨	🟨	🟨			2001	20	0	USA	5	1	3	3	3	0
Inventux		🟩						🟨	🟨						2007	33	0	Germany	2	1	2	2	3	-1
Kaneka		🟩						🟨	🟨		🟨	🟨			1980	120	120	Japan	5	2	3	3	3	0
Konarka					🟩	🟦					🟨	🟨	🟨	🟨	2001	1000	0	USA	4	4	5	5	1	4
Miasole				🟩		🟦		🟨	🟨				🟨		2003	150	0	USA	4	2	4	4	1	3
Nanosolar				🟩		🟦	🟨	🟨	🟨		🟨				2002	115	0	USA	4	2	4	4	3	1
Odersun				🟩		🟦		🟨	🟨	🟨	🟨	🟨			2010	20	0	Germany	4	1	4	5	2	2.5
Oxford PV					🟩	🟦					🟨	🟨	🟨		2011	0	0	UK	1	1	5	5	3	2
Panasonic		🟩					🟨	🟨	🟨						1975	980	1500	Japan	5	4	2	1	2	-0.5
Polysolar		🟩			🟩			🟨	🟨	🟨	🟨	🟨	🟨	🟨	2007	30	30	UK	3	1	4	5	2	2.5
Schott	🟩	🟩					🟨	🟨							1990	483	0	Germany	5	4	2	1	4	-2.5
Schueco		🟩						🟨	🟨		🟨	🟨	🟨		1999	66	0	Germany	5	2	2	3	3	-0.5
Sharp	🟩	🟩					🟨	🟨	🟨		🟨	🟨	🟨	🟨	1959	2320	0	Japan	5	5	2	2	4	-2
Siva				🟩			🟨	🟨				🟨			2006	0	300	USA	3	1	3	2	4	-1.5
SolarFrontier				🟩			🟨	🟨				🟨			1993	980	1130	Japan	5	4	3	2	4	-1.5
Solibro				🟩			🟨	🟨	🟨						2006	135	0	Sweden	3	2	3	2	3	-0.5
Solopower				🟩		🟦		🟨	🟨	🟨			🟨	🟨	2005	300	400	USA	3	3	4	4	2	2
Soltecture				🟩				🟨	🟨	🟨		🟨			2001	35	0	Germany	3	1	3	3	2	1
Solyndra				🟩					🟨				🟨		2005	300	0	USA	2	3	4	3	3	0.5
Stion				🟩			🟨	🟨	🟨						2006	110	500	USA	3	2	3	2	3	-0.5
Sunpower	🟩						🟨	🟨	🟨						1985	1200	1700	USA	5	5	2	2	4	-2
TSMC				🟩			🟨	🟨	🟨						2009	40	1000	Taiwan	2	1	3	2	4	-1.5
Unisolar		🟩				🟦		🟨	🟨	🟨		🟨			1981	150	0	USA	5	2	3	4	2	1.5

Figure 7.9: Characteristics of researched firms (author's elaboration based on published data).

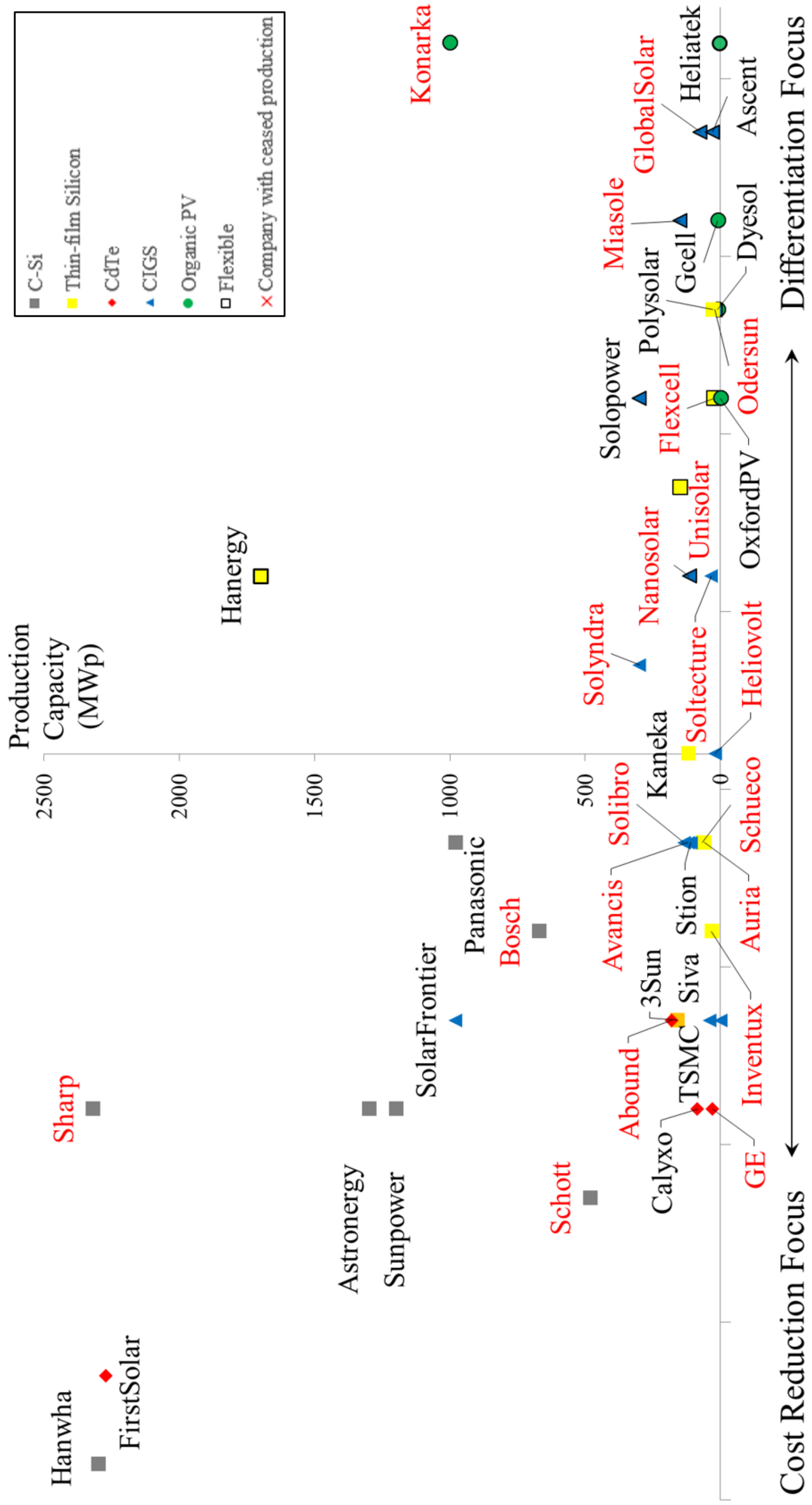


Figure 7.10: Mapping of PV manufacturers according to strategic focus and manufacturing capacity (author's elaboration based on published data and empirical evidence).

Relative strategic orientation

Using findings from the research outlined in the previous paragraphs, strategies and commercial success in terms of size and corporate sustainability were brought together in one graph for comparison (see Fig. 7.10).

In order to reduce complexity in the visualisation of the three dimensional strategic orientation, an additional secondary indicator was used for the overall strategic focus of each firm, calculated as the average of technological and market differentiation minus cost reduction focus. The new metric forms the horizontal axis of the graph and ranges from -4 for a cost-oriented firm with no differentiated production to +4 for a fully diversified company with no cost-reduction strategy.

Size in terms of manufacturing capacity in MWp/year forms the vertical axis. Companies that ceased production are displayed in red colour, while different symbols are used for different technologies adopted by the firms.

On the left side of the graph are located firms that focus on reducing their manufacturing costs by achieving high asset turnover, offering high volumes of standardized products and integrating parts of the entire PV value chain, both upstream (materials extraction) and downstream (design and installation). Manufacturers that obtain a cost leadership business strategy usually adopt established PV technologies (e.g. c-Si and CdTe) and target the developed ground-mounted and industrial roof-mounted market segments, where standardised systems can be deployed in large volumes in an efficient cost-effective way.

On the right lie firms that focus on product differentiation and the creation of new market segments, especially in the BIPV and EIPV sectors. Most of these firms utilise thin-film and organic PV technologies due to their technological advantages in these market segments, including better temperature coefficient that allows for higher energy yields at high temperatures and the prospect for non-ventilated modules, the possibility of deposition on flexible plastic or metallic substrates and the potential for coloured and semi-transparent modules that can be used for glazing.

Recent developments in the PV industry that have been discussed earlier, including low-cost manufacturing of c-Si modules in China and slower-than-expected market growth, have resulted in a highly antagonistic commercial environment and consequently diminishing profit margins for manufacturers. The result has been a significant and distinctive consolidation of the industry (see also Subsection 7.1.2). During this process, over 100 PV companies have experienced some form of restructure, bankruptcy or acquisition since 2009 [Willis (2014d)].

The affected firms include PV manufacturers and system developers across the strategic spectrum illustrated in Fig. 7.10. Unless they had alternative sources of revenue, companies that were not able to ramp-up their production capacity fast enough to achieve cost leadership were deemed non-competitive and forced to cease production. All surviving companies on the left side of Fig. 7.10 are active in the established utility-scale market, and with the exception of two TF companies (First Solar and Solar Frontier), utilise the mature c-Si technology.

A range of cost-oriented firms have responded to the ongoing consolidation by diversifying their activities and integrating additional elements of their supply chain. Responding to rising polysilicon prices in mid 2000s, many companies using c-Si technology developed vertically-integrated manufacturing lines in order to minimise their dependency on volatile feedstock costs [Candelise *et al.* (2013)]. However, the most prominent strategy presently is the inclusion within the core business model of activities downstream the value chain, including development, construction and operation of PV systems {F4}. Wider profit margins in these activities ensure positive and stable cash-flows. Examples include First Solar, Sharp and Solar Frontier who have all expanded their operations into project development and power production [REN21 (2014)].

Pressure has also been great on firms that focus on technological and market differentiation. The competitive advantages of second- and third-generation PV technologies have not yet been realised to a level that could make them cost-competitive with incumbent c-Si modules. On the other hand, developing market segments including BIPV have not demonstrated the expected growth and therefore, companies with aggressive deployment strategies (e.g. Solyndra) are confined within niche markets that render their business plans unsustainable.

A limited number of new investments on differentiated companies still occurs, with the most prominent examples of TSMC and particularly Hanergy, who acquired the intellectual property of three CIGS firms. The main characteristic of these investments is that they are backed by strong conglomerates with easy access to capital and parallel revenue streams, able to experiment with the development of new technologies and markets {F3, F6}.

Comparison of strategic characteristics

In order to achieve a better understanding of the association of certain strategic choices with commercial success, business models of nine firms were further investigated. Their main strategic characteristics were quantified using the framework outlined in Fig. 7.8 and are illustrated collectively in Fig. 7.11.

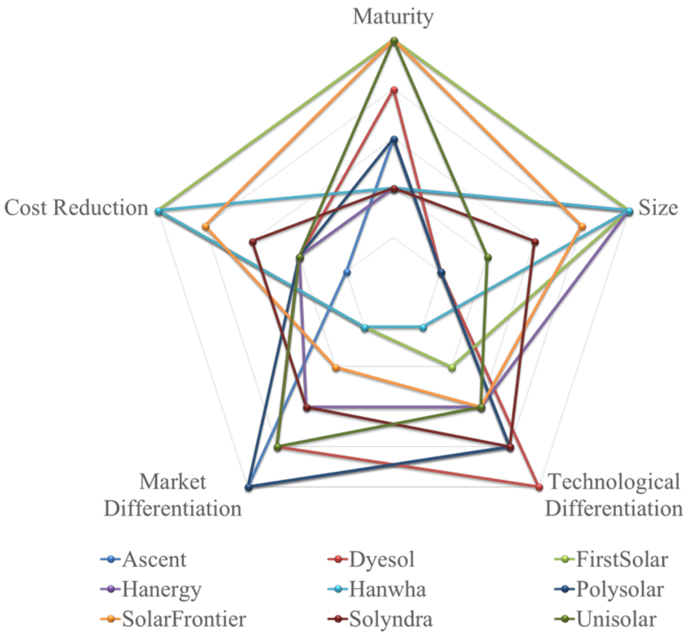


Figure 7.11: Strategic characteristics of researched firms (author's elaboration).

Ascent Solar is a developer of flexible lightweight modules based on the CIGS technology [AscentSolar (2014a)]. The firm is based in the USA, but has expanded its manufacturing capacity to Asia after strategic alliances with the Singapore-based investment firm TFG and Radiant, a Chinese conglomerate active in the construction and real estate industries {F2, F6} [Cheyney (2011a)].

Although initial commercial plans focused on the development of BAPV and other BIPV systems, the company diversified into a range of niche market segments where it has identified an opportunity for higher profit margins. It currently possesses one of the most differentiated portfolios in the PV industry, with products designed for the aerospace, military, automotive and particularly the consumer electronics sector (EIPV) {F7} [Johnson (2012)]. The development of strategic partnerships with key stakeholders in these sectors and the commercialisation of such products has facilitated the establishment of growing revenue streams and allowed its corporate sustainability despite its small size and overall market share [AscentSolar (2014b)].

Dyesol is an Australian supplier of dye-sensitised PV materials [Dyesol (2014)]. The firm has established an international network of research partners in Australia, Japan, Singapore, Saudi Arabia, Switzerland and the UK. Furthermore, it has formed several partnerships with major industrial companies for the development of BIPV materials [Gifford (2011); Osborne (2013a); Nkwocha (2013); Dyesol (2013); Osborne (2013g)].

Despite its long R&D presence, the strong financial support and the development of a range of demonstration projects, including the world's largest dye-sensitized steel-based module in partnership with British steel manufacturer Tata Steel, the firm has not yet achieved commercialisation of its projects {F2} [Gifford (2011); Osborne (2013a); Dyesol (2013)]. It is currently involved in the development and commercialisation of perovskite-based OPV thin-film products {F1} [Osborne (2014a)]

First Solar is a USA-based manufacturer of CdTe modules with production lines in the USA, Malaysia and Germany {F2}. By adopting a cost-reduction strategy through economies of scale, it became the first PV company to reach GW-scale annual capacity and reduce manufacturing costs below the $1/Wp threshold [FirstSolar (2014)].

The firm has invested significantly on the development of CdTe technology, through both in-house R&D activities and acquisition of IP [Montgomery (2013)]. It has also experimented with CIGS and c-Si technologies in order to develop high-efficiency products that serve a wider spectrum of PV applications {F3} [Osborne (2013e)]. First Solar has developed a copyable manufacturing methodology that facilitates upgrading through uniform transfer of R&D developments into production [Osborne (2013b)].

Efficient manufacturing processes, high utilisation rate of facilities and technological advancements have rendered First Solar one of the leading manufacturers in terms of low-cost production. Average module costs for First Solar in late 2013 were \$0.56/Wp, when total production cost of the cheapest c-Si manufacturer (Yingli) was \$0.55/Wp, driven mainly by low polysilicon feedstock cost [Osborne (2013d, 2014b)]. At the system level, First Solar prices reach \$1.59/Wp, expected to fall below \$1/Wp in 2017 [Martin (2014)].

Following the significant module oversupply in early 2010s, the company reorganised and changed its cost leadership strategy from aggressive capacity expansion (supply-push) to project development using First Solar modules (demand-pull) {F4, F9} [Colville (2014b)]. By creating joint ventures with established firms and developing a massive pipeline of solar farms in Europe and the USA, First Solar became the world's largest PV engineering, procurement and construction contractor (EPC) in 2012 and 2013 [Willis (2013a); Osborne (2013c); Willis (2014a)]. These activities increased corporate revenue significantly and maintained a positive cash-flow [Doom and Martin (2012)].

The geographical focus of First Solar is on markets without renewable energy subsidies, where its low-cost modules demonstrate a competitive advantage, including the Middle East, North Africa and China [Osborne (2011b); Willis (2013b)]. Despite restrictions against Cadmium-containing products in the EU and Japan, the company has obtained exemptions allowing the free installation of CdTe modules in both regions [Gifford (2013a)]. The firm has also expressed particular interest in the large-scale solar market segments in Germany and the UK where it currently constructs the country's largest solar farm, as well as the medium-scale industrial and commercial rooftops market [Woods (2014); Martin (2014)].

Hanergy is a Chinese PV manufacturer with one of the largest manufacturing capacities of TFSi PV modules [Hanergy (2014)]. With the financial support of a major Chinese power utility company, Hanergy has acquired a range of struggling TF manufacturers including CIGS-based Solibro, MiaSolé and Global Solar, and the

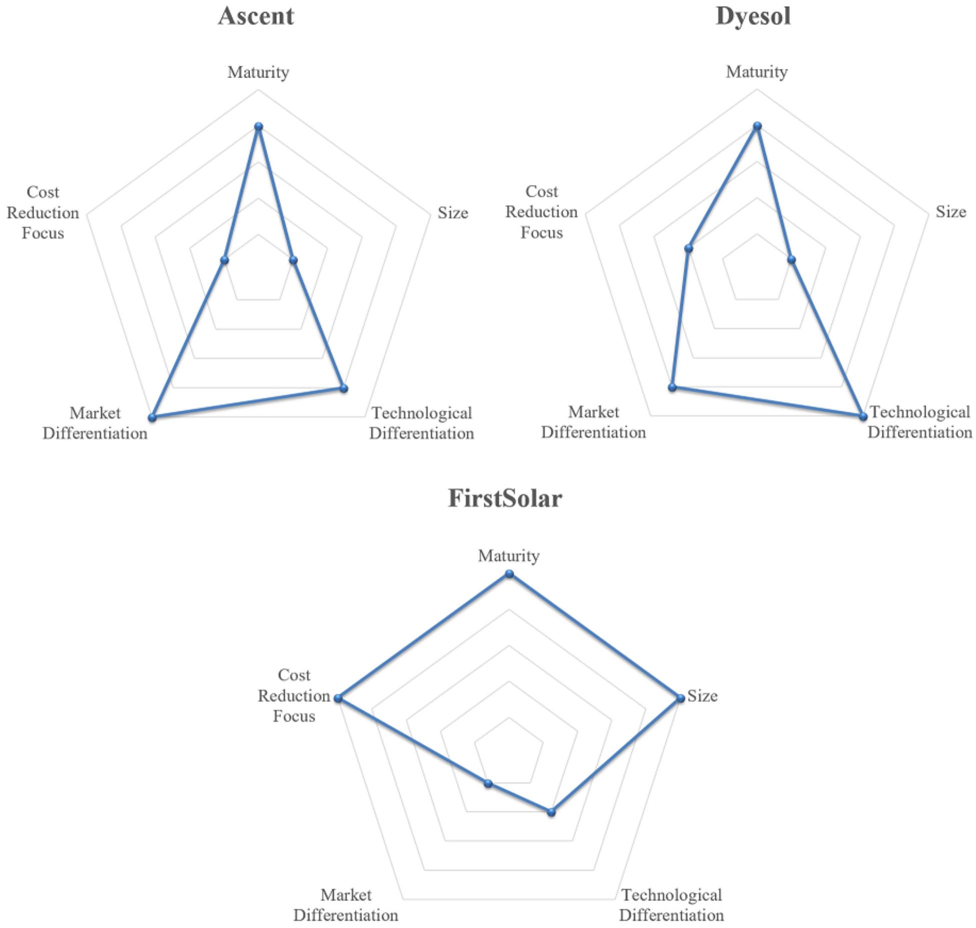


Figure 7.12: Strategic characteristics of Ascent, Dyesol and First Solar (author's elaboration).

GaAs start-up Alta Devices, developing a wide intellectual property portfolio and developing a significant TF manufacturing capacity expansion to 5.25GWp {F1, F2} [Wang (2012); Osborne (2012a); Shen (2013); Osborne (2013f); Colthorpe (2014a); Parnell (2014b)]. It has also established research centres in the USA and China for the development of innovative applications for the buildings and auto-mobile industries [Parnell (2014a)].

The corporate strategy of the firm includes a comprehensive integration of the value chain. Upstream activities include equipment tool manufacturing through its subsidiary Apollo Solar while downstream they span over the whole spectrum of development and procurement of BIPV, BAPV, EIPV and ground-mounted projects {F4} [Colville (2014c); Choudhury (2013)]. The company has created retail channels in Europe through a partnership with IKEA for the direct sale of products to consumers, while a collaboration with major electric-vehicles manufacturer Tesla Motors for the construction of carport charging stations has facilitated not only the development of additional revenue streams, but also the expansion of the brand visibility to the public {F10} [Bennett (2012); Colthorpe (2014b)].

Hanwha is a South Korean manufacturer of c-Si PV modules [Hanwha (2014)]. The firm implemented an aggressive growth strategy, acquiring in 2010 the Chinese Solarfun and the former largest PV manufacturer QCells in 2012 [Font (2012); Willis (2013c)]. The company has achieved significant cost-reductions through scale production, by maintaining high utilisation of its manufacturing lines. Although its main market focus is utility-scale ground-mounted projects, it has also established a division in the USA for the development of commercial-rooftop projects [SolarIndustry (2013)].

Polysolar is a British developer of TF and OPV systems, focusing on BIPV applications. Although it has identified commercial buildings as its major market segment, the company has diversified into the more developed residential rooftop market in order to generate revenue to finance its ongoing R&D activities [Polysolar (2014a)]. Its business model and strategic choices will be further discussed in Section 8.3.

Solar Frontier is a Japanese manufacturer of CIGS modules, subsidiary of the Showa Shell Sekiyu group company [SolarFrontier (2014)]. Focusing on cost reduction

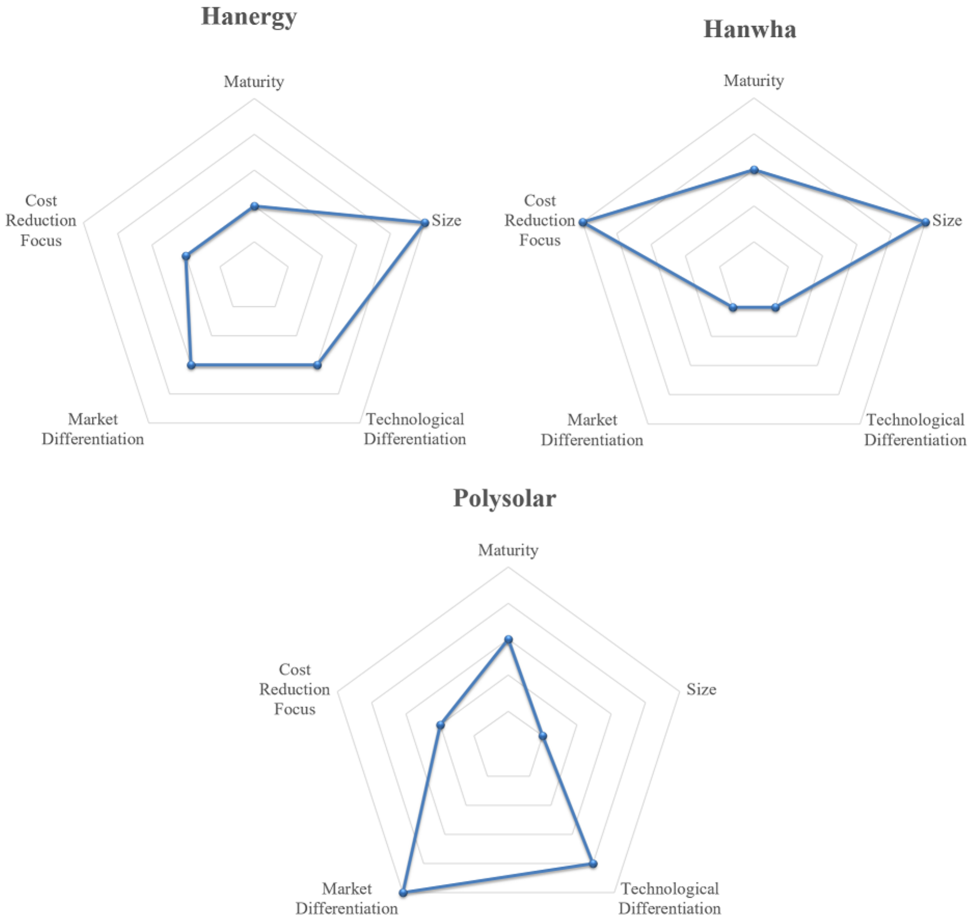


Figure 7.13: Strategic characteristics of Hanergy, Hanwha and Polysolar (author's elaboration).

through scaling of production, the firm became the second GW-scale TF module manufacturer after First Solar in 2011 [SolarFrontier (2011)]. In an attempt to standardise processes and equipment and reduce costs, the company plans to establish a manufacturing line in Japan that will be used as a blueprint for future facilities planned in the USA and the Middle East {F2} [Osborne (2014e)]. The firm also leads in R&D activities, holding many efficiency records among TF PV technologies {F1} [Colthorpe (2014c)].

The firm's market focus is on utility-scale ground-mounted and commercial-rooftop projects [Reuters (2012); Osborne (2013i)]. It has established a significant pipeline through collaborations with major EPC companies in Germany and Japan [SolarFrontier (2011); Willis (2013d)]. Although 90% of its revenue still derives from its domestic Japanese market, the company pursues international product deployment with particular interest in the German and UK markets [Colthorpe (2014d)]. The firm announced in August 2014 its split from the parent company in order to increase its flexibility and competitiveness {F4} [Colthorpe (2014c)].

Solyndra was a USA-based manufacturer of lightweight tubular CIGS modules that were mainly used on flat commercial and industrial rooftops. Despite significant public support, and international market deployment, the manufacturer was not able to create a viable cost structure, and resulted in its bankruptcy. The business model of the firm will be further investigated in Section 8.2.

Unisolar was a USA-based manufacturer of multi-junction TF-Si modules focusing on the BIPV and BAPV market segments [Unisolar (2009)]. Due to their flexible, light-weight design and easy installation process, Unisolar products were suitable for installation in large commercial roofs. The firm achieved significant deployment internationally and established partnerships for the development of BIPV materials [Unisolar (2009); ECD (2011)].

Despite multiple announcements regarding the development of new-generation products with high conversion efficiencies, the firm was unable to transfer such innovations into its manufacturing lines. After the significant decline of c-Si module prices, Unisolar products were not cost competitive on a per Wp basis with mainstream panels, and the company filed for bankruptcy in early 2012

{F9} [Osborne (2012b)]. This case highlights the difficulties faced by companies that develop radical products to achieve swift cost-reductions and compete with established designs.

Figure 7.14: Strategic characteristics of Solar Frontier, Solyndra and Unisolar (author's elaboration).

The analysis of different strategic paradigms highlights the importance of the contemporary socio-economic environment to the commercial success of particular business models {F9}. The rapidly growing solar market in addition to the financial crisis have shaped a demand-driven industry that requires high manufacturing throughput at a low cost. In order to maintain such a high throughput, large manufacturers demonstrate business model flexibility by moving their activities downstream the value chain, becoming project developers, establishing long-term pipelines and creating retail channels {F4}.

Despite impressive technological improvements and potential advantages, novel materials often do not reach commercialisation status, unless they achieve significant cost reductions. Firms that are financially supported by strong parent companies with alternative revenue streams have the resources and time to scale up their production and achieve price competitiveness with incumbent products.

On the contrary, firms based on the support of venture-capital have a short window of opportunity to transfer technological improvements to production lines {F6}. Companies that are not successful in achieving such a transfer in a cost-effective way are either driven to bankruptcy through the suspension of financial support, or limited within niche market segments which are inaccessible to incumbent technologies due to technological or economic reasons {F7}.

These observations and first findings regarding the correlation of business strategies and market success will be further explored in the firm-level empirical research in Chapter 8, and particularly the first case study (see Section 8.2).

7.4 The role of policy

The considerable growth in solar PV markets around the world (see also Subsection 7.1.1) has been mainly driven by the sustained implementation of policy instruments {F7} [inter alia Candelise (2009); Marigo (2009); Wiser *et al.* (2011); Lüthi and Wüstenhagen (2012); Sener and Fthenakis (2014); Dusonchet and Telaretti (2015)]. These instruments are part of a wider strategy to support renewable energy technologies that is based on a threefold rationale: to reduce greenhouse-gas emissions within the context of climate change mitigation efforts, to increase security of energy supply and to improve the competitiveness of the energy sector {F9} [EPIA (2011b); PVPS (2012)].

A wide range of support schemes for the adoption of BIPV systems have been implemented in different energy systems [Fouquet and Johansson (2008); Burns and Kang (2012); Sarasa-Maestro *et al.* (2013)]. Empirical evidence suggests that the effectiveness of policy frameworks varies wildly among countries, depending on both economic and non-economic processes including administrative procedures, grid connection and use, and -in the case of BIPV- regulatory frameworks regarding the building sector [Candelise

(2009); Lüthi and Wüstenhagen (2012)]. The main incentives and enablers that have been historically adopted are illustrated in Fig. 7.15.

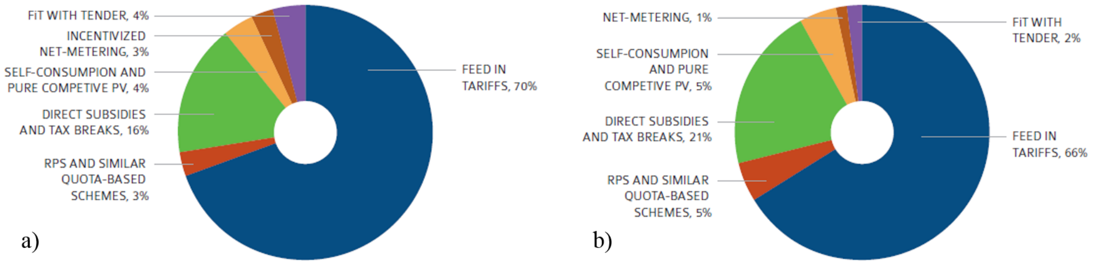


Figure 7.15: PV market incentives and enablers in 2013 (a) and historical (b) [PVPS (2015)].

Public policies can be categorised using the linear model of innovation into technology-push and market-pull mechanisms (see Fig. 7.16a) [Mowery and Rosenberg (1979)]. An alternative approach that takes into consideration the complex nature of innovation is the ‘stick, carrot and sermon’ perspective, where policies are classified based on whether they deter, reward or shape certain behaviours and decisions (see Fig. 7.16b) [Bemelmans-Videc *et al.* (2011); Al-Saleh and Mahroum (2014)].

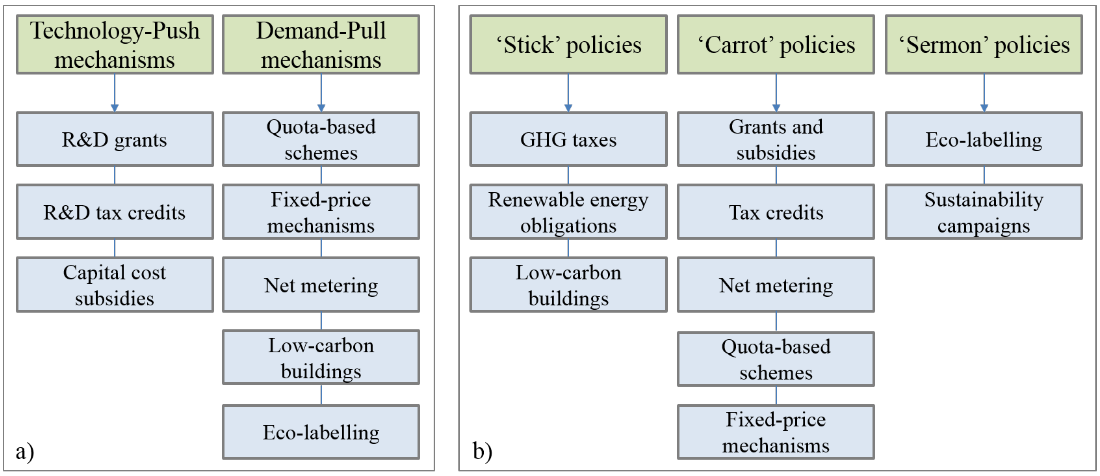


Figure 7.16: Mapping of example BIPV policy instruments according to a) the linear model of innovation and b) the ‘stick, carrot and sermon’ perspective (adapted from Candelise (2009); Marigo (2009); Al-Saleh and Mahroum (2014)).

The following paragraphs focus on particular deterrent and reward policies used internationally for the stimulation of the BIPV and other energy sectors.

7.4.1 Deterrent policy instruments for BIPV system adoption

The adoption of BIPV systems has been aided indirectly through the development of environmental policies and the enforcement of national and international guidelines regarding the use of renewable energy technologies and the development of low-carbon buildings {F12}.

Carbon emissions and renewable energy obligations

The United Nations Framework Convention on Climate Change (UNFCCC) is an international treaty aiming at the stabilisation of greenhouse-gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic climate change {F9} [UNFCCC (1992)]. Despite its wide legitimacy, the treaty does not provide binding targets regarding emissions for individual countries. The Kyoto Protocol signed in 1997 extended the UNFCCC treaty and provided committing emission reduction targets for 37 countries [UNFCCC (1997)]. The first commitment period of the Protocol ended in 2012, while a second one extending its effect to most industrialised countries is currently under negotiation.

The European Union has adopted a comprehensive climate change mitigation strategy by endorsing binding targets for 2020, including a 20% share of renewable energies in the overall EU energy consumption, 20% reduction (with reference to 1990 levels) of greenhouse-gas emissions and a 20% reduction of energy use below projected levels {F11} [CEU (2007)]. In order to meet these targets, EU has also developed a framework of indicators and trajectories for the different Member States [EC (2009)].

Regulatory frameworks for low-carbon buildings

A significant proportion of the overall energy consumption is attributed to the building sector in developed countries [Pérez-Lombard *et al.* (2008)]. Therefore, a range of policies have been developed aiming to increase the energy efficiency of buildings and stimulate in situ power generation {F9}.

The Energy Performance of Buildings Directive (EPBD) was developed by the EU and came into force in 2003 [EU (2010); EC (2013)]. In response to the directive several countries including France and Italy developed regulatory frameworks that enforced certain requirements regarding the adoption of both passive and active solar technologies, including BIPV systems [EPIA and GREENPEACE (2011)]. Despite these policies, established building codes, restrictions and practices can be major barriers to BIPV implementation {F9} [Candelise (2009)].

7.4.2 Reward schemes for BIPV system adoption

Public policy targeted explicitly to the promotion of BIPV technologies consists mainly of schemes that either sustain research and development or incentivise market growth {F6}. The development of a self-sufficient sector is considered to rely on a balanced combination of the two mechanisms [Sener and Fthenakis (2014)].

R&D programmes aim at the development of new materials and processes that facilitate growth within the manufacturing industry {F1, F2}. The 6^{th} and 7^{th} Framework Programme for Research sustained R&D investment in the EU from 2003 to 2013, while Horizon 2020 is expected to continue the support for the development of efficient, reliable and cost-competitive solar energy systems through 2020 {F12} [I2; PVPS (2012)].

Market incentives usually take the form of subsidies and fiscal mechanisms that aim to converge electricity costs between PV and conventional power generation technologies, as well as to reduce risk associated with investment in PV applications {F7} [Lüthi and Wüstenhagen (2012); Dusonchet and Telaretti (2015)]. The various schemes may be categorised according to whether they intend to achieve certain levels of installed capacity or stimulate BIPV power output.

Input subsidies

Input subsidies include grant schemes, soft loans and tax credits aiming at reducing capital investment barriers, which can be substantial in the case of BIPV [Marigo (2009); EPIA (2009)]. They are usually used in parallel to other fiscal mechanisms to assist the deployment of mainly microgeneration technologies. Such incentives have been implemented at national and state level, including Germany, Japan, the USA and the UK [Candelise (2009)].

Output subsidies

Output subsidies have been historically the most effective mechanism to stimulate PV market growth. They are used to regulate either the quantity or the price of BIPV electricity [Marigo (2009); Candelise (2009)].

Quota obligation schemes usually mandate a minimum share of electricity generation to be sourced through renewable resources. The obligations are satisfied through tradable green certificates or tendering power-purchase agreements based on price bids from generators [Candelise (2009)]. In spite of providing certain long-term certainty, these schemes have been criticised for their long waiting periods and high transaction costs [I13; I15; Sarasa-Maestro *et al.* (2013)]. Quota-based policies have been popular in the USA in the form of Renewable Portfolio Standards (RPS) and the UK in the form of Renewable Obligation Certificates (ROC) [Burns and Kang (2012); Sener and Fthenakis (2014)].

Fixed-price mechanisms take the form of long-term power-purchase agreements at a premium price that allows for a reasonable return for the investor [Sener and Fthenakis (2014)]. Feed-in tariffs (FIT) were first introduced in Europe in the early 1990s and were arguably responsible for the establishment of PV as a mainstream power generation technology [I1; I14; I16; Lüthi and Wüstenhagen (2012)]. Despite the application of mechanisms that intended to take market dynamics into account, growth was of an unanticipated extent, leading to the reduction of support, introduction of caps and restricted access to finance [PVPS (2012)].

7.4.3 Support to the wider energy sector

Renewable technologies are not the only beneficiaries of public policies within the wider energy regime {F9, F12}. Research and deployment activities within all energy sectors have been historically sustained through various forms of incentives and regulations, including tax breaks and direct subsidies [MISI (2011); Adeyeye (2009); John (2012)].

The main recipient of support has been the fossil-fuel industry with worldwide consumption subsidies amounting to $548 billion in 2013. This figure is over four times the value of subsidies to renewable energy and more than four times the amount invested globally in improving energy efficiency [IEA (2014b)].

Fig. 7.17 provides a breakdown of the support received historically by energy sectors in the USA.

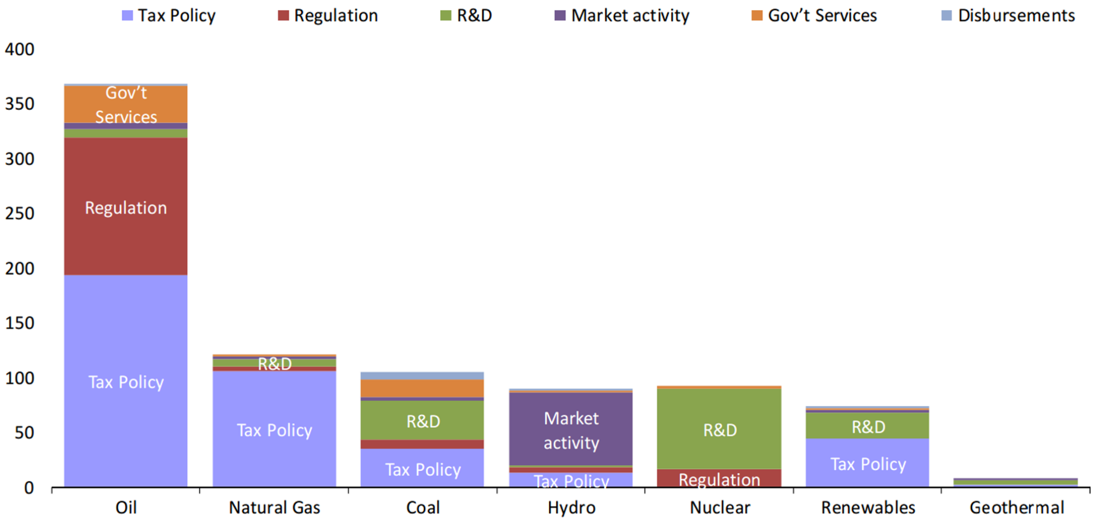


Figure 7.17: Breakdown of federal expenditures for energy development in the USA from 1950 to 2010 [MISI (2011)].

7.5 BIPV policy in the UK

BIPV is not clearly recognised as a separate sector within the UK policy configuration {F10}. Technology development and market deployment is supported within the wider context of renewable energy systems promotion and energy-efficiency improvement in the building sector {F12} [I12; I15; I16]. A range of national organisations support innovation processes at different levels of technological and commercial maturity as illustrated in Fig. 7.18.

The Carbon Plan was developed in 2011 to set out the Government's ambition to halve GHG emissions (compared to 1990 levels) by the mid 2020s {F9} [HMGovernment (2011)]. According to the plan, and complying with the EU obligation, renewable resources are expected to contribute a 15% share of the final 2020 energy mix in the UK [Jäger-Waldau (2011)]. Although the contribution of each of the technologies to that share is not bindingly determined, microgeneration and BIPV in particular is expected to play a significant role {F11} [I16]. That is due to not only its expected contribution to the electricity mix, but mainly the increased awareness that will raise within the public regarding renewable energy technologies and energy efficiency [Keirstead (2007)].

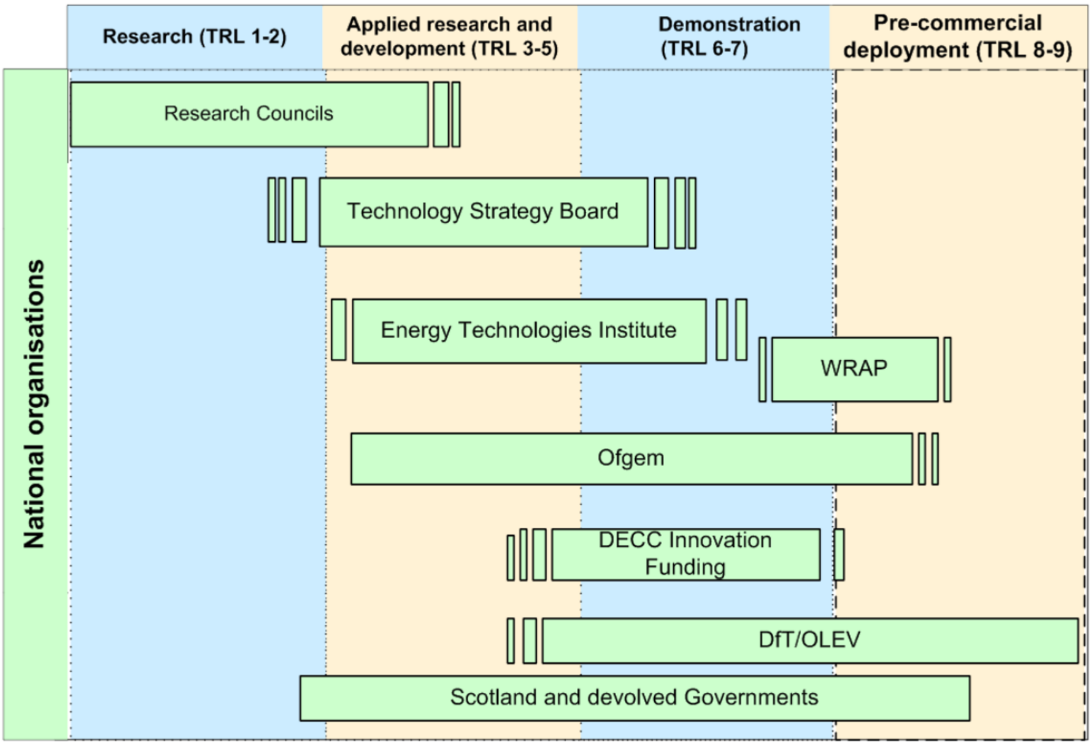


Figure 7.18: National UK organisations for the support of the energy sector (unpublished DECC energy innovation map 2013 from Skea (2015)).

Despite early scepticism regarding BIPV suitability for the UK, its potential has been recognised and addressed in recent policy updates, where microgeneration technologies and particularly small- and medium-scale BIPV systems are explicitly supported {F10, F12} [I12; DECC (2013a)].

The UK government set out in 2006 the Code for Sustainable Homes assessment framework and launched the Low Carbon Building Programme (LCBP) grant scheme to support distributed generation in buildings [Gardiner *et al.* (2011); DECC (2012)]. LCBP was replaced in 2011 by the Renewable Heat Incentive (RHI), a fixed-price mechanism used to promote heat from renewable energy sources in commercial and domestic buildings [DECC (2014b)]. The internationally recognised Microgeneration Certification Scheme (MCS) was introduced in 2008 for the accreditation of microgeneration technologies (including BIPV) and installers [I13; MCS (2014)]. A zero-carbon standard was also established for all new homes from 2016 and for all new non-domestic buildings by 2019 {F9} [UK-GBC (2014)].

UK Research Councils have invested on the development of solar materials and the improvement of PV systems performance through two SUPERGEN consortia, the SUPERSOLAR Hub, and the SUPERGEN Solar Energy Challenge {F1, F2, F12}. The establishment of the National Solar Centre (NSC) in Cornwall in 2013 is expected to create a centre for the development of PV technology, awareness raising and education {F5, F10} [I12; I16; PVPS (2011, 2012)].

In 2002 the Renewable Obligation Certificates (ROC) scheme was introduced in the UK as the principal mechanism for supporting investments in renewable energy projects. Although it started as a technology-neutral mechanism, it was reformed in 2008 to include different bands, in order to reflect discrepancies in costs and risks associated with early-stage technologies (e.g. PV) [Candelise (2009)]. The scheme will be closed to all new projects in 2017, and will be substituted by Contracts for Difference (CfD), a 15-year long fixed-price contracts mechanisms that is expected to reduce investment risks {F7} [Baringa (2013); Bolton and Foxon (2014)].

FIT were introduced in the UK in 2010 in order to stimulate certain niche renewable technologies and markets {F7}. The scheme has been adapted many times in order to reflect market developments and accelerated price reductions [Jäger-Waldau (2011)]. In its current form it is designed to mainly support rooftop and stand-alone applications of small and medium size [Ofgem (2014)]. A similar price mechanism for the support of storage systems could maximise the cost effectiveness of BIPV and boost their adoption [I12].

Solar PV has proved to be the most successful technology under the FIT scheme with rapidly falling costs and ramped-up uptake {F8}. The unpredicted success led to the introduction of measures to slow down the rate of installations, including a tariff degression mechanism based on levels of deployment and the reduction of the FIT lifetime for new systems from 25 to 20 years [PVPS (2011)]. Although these measures were developed in order to promote a predictable and stable environment, they have been often criticised for creating short-term market surges and insecurity among investors {F3, F6} [I13; I14; PVPS (2012); Smith *et al.* (2014)].

7.6 Summary and conclusions

The PV industry consists of a globalised supply chain spanning a range of market segments and technologies. The significant growth experienced in recent years has been driven by a combination of technological breakthroughs and market stimulation mechanisms. Developments in the broader socio-economic context have created a highly antagonistic market environment, and a distinctive consolidation in the industry. This process has mainly affected differentiation and experimentation with novel technologies, influencing growth in radical application domains including BIPV.

Empirical evidence shows that the BIPV sector is characterised by limited visibility within both the solar PV and construction industries. This is particularly apparent in existing industry and market reviews, perspectives, road-maps and economic assessments that rarely identify it as a separate sector with distinct characteristics, but rather as a segment of these mature industries. Further development in the BIPV sector is expected to be aided by the establishment of a common vision and a set of definitions and metrics among different stakeholders.

The cross-firm analysis revealed that the urgency for swift product deployment has benefited firms with a cost-reduction strategy, i.e. those focusing on production scaling and high throughput. The industry-wide assessment also revealed that the consolidation process experienced by the sector has significantly impeded both technological and market diversification, confining most differentiating firms within limited niche markets.

The regulatory framework regarding the BIPV sector consists of a range of policies that have been developed as part of a wider strategy driven by environmental and economic motivations. However, the lack of mechanisms that are specific to the sector is often viewed as an impediment that does not allow acceleration of deployment similar to that experienced by analogous sectors. Growth is expected to be assisted by the shift of the power grid paradigm towards distributed microgeneration with electricity storage capacity, as well as the increased adoption of efficiency-improving technologies in buildings.

Chapter 8

Empirical Research at the Firm Level

Introduction

It has been pointed out earlier in this thesis that the BIPV sector is a complex multi-sectoral technological domain, requiring cross-disciplinary approaches for its investigation. In line with this observation, this research uses a range of empirical methodologies in order to facilitate analysis of technical and non-technical processes affecting market deployment of emerging BIPV technologies at multiple conceptual levels.

Extending the research outlined in Chapters 6 and 7 on the technical and socio-economic context related to the BIPV sector, and reflecting on the second research question (see Section 5.1), this chapter focuses on intra-firm dynamics, aiming to address and better understand the role of agency within the innovation system (see Subsection 5.2.1).

The case-study approach is used to investigate two clusters of firms, maintaining the global and national-UK perspective adopted by this research. Elements from the Business Studies literature are used to explore links between certain business strategies and commercial success in terms of market share and corporate sustainability. The general methodology for the case-studies is outlined in Section 8.1.

The aims of the two cases are different and therefore, they are presented in a similar but not identical format. The first one (Section 8.2) investigates the effect of generic strategies (e.g. cost leadership and differentiation) on commercial success, also through the comparative analysis of business models adopted by different manufacturers in the global PV industry presented in Section 7.3. The second case (Section 8.3) focuses more on internal processes and micro-economic dynamics within a firm's ecosystem. Findings from both studies will be used in a complementary way to facilitate the overall examination of the complex BIPV innovation system in Chapter 9.

8.1 Methodology

The general methodology for the conduct of the studies was introduced in Subsection 5.3.4 and will be further discussed for each case in Sections 8.2 and 8.3. After an extensive bibliographic research and a preliminary techno-economic analysis, empirical evidence was gathered for each cluster of firms through personal communications, interviews and field trips. All evidence was then combined into narrative descriptions of the history, the business model and the industrial context of each company. These narratives are chains of events related to each cluster of firms, according to the event history analysis methodology (see Subsection 5.2.4).

With regards to analysing the business model of each firm, this research adopts a structure based on the functions and building blocks of a business model identified by Chesbrough and Rosenbloom (2002) and Osterwalder and Pigneur (2010) (see Section 4.3):

- *Value proposition* addresses the products and services offered by the firm
- *Market focus* encompasses the targeted commercial and geographical market segments
- *Revenue model and cost structure* outline expenditure and revenue streams
- *Value network* highlights the position of the firm within the supply chain
- *Competitive strategy* addresses the long-term plan of the firm for growth

This amalgamated structure is used to organise the gathered empirical evidence into coherent and useful, from an analytical point of view, narratives. It facilitates the assessment of innovation dynamics within firms by providing insights regarding the organisation, internal procedures, strategic orientation and responses to external developments of the focal companies.

Throughout the narratives, events provide partial insights regarding BIPV innovation dynamics at the UK and international level. They are linked to functions of the hybrid framework outlined in Section 5.2 using their reference codes presented in Table 5.2 within braces (i.e. $\{Fi\}$). These links are discussed in an aggregated way in the analytical part of each case study (Subsections 8.2.5 and 8.3.5) and are combined with findings from the wider empirical research in Chapter 9.

8.2 C.S.1: Strategic choices at the international level

The first case study focuses on Solyndra, a manufacturer of innovative building-applied PV (BAPV) systems. The study documents the path of the firm from international product commercialisation to bankruptcy. The adoption of a novel PV technology, a radical system design and the focus on the emerging medium-scale BAPV market segment render the firm a particular example of technological and market differentiation.

The aim of the study is to explore the reasons behind the corporate failure of the firm. Using a comparative examination of its business model with that of other companies that have chosen alternative strategic orientations (see Section 7.3), a range of findings emerge regarding the correlation of strategies and commercial success in terms of corporate sustainability and market share, given the international PV industry context.

The case was selected in order to highlight the significance of strategic choices within a dynamic industry and add an international perspective regarding drivers and barriers to market diffusion of emerging BIPV products. In addition to assessing macro-economic developments and reflecting on the ongoing consolidation of the PV industry, the study is designed to provide insights regarding competition within a globalised supply chain, market creation beyond the niche level and the sustainability of cost structures in highly antagonistic environments.

Despite the international nature of Solyndra's commercial activities, the case study also provides observations regarding the BIPV sector in the UK. The strong presence of the company in the early phases of the commercial-roof market segment allowed for the gathering of empirical evidence through communications with multiple former employees, collaborators and clients of the firm.

After a historical review of the firm's life-cycle, a brief overview of its business model and its socio-economic environment are studied. The crossfirm analysis presented in Section 7.3 is then used as background in order to identify patterns and potential association of strategic choices with commercial success.

8.2.1 Methodology

The research methodology started with a preliminary techno-economic and organisational assessment of the company and its competitors based on a broad literature review. Although Solyndra received extensive publicity after the initiation of insolvency procedures, information regarding its internal organisation and structure is still limited. Publicly available data allowed for a restricted techno-economic assessment of the available products and, therefore the research focused on conspicuous strategic choices and operations of the firm within the BIPV sector, as well as the analysis of the targeted market segment.

In the second phase of the study, empirical evidence was gathered through interviews with former employees, collaborating installers, users and researchers related to the firm's products. The disengagement of interviewees from the company and the absence of vested interests offered a safe distance from an analytical point of view, allowing for a better depiction and assessment of its history and strategic orientation. On the other hand, the secretive profile of the company and the wide publicity it received increased the levels of confidentiality regarding its internal organisation and processes and impeded the acquisition of information. Consequently, part of the research relied on empirical evidence gathered during informal communications with external collaborators as well as secondary sources including published interviews, surveys and reports.

The most important communications regarding the case study were held during two phases. The initial empirical research took place in March 2011, before the announcement of the bankruptcy proceedings, while the second phase took place from October 2012 to March 2013. Feedback from engineering companies involved in installation and maintenance as well as users of the systems provided insights regarding the end-use of the products. A list of these communications is provided in Table 8.1. The codes in the first column will be used within brackets throughout the case study for referencing, in a similar style to bibliographical citations (i.e. [Si]).

Ref.	Position	Organisation	Date of Communication	Type
S1	Senior Director	Solyndra	3/2011	Management
S2	Country Manager UK & Ireland	Solyndra	3/2011, 11/2012 3/2013	Management and Sales
S3	CEO Director	Renewable Resources	3/2011,/2012	Installation and User Feedback
S4	Technical Director	Renewable Resources	12/2012	Installation
S5	Design Engineer	Renewable Resources	11/2012	Installation and User Feedback
S6	Head of Sustainability	Sainsbury's	3/2013	User Feedback
S7	Engineering Manager	The Sheffield Solar Farm	3/2013	Research
S8	Principal Consultant	BRE	2/2013	User Feedback

Table 8.1: Main communications regarding the Solyndra case study (author's compilation).

Finally, a firm-level comparison with a range of competing companies was carried out in order to identify a potential affinity of certain strategic choices to market success (see also Section 7.3). The observations were combined into narratives that facilitated the extraction of insights regarding the dynamics within the international BIPV sector, as well as the particular characteristics of the domestic UK market. Initially, an event history was constructed to outline the life-cycle of the company and its business model, highlighting strategic choices and market orientation. Wider developments in the socio-economic environment of the firm provide the context for the business strategies comparative study and facilitate the understanding of certain growth patterns within the international BIPV sector.

8.2.2 Background

Solyndra was a manufacturer of CIGS-based cylindrical PV modules based in the USA. It was founded in 2005 by Dr. Chris Gronet, a materials scientist with experience on semiconductor processing [S1; S2; Cheyney (2008); Solyndra (2011b)]. Recognising the potential of CIGS to provide efficient low-cost PV products, but also identifying its sensitivity to moisture as the major manufacturing challenge, Gronet's scientific team invented a new type of PV collectors that conflicted in form with the dominant design of flat solar panels. The new *module* consisted of a glass tube with an etched layer of CIGS on its outer surface hermetically sealed within a second glass tube (see Fig. 8.1) {F1} [Hull and Johnson (2011); Solyndra (2009)].

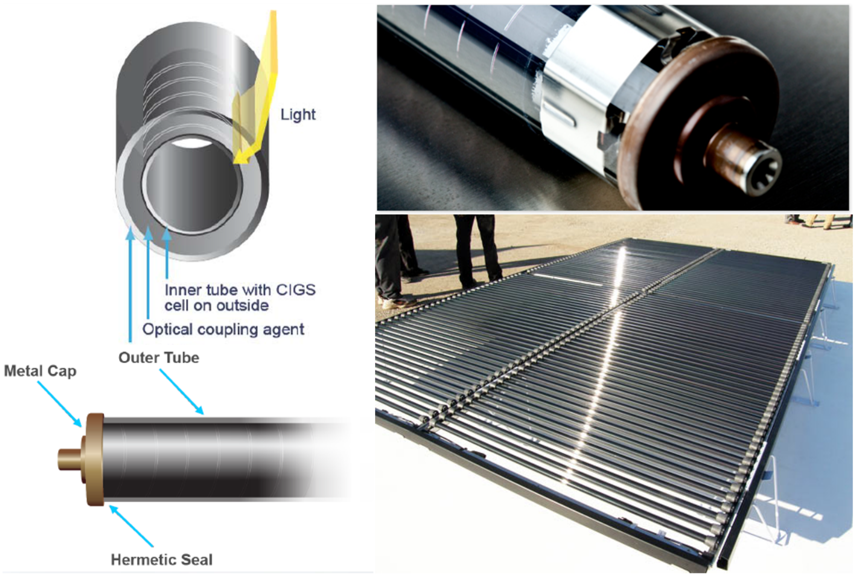


Figure 8.1: Schematics and pictures of Solyndra's module and panel [Solyndra (2009)].

With the intention to commercialise the new technology, the company was incorporated as Gronet Technologies in 2005 and renamed to Solyndra a year later {F3}. Responding to a solicitation towards investment on clean-energy innovation from the US Department of Energy (DoE) {F12}, the company applied for a federal loan in 2006 under the Bush administration. After being short-listed, Solyndra was invited to submit a full application, while the DoE initiated a comprehensive due diligence on the company [Hull and Johnson (2011); Cheyney (2011b)].

The firm began the construction of its first manufacturing plant (Fab1 - 110MWp/year) in Fremont, California in 2007 after raising $79 million in venture capital {F2} [Solyndra (2011b)]. The significant interest from the investors can be attributed to the original design of the system that provided the potential for higher energy yields and therefore lower levelised cost of generated energy (see also Section 6.4) {F6} [Kanellos (2010b, 2009)]. Additionally, manufacturing costs of mainstream c-Si modules were demonstrating an upward trend at the time due to the shortage of polysilicon feedstock [Candelise *et al.* (2013)]. This created a window of opportunity to innovators, by driving investment to alternative technologies {F11}.

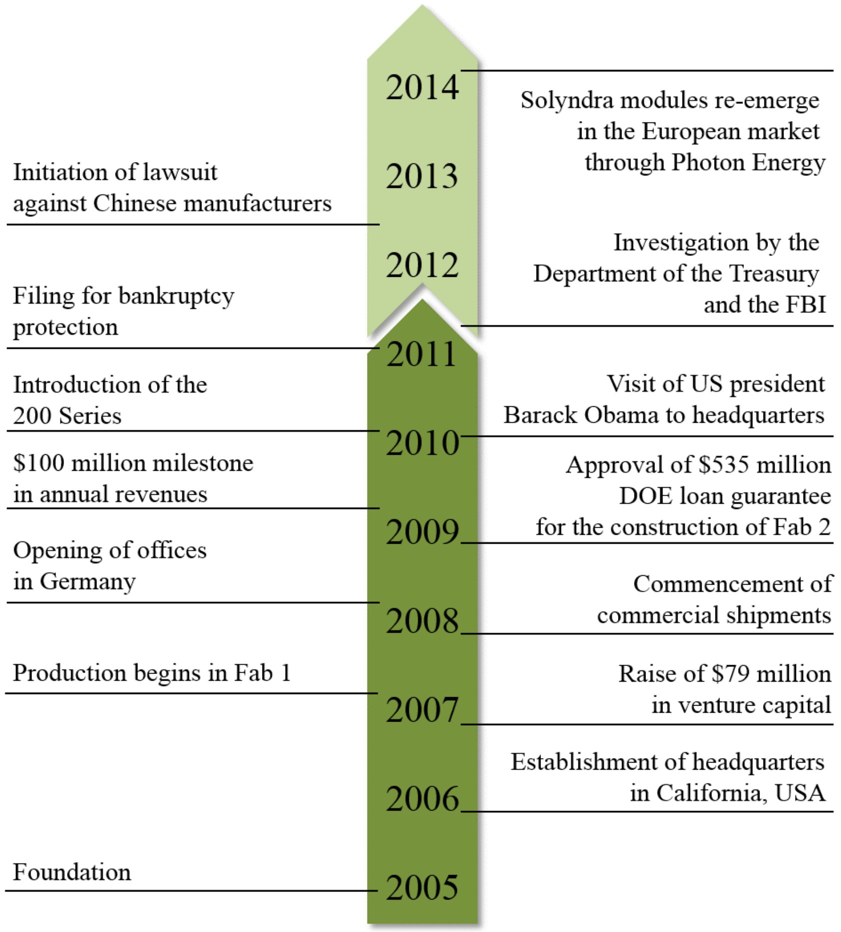


Figure 8.2: Solyndra's history and milestones [S1; S2; Solyndra (2011b)].

After having amassed $600 million in venture capital and private equity investment, Solyndra commenced its commercial operations in 2008 and opened offices in Germany, targeting the developing flat-roof market segment {F2, F6, F7} [Cheyney (2008). At the same time, changes in the internal organisation of the company that included the leaving of three founding members, two former vice-presidents and one chief technology officer, started drawing the attention of contemporary analysts regarding the engineering challenges of the new technology [Kanellos (2008)].

In 2009 the DoE approved Solyndra's application and awarded the company with a $535 million federal loan guarantee for the construction of a second manufacturing

Figure 8.3: Visits to Solyndra facilities by USA Energy Secretary Steven Chu, Governor of California Arnold Schwarzenegger, and USA President Barack Obama [GTM (2010-2014)].

facility (Fab2 - 500MWp/year) {F2, F6} [Solyndra (2009)]. This major investment became a key component of the new Obama administration's green agenda for its high job-creation prospect {F9, F10} (see Fig. 8.3) [Wesoff (2010b); Hull and Johnson (2011)].

Despite the strong financial and political backing, the company decided to cancel the initial public offering (IPO) of its shares in early 2010 {F6}. This move triggered concerns regarding Solyndra's capital intensity and the viability of its cost structure [Wesoff (2010a)]. It also caused the removal of Chris Gronet from the role of chief executive officer (CEO) in July 2010 [Kanellos (2010b); Hull and Johnson (2011)]. However, the company still managed to attract further private investments, raising the total to over \$1 billion {F6} [Kanellos (2010a)].

After Fab2 commenced operation in late 2010, Solyndra announced the closure of Fab1 and the scaling back of its manufacturing capacity goals from 610MWp to 300MWp by 2013 {F2}. The reason cited by the company was the diminishing c-Si module prices driven by cheap manufacturing lines in China {F9} [Kanellos (2010b)]. At that point, according to calculations on published financial data, the average manufacturing cost of Solyndra's panels was 83% higher than their average selling price, creating a significant loss for the company [Wesoff (2010b)]. The firm's plan was to continue production in the more efficient Fab2 where costs were expected to halve through economies of scale when the utilisation rate of the lines increased [Kanellos (2010a)].

Solyndra continued production through 2011 reaching a cumulative production of 100MWp. Systems were installed on commercial and industrial roofs including supermarkets, distribution centres and factories throughout Europe, the USA and Asia {F7}

[S1; S5; Jargon (2011)]. In the UK the company established a significant presence through long term contracts with major retailing companies [S2; S3; S6]. In June 2011, a new series of products was introduced that offered non-penetrating mounting for flat and low-angle roofs [Solyndra (2011a)].

On the 31^{st} of August 2011, Solyndra announced that it would discontinue production and lay off most of its 1100 employees [Cheyney (2011e); Leone (2011)]. In its official statement, the company cited the negative impacts of global economic and solar industry market conditions as the reasons for the suspension of operations {F9}:

> *[Despite the] ... strong growth in the first half of 2011 and traction in North America with a number of orders for very large commercial rooftops, ... [Solyndra] ... could not achieve full-scale operations rapidly enough to compete in the near term with the resources of larger foreign manufacturers. This competitive challenge was exacerbated by a global oversupply of solar panels and a severe compression of prices that in part resulted from uncertainty in governmental incentive programs in Europe and the decline in credit markets that finance solar systems.* [Cheyney (2011e)]

The firm filed for bankruptcy protection on early September 2011 [Cheyney (2011d)]. Contemporary analysts speculated that private investors realised that Solyndra's cost structure was not sustainable and decided to liquidate its assets [Cheyney (2011c)]. The headquarters of the company were raided by FBI officers investigating charges of accounting fraud later that month [Knapp (2011)].

Solyndra failed to reorganise and restart operation, and was forced to sell its assets. Despite the expectations that the facilities would be sold on a turn-key basis, since it would not be possible to use the proprietary equipment for the manufacturing of conventional modules, this was not possible, and the assets were sold on several auctions {F2} [Reuters (2011)]. According to the bankruptcy plan, the proceedings will go towards creditors, and will unlikely cover the $528 million drawn from the federal loan [Bathon (2012)].

On October 2012, Solyndra initiated a lawsuit against three major Chinese manufacturers over allegations of running an illegal cartel. The lawsuit demanded a compensation of $1.5 billion and claimed that the firms were selling products to the USA at prices below cost in order to create an unsustainable market for domestic manufacturers [Bathon (2012)]. Similar allegations had driven a US investigation that resulted in the announcement of punitive tariffs against Chinese solar panel makers [Young (2012)].

Despite the suspension of manufacturing, Solyndra's modules are still being resold throughout Europe in small quantities. Photon Energy, a Dutch system developer, has sold 3MWp of modules to customers in South Europe [Colthorpe (2014e)]. In the UK, retailer Sainsbury's continued the installation of rooftop systems well after the cessation of commercial production [S2; S4]. The procurement of excess modules would compensate for the absence of a guarantee from the manufacturer [S4].

8.2.3 Business model

The history outlined in previous paragraphs provides the basis for the analysis of strategic choices and their impact on Solyndra's commercial trajectory. Further insights will emerge through the examination of its business model.

Despite the wide journalistic coverage of Solyndra's federal financing and bankruptcy, availability of public data regarding its internal organisation, financial status and strategic planning has been very limited. This has been a significant impediment to this research, which consequently has been based on evidence gathered through personal communications and secondary literature.

Value proposition

The value proposition of a firm encompasses all the products and services the firm offers to its customers [Osterwalder and Pigneur (2010)]. Solyndra developed a limited range of building-applied and more integrated PV systems for flat, sloped and greenhouse roofs. All systems were based on the cylindrical CIGS modules invented by its founder Chris Gronet [Hull and Johnson (2011)].

Using original equipment developed for this radical design, a thin-film semiconductor layer was deposited on a glass tube (see Fig. 8.1). CIGS cells of a 12-14% light-conversion efficiency were then etched on the outer surface of the tube and electrically interconnected [Cheyney (2008)]. The tube was then enclosed in a second glass tube and the gap between the two was filled with a fluid 'optical coupling agent' that performed as a light-concentrating (around 150%) lens. The modules were finally hermetically sealed and assembled into flat panels, the nominal efficiency of which can be calculated at around 8.8% [S1; Solyndra (2011a, 2009)].

The potential advantage of the cylindrical design is the absorption of not only direct, but also diffuse and reflected sunlight. The effect is higher when the system is installed on a 'cool roof', covered with a high-reflectance membrane [S3; Solyndra (2011a)]. If the system is positioned parallel to the meridian, a part of each module is constantly at an optimal photon-absorption angle throughout the day, offering a 'self-tracking' mechanism and increasing the power output at times when the sun is low at the horizon. The sparse distribution of modules minimises soiling and snow deposition, and enables wind movement through the panel offering a cooling effect [S5; Solyndra (2009)].

The dimensions of the panel were $2.28m \times 1.07m$ and its weight was just below 32kg. This relatively light-weight design required no ballasting nor roof-penetration, eliminating the risk of leaks or roof-warranty becoming void [S2; Solyndra (2009)]. The flat positioning of the modules followed the shape and the contours of the roof, maximising coverage when compared to the pitched conventional flat panels [S5].

The second generation of the system claimed to offer fast tool-free assembly, minimising disruption from the installation process and allowing the removal of the system in case of relocation or roof-servicing [S6; Solyndra (2011a)]. In early 2011 the firm introduced a new mounting system suitable for metal roofs [Hughes (2011)].

The potential competitive advantage of Solyndra's products was three-fold. Firstly, the design of the system offered higher energy yields compared to competitive technologies, allowing for a lower long-term cost per unit of generated electricity, despite the higher initial investment. Additionally, the simple and fast installation process minimised cost of labour, which forms a significant proportion of the total PV system price. Finally, the reduced weight of the systems enabled the installation on low weight-bearing industrial and commercial roofs, a market segment that had not not accessible to the PV industry [S1; S2; S8].

> *Using proprietary cylindrical modules and thin film CIGS technology, Solyndra systems are designed to provide the lowest levelised cost of electricity and the highest kilowatt hour production per rooftop for typical installations. The unique Solyndra form factor is designed specifically for the commercial rooftop, offering fast installation, a non-penetrating mounting system, superior wind, snow and soiling performance, and energy and conservation advantages when installed in conjunction with a white or cool roof.* [S1]

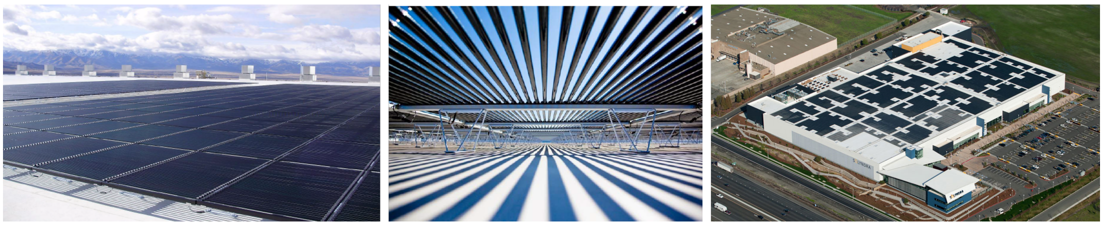


Figure 8.4: Examples of BAPV installations by Solyndra [Solyndra (2009)].

Market focus

Specification of relevant customer and geographical market segments is the second major component of a business model [Chesbrough and Rosenbloom (2002); Osterwalder and Pigneur (2010)].

For their BAPV applications, Solyndra developed mounting systems targeted to flat and low-angle commercial and industrial roofs (see Fig. 8.4). According to its founder, the power capacity of this segment in the USA was estimated at 150 GWp, offering a PV market potential of around $650 billion {F7} [Cheyney (2008)].

The main target group of Solyndra marketing was major retailers with multiple large-surface stores and distribution centres [S2]. The development of sustainability agendas from such corporations created an increasing need for distributed renewable generation {F6, F9} [S7; S8]. Additionally, the firm was actively seeking for high-profile installations in order to increase awareness regarding their technology and brand {F10} [S1].

The company offered a limited range of more integrated products targeted mainly at large-scale greenhouses (see Fig. 8.5). The proposition of these applications was the additional revenue stream from consuming and selling to the grid power generated in situ [Solyndra (2011a, 2009)]. However, the semi-transparent configuration eliminated the added-value gained by absorbing reflected light, thus reducing the potential energy yield of the low efficiency modules [S7; S8].

Regarding geographical market focus, Solyndra was active mainly in the USA and Europe, with some limited installations in Asia. The firm was particularly interested in the growing UK market, having identified a major opportunity in its commercial-roof market segment [S1; S2; Jargon (2011)].

> *[BAPV] ... is still a niche market in the UK but offers huge potential because*

Figure 8.5: Examples of BIPV installations by Solyndra [GTM (2010-2014)].

> *of favourable tariffs, and declining incentives in the rest of Europe. The upcoming FiT reductions*[1] *will not affect Solyndra systems, as they are mainly large-scale projects. We already have two distributors in the UK and we are planning to open an office in London.* [S1]

Revenue model and costing structure

A crucial part of any business model is the identification of the sources of capital and operational expenditure, as well as the estimation of the cost structure of the product that will in turn define the revenue model of the company [Chesbrough and Rosenbloom (2002); Osterwalder and Pigneur (2010)].

In order to manufacture the uniquely shaped modules, Solyndra required the development of original production facilities and materials {F2}. This requirement involved equipment and consumables costs that were significantly higher than the competition. Additionally, the firm selected to keep all of its manufacturing capacity in California, when most PV manufacturers were ramping-up production in China and other areas with lower labour cost in South East Asia [Mehta (2014)].

Despite its high capital intensity the firm attracted over $1 billion of private investment and $535 million of a federal loan, which were used for the development of the two highly automated state-of-the-art manufacturing lines {F2, F6} [Kanellos (2010a); Solyndra (2009)]. The substantial financial support can be justified by the innovative PV technology that offered the potential for high energy yields using alternative materials, at a time when prices of conventional c-Si modules where on the rise {F9, F11} [Kanellos (2010a)].

Although there has been no official disclosure regarding Solyndra's operational costs or revenues, analysts have speculated on these figures based on calculations of the

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[1] This comment was made a few days before the FiT reform in the UK which mainly affected small-scale installations (see also Section 7.5).

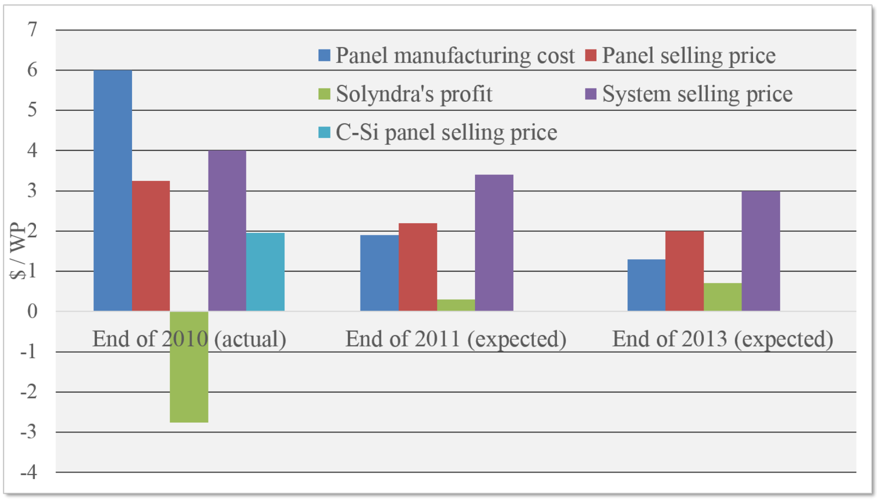

Figure 8.6: Actual and roadmapped cost structure of Solyndra's systems (author's elaboration using data from Kanellos (2010a); Wesoff (2010b); Kanellos (2010b)).

production volumes and financial data disclosed during the IPO (see Fig. 8.6) [Kanellos (2010a); Wesoff (2010b); Kanellos (2010b)]. According to them, throughout its short operational life, Solyndra's manufacturing cost per unit remained significantly higher than its average selling price that was kept competitive in order to maintain shipments growth [Mehta (2014)]. Based on the total revenue generated throughout the first nine months of 2009 ($58.8 million), the cost of goods sold ($108.3 million) and total module shipments during that period (17.2MWp), the average selling price can be calculated at $3.42/Wp while the respective cost at $6.29/Wp, implying losses of over $500 for every panel sold by the company [Wesoff (2010b)].

The company's expectation was that manufacturing costs per unit would halve once the second manufacturing facility was ramped-up and fully operational. Production in Fab2 would be much more efficient, allowing for higher throughput and significant cost reductions through economies of scale [Kanellos (2010a)]. Despite the confident predictions from firm's executives, contemporary analysts were sceptical regarding the potential cost reductions that could be achieved, given the radical design and manufacturing processes [Wesoff (2010a)].

Solyndra's rooftop application required a very fast installation process that implied minimal labour costs and disruption for the user [Solyndra (2011a); Kanellos (2010b)]. Consequently, the higher cost of the modules was expected to be annulled at the system level [S1; S8]. According to the firm's management, the total cost of installed systems was starting to be cost competitive with standard PV systems in mid 2011 [Cheyney (2011c)].

An additional element that could lower the final cost of the generated electricity was the higher energy yield of the panels due to the 'self tracking' design of the module and the arguably better performance of CIGS in low-light conditions [S2; Solyndra (2011a)]. Solyndra's systems demonstrated more consistent power generation curves throughout the day, implying the use of smaller and lower-cost inverters [S4; S5]. As for the actual performance of real applications, it has been tested in various locations and different configurations, and no convincing evidence has yet been provided [S7; Mehta (2014)].

Competitive strategy

The competitive strategy of a firm addresses its long-term plan for growth, including competitive assets, marketing strategies and additional methods to create value [Chesbrough and Rosenbloom (2002)].

Solyndra's plan was to become the market leader in large-scale commercial and industrial roofs. Its main product was designed for optimal area utilisation of flat and low-angle roofs [S1; Jargon (2011)]. Additionally, having identified in limited weight-bearing roofs a considerable market segment that remained under-served by the PV industry, the firm developed a light-weight system that could be mounted on a range of roof types [Hughes (2011)].

The competitive advantage marketed by the company was not lower module prices than competition, but rather lower levelised cost of electricity throughout the life-span of the system [S2]. This proposition was based on the low BoS costs (low labour intensity and mounting needs) as well as the potential for higher energy yield.

Although cost competitiveness at the system level was in its long-term strategic plans, the initial priorities of Solyndra was to ensure functionality, reliability and safety of its products [S1; S2; Mehta (2014)]. Additionally, the fact that all products were manufactured in the USA under the highest environmental standards was central to the marketing strategy, as was the premium customer support [Jargon (2011)].

8.2.4 Socio-economic environment

In order to assess the strategic choices of a firm and its positioning within its industry, an investigation of the socio-economic and technological context is required in addition to the analysis of its business model. The PV and BIPV technological domain was reviewed in Chapter 6, while Chapter 7 focused on market dynamics and policy frameworks. This section will outline these contextual processes, using the perspective of the firm in focus.

Solyndra's business model was developed during the height of a crisis for the PV industry the mid 2000s [Mehta (2014)]. Concerns regarding polysilicon availability and the subsequent silicon feedstock shortage reversed the downward price trend of incumbent c-Si modules, driving investments to the development of modules that used alternative semiconductor materials {F6, F9, F11} [Candelise *et al.* (2013)]. In order to maintain sustainable shipments growth, major PV manufacturers focused on the established and growing utility-scale market segment which was driven by financial incentives for renewable power generation, rather than experiment with higher-risk niche market segments such as BIPV applications {F3, F4}.

Solyndra's plan was based on both a technological and a market differentiation strategy, by utilising CIGS PV materials and targeting an under-developed segment with a high potential [S1; S2]. However, by the time Solyndra' products were commercially available, the polysilicon market had undergone a substantial correction, with spot prices having dropped from \$500 per kilogram to less than \$100 [Mehta (2014)].

The steep decline of silicon feedstock and the widespread overcapacity of PV modules resulting from aggressive production capacity expansion in China and diminishing incentives in Europe, drove the reduction of the average selling price of c-Si modules by 63% from 2008 to 2011 (see Fig. 8.7) {F9} [GTM (2010-2014); Mints (2012a,b)]. This eliminated the competitive advantage of silicon-free technologies that had not realised by that time competitive cost structures through either ramping-up of production or processing innovation {F4}.

At the same time, an increasing number of module manufacturers identified the growing PV potential of commercial and industrial roofs, and designed a range of low-cost mounting solutions for that market segment {F9} [S3; S8]. This development further threatened Solyndra's diversified strategy that was based on offering an application-

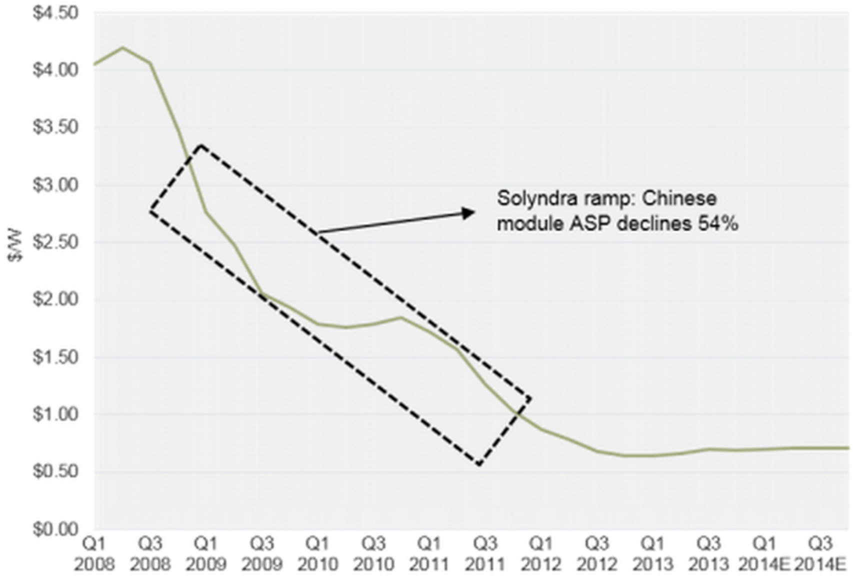

Figure 8.7: Chinese c-Si module average selling price [Mehta (2014)].

dedicated product at a premium price [S2].

8.2.5 Analysis

The case of Solyndra has received significant attention not only for the radical product design that attracted a considerable amount of investment during its development, but also for its notable downfall that marked the beginning of a wide consolidation process across the PV industry, triggered a series of international trade disputes and changed the perceptions and attitudes of investors and governments towards innovating firms.

The firm's business model was designed at a time when selling prices of c-Si PV modules were rising, with the expectation that there would be a shift in the technological paradigm within the PV industry towards thin-film and organic materials {F9}. Despite their low efficiencies and non-competitive cost-structure, these technologies gained momentum and market share due to their potential for low-cost manufacturing and versatility of applications {F6}.

The innovative technological characteristics and design of Solyndra's product drew attention and investment not only from venture capitalists that are characterised for their high-risk-high-returns strategy, but also from federal US loans that were awarded after the conduct of substantial investigation and due diligence. This shows the initial willingness of both investors and governments to support disruptive technologies when the incumbent dominant design is challenged, as it happened with rising prices of c-Si modules {F8, F9}. However, this support is not sustained if there is no evidence of fast cost reduction and competitiveness. The subsequent failure also highlights the potential flaws in the strategy of picking certain technologies for support by governments {F12}.

The value proposition of such disruptive technologies collapsed after the extraordinary correction of c-Si module prices {F9}. Innovation efforts were focused on optimisation of manufacturing processes rather than the development of new products and cost competitiveness became the decisive factor for the sustainability of manufacturers. Under these circumstances, Solyndra was forced to reconsider its strategic priorities and streamline cost reductions through iterative learning gains and scale-up. These activities were part of the firm's long-term strategy, but the efforts did not occur in time to avert its bankruptcy {F4}.

On the other hand, Solyndra's products were designed for a specific market segment that was largely unexploited by the PV industry at the time. The re-emergence of modules in European markets well after the suspension of production highlights the suitability and appeal of the product to the large-scale roof market. Despite the absence of a guarantee or any form of customer support from the manufacturer, customers are still willing to invest in the technologically complex systems that aim at a 25-year life expectancy.

Solyndra's strategy was built on the premise that a product with a design focused on one market segment would be more cost-effective in the long term than sub-optimal adaptations of mainstream products. However, the significant price erosion of standardised modules discussed earlier, in conjunction with the commercial agility of established manufacturers that developed a range of low-cost mounting solutions, increased the competition within the large-scale roof market and put pressure on Solyndra, which had no revenue streams from activities in other sectors {F4, F9}.

The effect of Solyndra's corporate strategy on its commercial pathway can be better assessed when juxtaposed with examples of different strategies adopted by a range of firms that have been active in the PV and BIPV sectors in a similar technological and chronological frame. The cross-firm analysis presented in Section 7.3) highlighted the importance of demonstrating strategic flexibility in times of high uncertainty and a rapidly changing socio-economic environment {F4, F9}.

Manufacturers utilising novel materials and radical product designs are not able to sustain their financial support and scale-up their production. Unless they are supported by strong parent companies with additional revenue streams, such companies have a short window of opportunity to transfer technological developments into production lines, and achieve fast cost-reductions so that they become competitive in real market conditions {F6, F7}.

8.3 C.S.2: Commercialisation of BIPV technologies in the UK

The second case study focuses on Polysolar, a British developer of TF and OPV systems. It was chosen and designed with the aim to address specific characteristics of the BIPV innovation system and market related to the country within which a firm attempts to commercialise its products. Focusing on the growing UK BIPV sector, the study investigates the micro-economic dynamics within a firm's 'ecosystem' and evaluates the developments in the national regulatory framework and market. On the other hand, it does not neglect the international context, reflecting the globalised supply chain the focal firm is part of.

After a background-setting account of the historical activity of the firm in focus, its business model is analysed. In order to provide a broader understanding and a better evaluation of the performance of the firm, developments within its socio-economic environment are investigated and practices of other firms active in the same market segments are juxtaposed for context.

Compared to the first case study, this analysis provides insights regarding strategic choices of significantly smaller-scale firms, and markets which are more geographically focused. From a methodological and analytical perspective, the cases are used in a complementary way in order to facilitate the overall examination of the BIPV sector.

8.3.1 Methodology

The first stage included a techno-economic review of the products and the respective markets. System data-sheets and application specifications were gathered for all the commercially available products. A historical cost and price breakdown of the systems allowed for a preliminary economic assessment of the various system elements over time. Based on the market review presented in Chapter 7, the most relevant market segments were identified and investigated in the context of the UK BIPV sector. An initial interview with the CEO of the company provided product information that was not publicly available, and facilitated the exploratory phase of this research which spanned a period of 6 months from March 2012 to September 2012.

The second stage of the study included the collection of empirical evidence through semi-structured interviews, a field trip to the company headquarters in Cambridge and several visits to marketplaces where its products were being sold. The well-established relationship with higher management within the company permitted the conduct of interviews and discussions with executives, scientists, sales and marketing employees, as well as with industrial and market partners both upstream and downstream the value chain including researchers, system testers, product developers, retailers, installers and users. These communications provided evidence regarding not only the internal organisation and strategy of the firm, but also its positioning within the value network and the feedback from the market related to manufacturing, design and application of their systems. A list of the most important communications held between October 2012 and March 2013 is provided in Table 8.2. The codes in the first column will be used within brackets throughout the case study for referencing, in a similar style to bibliographical citations (i.e. [Pi]).

The third phase of the case study included the combination of the collected bibliographic and empirical data and the synthesis of narratives according to the process theory tradition. Initially, an event history was constructed to set the background for the case, describing the historical evolution of the focal firm. Its business model was then analysed following the theory outlined in Section 8.1. Finally, the socio-economic environment of the firm's eco-system was assessed, addressing dynamics in the wider innovation system, regulatory frameworks and relevant market segments. Practices and

Ref.	Position	Organisation	Date of Communication	Type
P1	CEO	Polysolar	3/2012, 10/2012, 11/2012, 12/2013	Management
P2	Director	Polysolar	11/2012, 12/2013	Management
P3	Marketing Manager	Polysolar	11/2012, 1/2013	Sales
P4	Sales Executive	Polysolar	11/2012	Sales
P5	Sales Administrator	Cambridge Glasshouse	1/2013	System Development and User feedback
P6	Sales Executive	Ridgeon's	12/2012	Sales and User feedback
P7	Technical Director	Renewable Resources	12/2012	Installation
P8	Design Engineer	Renewable Resources	12/2012	Installation and User Feedback
P9	Customer Programme Manager	CPI	2/2013	Research
P10	Engineering Manager	The Sheffield Solar Farm	3/2013	Research
P11	Principal Consultant	BRE	2/2013	User Feedback

Table 8.2: Main communications regarding the Polysolar case study (author's compilation).

strategic choices of other firms active in similar markets and of similar scale were also briefly included in the analysis as context, in order to give rise to potential patterns regarding innovation dynamics in the BIPV sector.

8.3.2 Background

Polysolar is a developer, manufacturer and distributor of thin-film and organic PV (OPV) systems based in Cambridge, UK [Polysolar (2014a, 2012a,b)]. It was established in 2007 by H. Watson, a business development consultant who was working at the time with Chinese companies interested in establishing international operations. The initial concept emerged after H.W. was approached by a company interested in creating a PV business portfolio in Europe. Having collaborated in the past with Cambridge Display Technologies (the leading developer of technologies based on Polymer - Organic Light Emitting Diodes, P-OLEDs, spin-out of the Cavendish Laboratory in the University of Cambridge) he used this technical experience to build a strategy on organic polymer PV. Although the developed strategy was rejected, H.W. set up a technology development team independently and founded Polysolar {F3}. The underlying technology originated in research of the Cavendish Laboratory {F1} [P1].

Polysolar led a consortium including glass manufacturer Pilkington (part of the NSG group), industrial gases supplier British Oxygen Company (BOC -now part of the Linde group), consultancy firm Sagentia (based in Cambridge and specialising in dots-printing technology) and an R&D group at Imperial College London {F5}. The consortium was awarded a £1 million grant from the Technology Strategy Board (TSB), and Polysolar became one of the first Small and Medium Enterprises (SME) to receive such a collaborative R&D award [CPI (2012); Polysolar (2014a)]. Although the consortium succeeded in raising £6 million from institutional investors through a private placement in London in 2008, the investment was withdrawn after the collapse of the Icelandic bank that was the brokerage firm facilitating the funding round, delaying the TSB award project by a year {F6, F9} [P1].

The consortium was reconstructed after the unsuccessful fund-raising. R&D activities were transferred to Sheffield University and Ossila (developer of organic polymer-based semiconductors, based in Sheffield). BOC was substituted by the Belgian company Solvay (among the leading chemical companies globally [CPI (2013)]) and

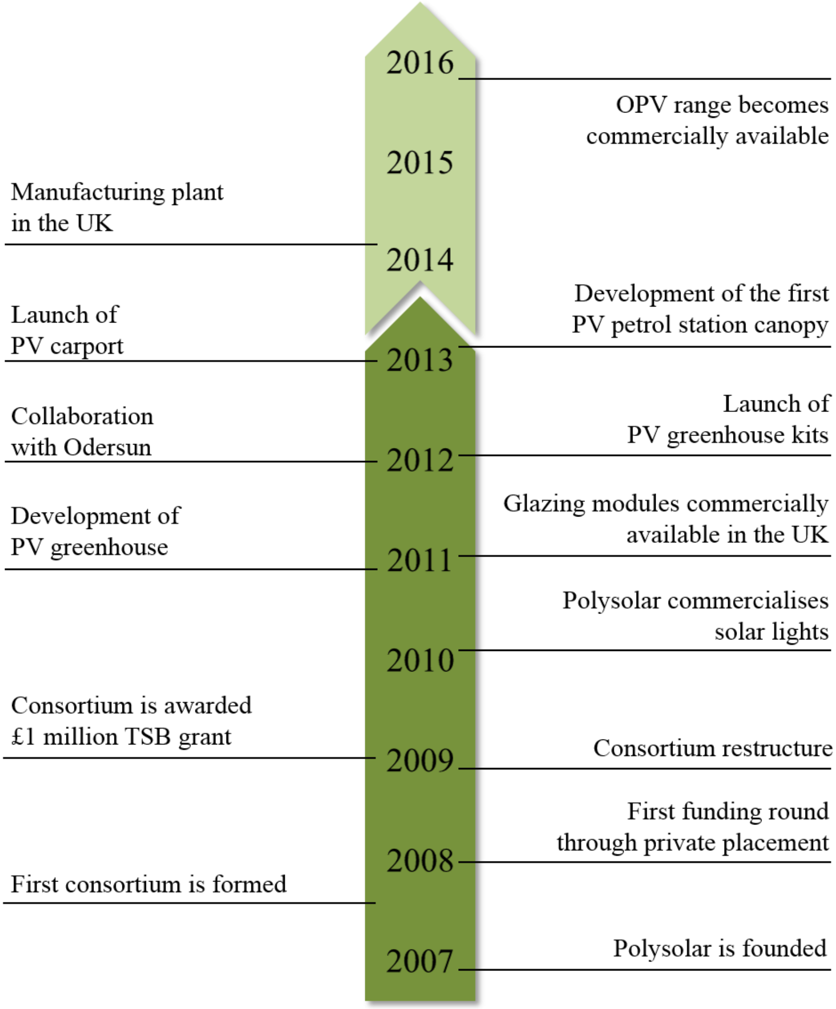

Figure 8.8: Polysolar history and milestones [P1; P2 and Polysolar (2014a)].

the collaboration with Sagentia was dropped {F5} [P1; P10]. Due to the limited funds (the consortium eventually raised £1.3 million after receiving the TSB grant in 2009) {F6}, technology development activities were outsourced to the Centre for Process Innovation - CPI and its National Centre for Printable Electronics - NPEC (then known as Printable Electronics Technology Centre - PETEC) in Durham {F1}. The outcome of the collaboration was the development of large-area organic photovoltaic cells that could be used as demonstration prototypes for the manufacturing of transparent PV glass applications {F2} [P9; CPI (2011)].

According to its directors, Polysolar is currently among the world leaders in the production of stable organic transparent PV modules. Their immediate targets include the refinement of the production processes in order to scale up manufacturing, development of new materials to resolve stability issues and allow for coloured modules, and the enhancement of the encapsulation process originally developed in Liverpool University {F1}:

> *We are probably the most advanced of the players we know in terms of stable and produced transparent organic PV module efficiency levels. The next thing is to decide on some material changes, primarily to get colours and address some stability issues. Then, it's the encapsulation.* [P1]

The company expects to deploy the first OPV products in the market within the next three years [P1, P2].

Polysolar is also a manufacturer, developer and distributor of a range of PV modules and applications based on amorphous silicon (a-Si) technology [Polysolar (2010a, 2014a)]. The mature technology was adopted by the company in order to generate capital and establish the BIPV supply chain in the UK until the full commercialisation of the emerging OPV technology {F7}. Despite the initial intention to set up a pilot plant in the UK, lack of funding led Polysolar to collaborate with an Original Equipment Manufacturer (OEM) based in Taiwan. Polysolar uses part of the 30MW-manufacturing plant to develop opaque and semi-transparent glass modules that are then used in glazing and other BIPV applications {F2} [P1; P3].

8.3.3 Business model

The history of Polysolar outlined in the previous paragraphs provides an overview of the firm's activities and organisation. Further observations and insights regarding strategic choices and its positioning within the BIPV sector will emerge through the investigation of its business model.

Value proposition

Polysolar develops a range of BIPV systems utilising two different PV technologies (a-Si and OPV). Contrary to most PV manufacturers, the company is not focusing primarily on the PV module technology itself, but rather on its incorporation into building materials:

> *Our strategy would be to produce window glass and quite frankly the PV is the secondary element to it. We are selling a building product and therefore we are pricing it at a* m^2 *basis, a functionality basis, not a Watt basis.* [P1]

Polysolar can be classified as a developer of glazing products that retain all functions of conventional materials used in the construction industry (structural, weather-proofing, thermal control, light transmission) and feature an additional power generation capability. This additional capability bears a long-term economical advantage stemming from the use and trade of generated electricity (see also Section 6). Therefore, the value proposition to users is the addition of a financial-returns element to building materials. The broad aim of the company is to minimise the discrepancy between additional manufacturing cost and prospective returns in order to suggest a justifiable investment to customers [P3].

The systems that are currently commercially available by Polysolar are based on modules featuring a bronze-tinted a-Si or micromorph (see Subsection 6.1.1) thin layer between two laminate glass sheets. These modules are either semi-transparent, transmitting about 20% of the incident light, or opaque with the addition of a white layer [Polysolar (2012b, 2010a, 2014a)]. The conversion efficiency of the modules is 7-8%, around half the average efficiency of conventional glass c-Si modules that are currently available in the market [Polysolar (2012c); Luque and Hegedus (2011)]. The low conversion efficiency renders the module non-competitive in applications where high power output in limited area is a priority.

The competitive advantages of a-Si modules are the potential for low-cost manufacturing compared to c-Si and the arguably higher energy yield in terms of annual generated electricity per installed rated capacity in conditions of low light, high temperature or high levels of dust (see Subsection 6.3.1). Additionally, semi-transparent modules are capable of generating power from light incident to either side, thus increasing the energy yield by utilising diffuse and scattered light. All modules are IEC/TUV and MCS/NQA certified, providing access to incentive schemes in a range of countries including the UK. They are warranted to provide at least 90% of their nominal power output for 10 years and 80% for 25 years, while their expected lifetime is over 40 years [P1; P2].

The OPV range of products which is currently under development has the potential of very low manufacturing cost compared to first and second generation PV technologies. The production of synthetic polymers does not depend on rare minerals while the printing processes used for the deposition of the active PV layers are very efficient on the use of materials. This technology also allows for a variety of colours and levels of transparency, thus widening the range of building-integrated applications and potentially increasing the appeal of PV systems to architects and the general public {F10} [Nelson (2002); EPIA and GREENPEACE (2011)]. The conversion efficiency of OPV modules currently does not exceed 5% and their durability is not certified, though Polysolar argues that there is high potential for improvement and that a life expectancy of 25 years is achievable [P1; P9].

Commercial applications of Polysolar products include facade glazing, domestic greenhouses, carports and petrol-station canopies [Polysolar (2012b, 2014a)]. Potential applications also include shelters, glazed roofs, windows, balustrades and conservatories [P2; P3].

In order to make the modules suitable for building glazing, two manufacturing steps are added to the conventional module production process (double glazing and electrical interconnection), increasing the production cost by 50%. In addition to the power generation utility, PV glazing has the potential for better thermal control than normal glass, complying with the increasing demand for the construction of sustainable low-carbon buildings (see Fig. 8.9a) [P1].

A major issue related to the use of these modules for glazing is the compatibility with established practices and norms within the construction industry regarding their size. Modules currently produced by Polysolar have predefined dimensions of 1300mm×1100mm, dictated by existing manufacturing equipment {F2}. The standard width of glazing panels used in most office buildings across Europe on the other hand is 1500mm [Polysolar (2010b)]. Company executives highlighted the case of retrofitting as the most significant problem, since existing building framework renders installation of such modules impractical, and downgraded the issue in the case of new buildings [P11]. However, this discrepancy still constitutes a limiting feature for architects and building developers, who need to consider panel integration at the very early designing stages of the building.

The second product available by Polysolar is a range of domestic greenhouses that incorporate semi-transparent PV modules, officially launched in March 2012 {F7} (see Fig. 8.9b) [Polysolar (2012a, 2014b)]. The idea of a domestic PV greenhouse emerged as an alternative solution for buildings that are not suitable for PV integration either due to planning regulations (e.g. listed buildings) or aesthetical reasons [P1; P3]:

> *The main driver for the clients is that this is a different product, it is suitable in applications where conventional PV cannot work. That's for people who are already interested in installing PV, also for people in conservation areas who cannot put it on their roofs. Instead, they can easily integrate it in their gardens or their carport.* [P3]

The range includes four prefabricated standard-sized greenhouses and bespoke designs that can be customised according to customer's needs [P5, P6]. According to the manufacturers, the modules offer various potential horticultural advantages, including a more consistent thermal control than simple glazing, the absorption of the UV light spectrum that causes plant scorching and mildew growth and the shading effect that is especially useful throughout summer [P5; Polysolar (2014b)]. However, the low energy yields due to the the non-optimal PV orientation and the low power capacity resulting from the use of low efficiency modules in a limited area, do not allow for significant economic returns that could justify the high price compared to conventional greenhouses [P8]. Additionally, the predefined size of the PV module poses manufacturing issues:

> *Design can be a challenge as the PV panels are only available in one size. We have to design the greenhouse around the size of the panels.* [P5]

The most recent commercial applications from Polysolar are a carport launched in November 2012 and a petrol-station canopy launched in late 2013 {F7} (see Fig. 8.9c). The semi-transparent PV canopies will have a rated power output of 12-20kWp and will benefit from the double-sided light-absorption feature that will utilise the high amount of side-reflection that is common in a petrol-station canopy configuration [Polysolar (2014a)].

Figure 8.9: Examples of BIPV installations by Polysolar: a) facade in Dortmund, b) PV greenhouse and c) petrol station canopy in the UK [Polysolar (2014a)].

Apart from their production, development and retail of BIPV products, Polysolar is also active in the establishment of the downstream BIPV value chain and the stimulation of awareness regarding the sector in the UK. The company has organised various Continuing Professional Development - CPD seminars educating construction companies about the available products, has sponsored BIPV conferences that intend to bridge the architectural community with system developers and has published a BIPV guide for designers and installers [P1; Polysolar (2010b, 2012d)]. These initiatives provide an indication of the limited development of BIPV as a formal sector with established channels for the creation and diffusion of knowledge {F5, F7}.

Market focus

Polysolar has identified the commercial building industry as the market with the highest potential for deployment of its products, although it has not yet established a wide presence:

> *We haven't done a lot of commercial projects, it takes longer and we just begun. Our systems are more viable as commercial products, margins are better for us and for the client. We have ongoing commercial projects, petrol station canopies, building facades, building materials and large-scale projects.* [P3]

The company focuses on medium-range new buildings where integrated PV systems could be included in the early design stages [P1; P2]. As mentioned previously, the modules that are currently available for use in glazing applications are of a size that conflicts with conventional standards. This can be a major issue in buildings where there is an existing framing structure and could potentially eliminate a market opportunity especially in countries with major building-retrofitting industries, including the UK [Polysolar (2010b)].

Despite the identification of the commercial sector as the target market segment, Polysolar diversified early on into the more mature domestic building market, adopting this strategy for interim revenue generation until the commercial BIPV value chain is established {F8}. Although profit margins for module suppliers in small domestic projects are not appealing, this market offers a low-risk commercial opportunity [P1]. A similar strategy is adopted with regards to the PV greenhouse, which is initially targeted to home owners rather than large scale commercial applications. Deployment to the horticultural trade will require convincing evidence that the semi-transparent glazing is safe and does not negatively affect crop yields, as well as the successful communication of the potential financial benefits from distributed power generation {F10}:

> *The commercial greenhouse market is difficult to break into, the reason being it needs a certain degree of faith or testing to say they could work. Although we have independent studies around the world, we have done testing, the general attitude in the horticultural trade has been that you need as much light as possible, that is why all the greenhouses lie at the south coast. That's where the have the highest sun, although the PV greenhouse will give improved or no different yields to the plants. It's quite a risk from their point of view, so it is quite difficult to persuade the trade to go ahead with it.* [P1]

The PV carport system is aimed at both the domestic and large commercial markets, while the petrol station canopy targets deployment to international supermarket chains [P3]. In collaboration with a major retailer group in the UK, Polysolar completed two canopies in December 2013, and is currently developing another project for a petrol-station in Canada {F2}. Polysolar is also involved in various high-end building applications including the World Cup stadium in Qatar, the Botanical Gardens in Sydney-Australia and skyscrapers in London and Beijing. Such buildings are not considered to be part of the main business development strategy, since medium-range commercial buildings have been identified as the target market segment. According to its directors, these demonstration projects are rather used as part of a marketing strategy to raise awareness regarding the brand, available products and facilitate their wider aesthetical acceptance by the public (see Fig. 8.10) {F10} [P3]. However, considering the high profile of the installations and the wide profit margins involved, these projects are inevitably a significant element of the firm's revenue stream {F6}.

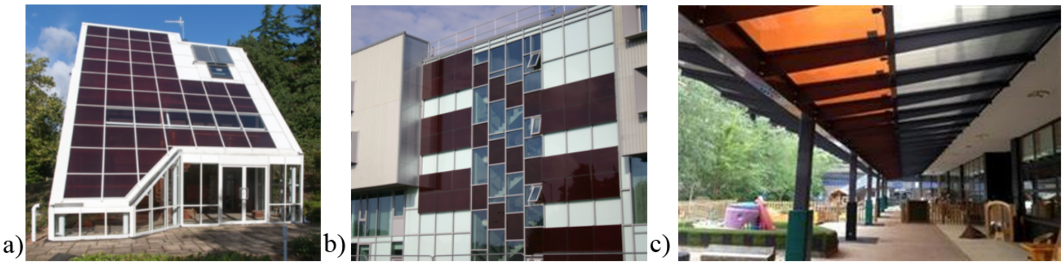

Figure 8.10: Polysolar's demonstration projects: a) atrium at BRE Innovation Park in Watford, b) facade at the Future Business Centre in Cambridge and c) walkway canopy at a school in London [Polysolar (2014a)].

In terms of geographical market focus, Polysolar is adopting an international deployment strategy but mainly targeting the UK and Europe. Glass industries are highly dependent on regulatory frameworks, and PV products need to accord with regional glazing specifications in order to be adopted by the construction sector. That requires long and expensive certification procedures, that cannot be justified given the current size of the company [P1; P2]. Another reason for the initial deployment to European markets according to its directors, is that glass prices in that region are higher than countries with larger building markets, for example China. Therefore the deployment of premium products such as PV glazing is easier and profit margins are potentially more significant {F9} [P1]. The UK is seen as one of the leading industries in building architecture, offering a significant opportunity for the BIPV sector. Additionally, the UK building sector is regulated by a comprehensive framework, and therefore, compliance with the UK standards potentially allows for easier international market penetration [P11].

> *The UK market is our focus because of resources and because the BIPV situation in the UK is very well placed. This is partly because we are leaders in building regulations. Building standards and regulations in the UK tend to be adopted elsewhere in the world, e.g. in China, which means that what*

> *is accepted here is acceptable worldwide basically.*
>
> *In terms of big design and architectural companies, the UK is a global centre, that gives us access to the world. In terms of new buildings, the UK is pretty useless, but the refurbishing market is quite good here. The glazing market is also good because it is high-end. Of the £50 billion worldwide glazing market, Europe represents about a third of that, although the construction is a tenth at most, the reason being that glass is much more expensive here than anywhere else in the world.* [P1]

Regarding the PV greenhouse, Polysolar is planning international deployment, especially in regions with hot climates in the USA and the Middle East where a-Si technology arguably performs better (see Subsection 6.3.1) and there is a higher need for protection from the UV light spectrum. Additionally, certification procedures for such external structures are subject to rather flexible regulations, and hence are suitable for international deployment [P1; P3].

Supply chain of the firm and position in the value network

Polysolar is involved in the development and manufacturing of PV modules based on OPV, a-Si and micromorph technologies, as well as the design and distribution of building-integrated systems utilising these modules. Therefore, the company collaborates with organisations in four broad areas (see Fig. 8.11):

1. *Materials partners:* Pilkington, part of the NSG group, is a British glass manufacturer that supplies Polysolar with module substrates. Solvay is an international chemical company that has been heavily involved in the development of the organic polymer PV technology with Polysolar {F2} [P1; CPI (2013)].

2. *Research, Development and Demonstration partners:* The Centre for Process Innovation (CPI) and its National Printable Electronics Centre (NPEC) developed the production processes for the manufacturing of the OPV technology and constructed the first demonstration module [P9]. Independent testing is carried out in the University of Sheffield where the energy yield of various modules is monitored and the University of Liverpool where the reflectivity of the modules is being tested {F1} [P10]. The Building Research Establishment is a British research-based consultancy that has collaborated with Polysolar in the demonstration of semitransparent PV modules. British Gas is a utility company that uses Polysolar's

panels in their smarter home exhibit in BRE's Innovation Park in Watford {F2} [P11].

3. *Manufacturing Partners:* An OEM in Taiwan is the manufacturer of Polysolar's a-Si modules [P1]. Cambridge Glasshouse designs and manufactures the PV greenhouses and also stores part of the stock in their factory in East Yorkshire in England [P5] {F2} .

4. *Commercial Partners:* Ridgeons is a British building supplies retailer that offers Polysolar's PV greenhouse kits and also demonstrates one fitted greenhouse in their show-room in Cambridge [P6]. Global-MSI, an English canopy manufacturer and Renewable Resources, a Scottish PV installation company develop the petrol-station PV canopy [P7;]. Polysolar also collaborates with a network of MCS-accredited installers, construction companies and around 20 distribution and sales agents across the UK and Europe [P1; P3].

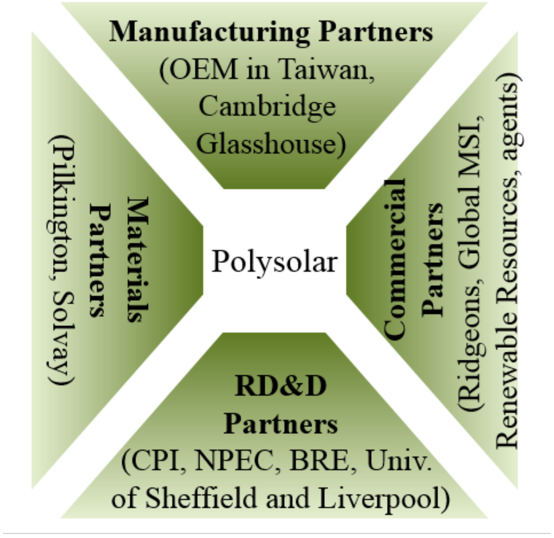

Figure 8.11: Ecosystem of Polysolar's partners [P1-P11].

Polysolar is involved in two separate supply chains as illustrated in Fig. 8.12. Products based on TF technologies are designed and assembled using modules manufactured by third-party companies. When they reach commercial status, OPV products will be manufactured by Polysolar, using the existing collaborations with materials and equipment suppliers. All BIPV systems are sold and installed by the established distribution and retail network [P1; P3].

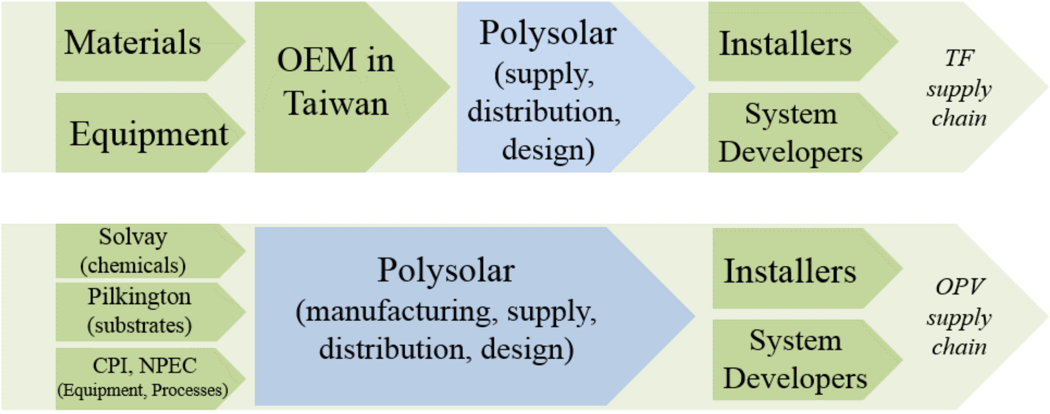

Figure 8.12: Polysolar's supply chains [P1-P3].

Part of Polysolar's business activity is the establishment of a BIPV sector in the UK that according to the company is currently underdeveloped. For that reason, one of the short-term goals is the construction of a manufacturing facility that could trigger the development of a supply chain for products that are complementary to the PV modules, including electrical components and mounting systems {F2, F4} [P1]. Although the transfer of manufacturing activities from Taiwan to the UK will initially increase production costs, this will be compensated by the elimination of packaging and shipping costs that are significant in the case of glass modules [P1; P2]. It will also reduce the dependence of local system developers on international partners, and eventually reduce total PV system price [P3].

As far as market competitors are concerned, Polysolar aims to not compete directly with conventional first and second generation PV module manufacturers, due to its diversification into the BIPV industry [P3]. A similar business model has been adopted by Onyx Solar, a Spanish BIPV system developer. Although it can be regarded as a direct competitor, this company has been relatively inactive in the UK, with most of its ongoing projects being developed in Spain and the USA [Onyx (2014)].

In terms of emerging product development, there exists a range of companies and laboratories developing OPV and dye-sensitised solar cells (DSSC), most of which are based in the UK {F1, F2} :

1. *Konarka*, a USA-based OPV developer, was the main player in the OPV sector

until it filed for bankruptcy in June 2012. The German segment was bought by Belectric OPV, which currently continues previous R&D operations [Choudhury (2012); Olson (2012)].

2. *Heliatek*, a Germany-based organic oligomers PV developer, is the technology leader, holding the world record on conversion efficiency of organic PV cells. It is currently in the process of developing commercially available products for the BIPV and automotive industries [Heliatek (2014)].

3. *Eight19* is a British OPV manufacturer that has diversified its business into small off-grid applications [Eight19 (2014)].

4. *Solar Press* is also a British flexible OPV manufacturer [SolarPress (2014)].

5. *Dyesol* is the Australia-based global market leader in DSSC. It has formed strategic collaborations with major industrial players for the development of building materials with integrated solar cells, including glass manufacturer Pilkington, Indian-based multinational conglomerate Tata and Saudi-Arabian Tansee [Osborne (2013g); Dyesol (2014)].

6. *GCell* (formerly G24i) is a Welsh DSSC developer that has diversified into electronics-integrated PV (EIPV) applications [Johnson (2013); GCell (2014)].

7. *Oxford Photovoltaics* is an English company that is currently attempting the commercialisation of perovskite-based BIPV products [PVinsider (2013); OxfordPV (2014)].

This market review has revealed that although there is a limited number of companies targeting exclusively the development of BIPV systems, there is a range of organisations with ongoing R&D activities within this sector. In addition to the aforementioned companies that have publicised their activities, a number of universities and firms are also believed to have some element of BIPV-oriented development activity {F1}. However, lack of financing opportunities and the under-developed BIPV supply chain forces them to remain in stealth mode {F6} [P1].

> *At the moment we have been looking for further funding opportunities to work together. Unfortunately, we have not come up with any funding, it is*

> *certainly something we try to get together, we all applied for an FP7 project which unfortunately wasn't funded, it's certainly something we are interested in progressing.* [P9]
>
> *Regarding the value chain for OPV, there is some big gaps in terms of our capabilities in this field. Some of the elements are missing, especially the engineering and the production side of things. In terms of the manufacturing side, the biggest problem is really the requirements for high through-put processing, equipment, robotics and automation. A lot of it has to come from Germany or the far East. There are some good strengths too, the UK is good on print deposition and conductive glass.* [P1]

Many of these organisations are based in the UK, where the plethora of research institutions and the growing BIPV sector create a favourable entrepreneurial environment {F3} [P1; P11]:

> *The UK recognises that OPV is sort of something they have some particular strength in, it's got the right people and the skill sets. However, in terms of capital grants aiding that field, they have dried the last couple of years, so there is no money going into it. It is a long-term technology, it needs the support, at least for the next few years.* [P1]

Revenue model and costing structure

Two significant components of a business model are the identification of the revenue streams that will finance firm's activities and the definition of the cost structures of the products, which are determined by the elements of the value chain of the firm [Osterwalder and Pigneur (2010)].

Current sources of revenue for Polysolar include the distribution of a-Si modules to the building industry, the design and development of PV glazing projects and the sale of standard BIPV systems including domestic greenhouses, carports and petrol-station canopies [P3; P4]. As an intermediate party throughout the installation process, Polysolar also benefits from the markup added to the installation costs and the balance-of-system (BoS) components supplied to installers [P1; P2].

Polysolar is not currently generating any revenue from the development of OPV technologies. The RD&D activities in that field are sustained by funding rounds and grants, which in the past included the European Framework Programme for Research and Technological Development (FP) which has now ended [P9]. The funding rounds are targeting private funds in the UK, South Africa and the Middle East rather than venture capitals {F6} [P1].

Polysolar's financial strategy highlights the difficulty of emerging companies to commercialise technologies into markets that are not well-formed {F7}. Without the support of an established revenue stream, new-coming firms need to explore parallel entrepreneurial activities in order to finance ongoing research and sustain operations during the period required until the developed product is market-ready {F4}.

Regarding the manufacturing cost of the modules, Polysolar quotes a figure between £0.30-0.40 per Wp. If the production is shifted from Taiwan to the UK, this cost is expected to increase to about £0.50 per Wp. Of that cost, about 40% is the glass including the transparent conductive layer, 20% is the active silicon layer and 40% is manufacturing processes. The packaging and shipping from Taiwan to the UK add an additional cost equivalent to about 60% of the manufacturing cost [P1]. The final selling price to the client of a 90-100Wp module is around £150-200, depending on the quantity of modules bought and including the revenue margin for Polysolar (see Fig. 8.13) [P4]. In comparison, manufacturing costs for the cheapest conventional flat-plate CdTe and c-Si modules are estimated at £0.30 and £0.32 per Wp respectively, while the average selling price of such modules is currently at £0.48-0.55 per Wp [P1; Osborne (2013h); Photon (2014)].

In the PV system level, the costing structure is divided in about equal thirds among modules, BoS components and installation (see Fig. 8.13). According to Polysolar, BoS components have demonstrated slower cost reduction rates than modules and are becoming a more significant portion of the final system cost. The company buys and supplies to the client all components including inverters, mounting systems, connectors, meters, switches and fuse elements, while the installation processes are subcontracted to certified technicians [P1; P2; P7].

In the case of building facades and window applications, production cost is increased significantly, since modules need to be double glazed and framed [P11]. Depending on the desired thermal performance of the system, additional coatings of the glass may be required, further increasing the overall manufacturing cost [P1; P2]. The pricing of such applications is done on a per unit area basis, complying with established practices within the building industry [P3]. The final selling price of glazing systems varies wildly: from £200/m^2 for a domestic window up to £1000/m^2 for a high-end facade application

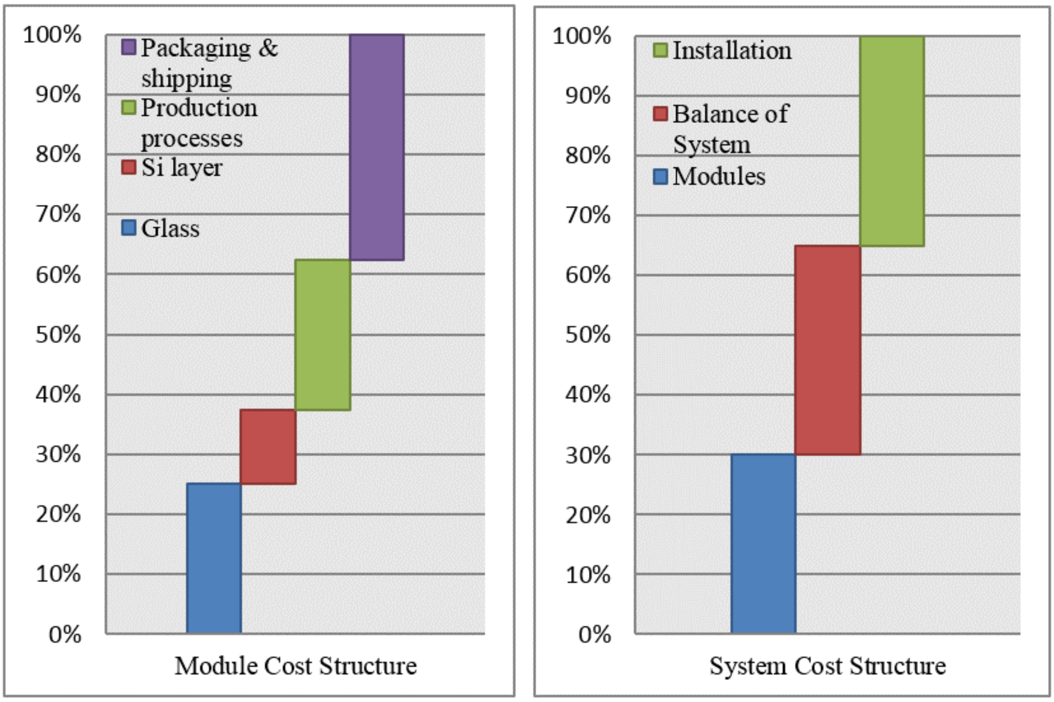

Figure 8.13: Cost structure of modules and systems excluding profit margins for Polysolar [P1; P3].

[P4].

From the customer's point of view, the expected economic returns derive from electricity savings from in situ consumption of the generated power and financial incentives related to renewable energy generation {F6} [P1; P3]. In the UK incentives include feed-in tariffs (FiT) and Renewable Obligation Certificates (ROCs) awarded to solar power generators for the total amount of electricity produced (see also Section 7.5). Taking all elements into consideration, the period that is required for the full amortisation of the initial capital expenditure is expected to be 6-7 years for glazing projects, 20-25 years for the greenhouses, 7-8 years for the carport canopy and 5 years for the petrol-station canopy [P3].

Competitive strategy

Polysolar's business strategy differs from that of most PV module manufacturers in the fact that it focuses on the energy saving properties of BIPV products in addition to their power generation capability. According to the company, the main driving force of the BIPV market is not the financial incentives for renewable power generation, but the regulations for energy efficient and near zero-carbon buildings (see also 7.4.1) [P3]. Therefore, its main aim is to manufacture building materials based on glass, that generate power in addition to performing all functions of traditional materials. This multiple functionality is recognised as a potential competitive advantage over other technologies that might be considered as competitive in the microgeneration sector {F9} [P1; P2].

In terms of competitive assets, Polysolar has an established skill-set on OPV production processes and materials and owns some intellectual property on system structures and demonstration-scale equipment {F1} [P1; P9]. Its short-term plan includes the construction of a manufacturing plant in the UK that is going to be used for batch-production of bespoke BIPV projects rather than a mass-production line {F2} [P2].

The basic marketing strategy of Polysolar for consumer products (greenhouses, carports, domestic systems) includes end-of-trade exhibitions, public-relations events and some limited advertising. For the deployment of the commercial-size products (petrol-station canopies, walkways, high-end glazing) particular retailers and oil companies are approached directly or through collaborating agents [P3].

Polysolar's long term strategy is to collaborate with glass manufacturers in order to install PV processing lines to existing production facilities. Having identified that a significant component of the overall production cost derives from handling, cleaning, packaging and transportation of glass panels, the company estimates that integration of glass and PV module manufacturing processes will reduce considerably these cost elements {F4} [P1].

Additionally, the company is trying to establish the BIPV supply chain by raising awareness regarding available products and applications within the construction industry and by creating links between the architectural community, the building industry and

PV system developers using BIPV-focused conferences, workshops and publications {F5} [Polysolar (2010b, 2012d)].

> *BIPV is still largely unknown and unrecognised, PV is better understood and recognised, but still at a very basic level. The problem we have as a company is that we have to educate the market as well as sell into the market, that is very difficult for a small company. We try to work with as many of the large construction companies as possible, but even that is difficult. We work quite closely with quite a lot of sort of educational training type organisations set up in this arena, in order to raise awareness. But none of that is easy, to stimulate that awareness.* [P1]

8.3.4 Socio-economic environment

Strategic choices and commercial status of a firm are better understood and assessed when set within its socio-economic and technological environment. Building on the research outlined in Chapters 6 and 7, this section presents these contextual processes using the perspective of the firm in focus.

Polysolar's business model is built on the premise that the advancement of second and third generation PV materials will facilitate the development of cost-effective and versatile BIPV products [P1; P2]. Although technological breakthroughs have allowed for materials in a range of colours and shapes, significant cost reductions that would render these technologies competitive with established c-Si products have not yet been realised {F8} [P9; P11]. This is particularly evident in the initial capital investment of TF manufacturing plants, where equipment costs are relatively high, hindering experimentation and learning processes {F2, F3} [P1; P9].

Additionally, the ongoing consolidation of the industry and relocation of the bulk of manufacturing capacity to the Far East, has limited product differentiation and driven the establishment of glass c-Si modules as a dominant PV product design. The limited applicability of this design to the BIPV sector has impacted the common perception regarding the suitability of PV for building integration and arguably impeded growth of market niches {F7, F8, F10} [P2; P8; P11].

On the other hand, the increasing need for renewable power and distributed generation systems, as well as the development of energy storage technologies are expected to aid the expansion of the BIPV market {F9} [P1; P3]. Regulatory frameworks around the world currently support the shift towards low-carbon buildings and microgeneration technologies, with BIPV applications being among the few options readily available {F11, F12} [P11].

Limited involvement of the construction industry and the architectural community is also viewed by Polysolar as a significant impediment for legitimation and growth in the BIPV sector {F10} [P1; P2]. Further educational activities by corporations and prominence within industrial associations is expected to raise awareness regarding the available products and their multiple socio-economic benefits {F5} [P1; P3].

Regarding the national UK sector, BIPV is expected to be the dominant PV market segment, driven not only by renewable energy policy, but mainly by a comprehensive regulatory framework regarding low-carbon buildings {F6} [P1; P11]. Market diffusion will depend on technological advancements as well as the simplification of a series of administrative procedures. With the exception of greenhouses, BIPV systems require long planning processes, while the MCS framework requires certification of every product, limiting manufacturing flexibility, and driving innovation towards incremental improvements of existing products rather than the introduction of new ones {F3, F4} [P1].

Despite significant R&D activity in emerging BIPV technologies and the recent expansion of the PV market in the UK, the national supply chain remains highly fragmented, missing the equipment developing and product manufacturing body that would allow for cost reductions and streamlined procurement of systems {F1, F2, F7}. Polysolar expects that the integration of BIPV production lines within glass manufacturing plants will provide a cost-effective growth pathway, making use of the extensive existing infrastructure {F4} [P1]. Furthermore, the establishment of the NSC and the further involvement of RIBA in industry meetings and trade events is also expected to facilitate communication among stakeholders and increase visibility of the sector {F5, F10} [P2; P3].

8.3.5 Analysis

Contrary to the prominent business model of PV manufacturers that aims at the development of systems that can be readily used for generation of electricity, Polysolar's focus has been the development of building materials that have the additional capability of power production {F3}. The substantial difference lies in the fact that application of such materials requires involvement of more stakeholders than the end-user, including the designer and the developer of the building. Furthermore, their adoption is not just driven by financial benefits of generating renewable power, but is rather affected by wider socio-economic processes, including building regulations and established practices within the construction sector {F6, F9, F12}.

Consequently, the BIPV sector remains rather small in size with only a limited number of actors and developed projects {F7}. The lack of technological breakthroughs that would lead to the cost-effective manufacturing of a range of products as well as the absence of a dedicated regulatory framework that would nurture growth, has led to minimal development of the sector. Polysolar is one of the companies that has been confined within this niche market, seeking revenue streams in alternative market segments in order to sustain ongoing R&D activities {F4}.

Two of the most fundamental issues faced by the company are the securing of investment capital and the establishment of revenue streams for the financing of its radical R&D activity on organic BIPV technologies {F1, F6}. In order to tackle both, Polysolar executed a range of strategic acts, diversifying its production activities as well as its marketing strategy towards more established technologies and markets (a-Si and residential BAPV respectively) {F8}. This dynamic change of strategy aimed at corporate sustainability and brand visibility growth throughout the time required to commercialise the new technologies and establish the supply chain {F4}.

In addition to financial issues, Polysolar faces a range of technical and socio-economic issues. The incompatibility of the manufactured PV panels with conventional glazing panels in terms of size is one example of the issues arising from the coexistence in the BIPV sector of two industries with different origins and priorities. Limited communication between the PV and construction industries, and the lack of a common knowledge base and practices do not allow for the development of products optimised for building integration. More comprehensive educational practices and stronger representation within industry associations are expected to establish networks and facilitate knowledge diffusion {F5}. The development of more demonstration projects is also expected to raise awareness regarding the technical capabilities and potential socio-economic benefits of BIPV products {F10}.

As far as the existing BIPV supply chain is concerned, the sector demonstrates a high level of fragmentation. Most developers of novel technologies that would be suitable for the development of BIPV products are small firms with mainly R&D activities. The involvement of major manufacturers could potentially increase the legitimacy of the sector and trigger the development of a comprehensive supply chain {F4, F10}. However, the current economic climate has arguably had a significant impact on both diversification practices from incumbent firms and the entry of new industry actors {F3, F9}.

8.4 Summary and conclusions

In order to better understand and assess dynamics within the complex BIPV innovation system, analysis at multiple conceptual levels is required. Extending the empirical research at the sectoral and techno-economic context presented in previous chapters, two case studies were conducted in order to address intra-firm agency both internationally and within the UK.

The first study focused on a well-documented case of product differentiation, international market deployment and corporate failure. It investigated the impact of the changing economic environment on the generic business strategy adopted by the firm, which initially received generous public and private funding to commercialise its disruptive technology, but was later driven to bankruptcy when it could not realise a competitive cost-structure against the fast-moving baseline set by conventional c-Si PV technology. The case highlighted the difficulty of a manufacturer adopting a radical product design to sustain its financial support and achieve production scaling and cost reductions.

The second study provided an in-depth understanding of the business model adopted by a smaller firm and the strategic changes required in order to adapt to its dynamic environment. By identifying itself as a developer of building materials with the additional function of power generation, rather than a PV system manufacturer, and by changing its technological and market focus, Polysolar has established its commercial presence in the UK.

The case study also revealed the limited commitment of large corporations to the BIPV industry, and the consequent difficulties of small firms to raise product awareness, increase the legitimation of the sector and stimulate the involvement and education level of stakeholders from the construction industry. Additionally, the geographically fragmented nature of the BIPV supply chain does not allow for significant cost-reductions through scale-economics, impeding the commercialisation of new products into newly formed markets, and driving small firms to seek revenue within adjacent established market segments.

From a methodological point of view, the investigation of individual strategic choices and dynamics within firms highlighted the importance of including agency in the assessment of innovation systems. This is particularly relevant to the study of cross-sectoral systems where the coexistence of multiple stakeholders with different backgrounds and priorities adds complexity to the analysis. Traditional conceptual methodologies (such as TIS) offer a structured perspective that only allows for limited representation of innovation dynamics. In order to address this complexity and extend the analytical capability of the approach, this research combines conceptual elements from three different literature strands, and synthesises empirical evidence collected through multiple methods. This synthesis will be carried out on the next chapter.

Part III

Synthesis of Findings, Discusion and Conclusions

Introduction

In this part of the thesis, findings from the literature and empirical research outlined in Chapters 6, 7 and 8 are combined using the cross-disciplinary perspective introduced in Chapter 5 in order to investigate the BIPV technological innovation system, and assess dynamics at multiple levels.

The following chapters relate to all three research questions formulated in Section 5.1. They aim to respond to the first two by applying the novel extended-TIS framework outlined in Section 5.2 for the analysis of the complex BIPV innovation system, and reflecting at the same time on the adopted methodology:

R.Q. 1 How can the Technological Innovation Systems conceptual framework be enhanced through the incorporation of elements from the Multi-Level Perspective and Business Studies, for the development of an original hybrid approach to better evaluate the emerging and cross-industry BIPV sector?

R.Q. 2 What insights emerge regarding innovation dynamics within the BIPV sector in the UK and globally, through the implementation of the extended new framework for the analysis of multi-level empirical evidence, and what are the methodological implications regarding the compatibility of the approaches within the framework?

They also contribute to the discussion regarding different types of innovation, with the aim to generalise findings from the investigation of the BIPV innovation system to similar sustainable systems, addressing the third research question:

R.Q. 3 What insights emerge regarding the argument of incremental versus disruptive innovation, and what are the implications for the assessment and governance of hybrid sustainable innovation systems more generally?

More specifically, Chapter 9 implements the hybrid analytical framework for the organisation and analysis of the empirical evidence, with the aim to identify innovation dynamics and link them to wider socio-technical transitions. Chapter 10 identifies overarching patterns within this analytical synthesis, and highlights methodological and policy implications.

Chapter 9

Analytical Synthesis of BIPV Innovation Dynamics

Introduction

This research is based on the proposition that innovation is both a collective and an individual process occurring in the context of an *innovation system*. This perspective highlights the importance of not only the structural composition of the innovation system, but also the interactions of its components with each other and with the wider socio-technical configuration.

In other words, the performance of an innovation system and its potential for success in terms of development and diffusion of novel technologies are affected by its *structure*, its *function*, as well as the *context* of the wider environment. Consequently, it has been argued here that innovation dynamics can be better assessed using a cross-disciplinary approach that spans multiple conceptual layers, and utilises evidence collected through different empirical methods.

The chapter is structured as follows: after an initial definition of the conceptual boundaries of the object of analysis and the methodology in Section 9.1, the structural elements of the innovation system are outlined in Section 9.2.

The operation of the innovation system is then assessed in Section 9.3 using the hybrid framework developed for this research. Data collected throughout the literature and empirical research are brought together and organised against the twelve indicators of the framework at three conceptual levels of aggregation. This section provides summaries of evidence and condensed findings based on the fuller analysis in the earlier chapters, in order to provide insights regarding the functionalities of the innovation system.

Finally, the dynamic state of the system and potential transition pathways over time within its wider socio-technical context are studied in Section 9.4, using a synthesis of the innovation dynamics identified within the analysis up to that point.

9.1 Boundaries of analysis and methodology

Following the scheme of analysis proposed by Markard and Truffer (2008a), a TIS can be conceptualised as a cluster of technological and market niches along with relevant institutions and resources. This framing can be considered as an abstraction of the real world and therefore, the boundaries of the system are not determined by definite criteria.

This research adopts a broad applications-based definition of the BIPV sector, that encompasses PV systems installed in existing and new buildings, as well as multifunctional systems incorporated in urban infrastructure and developed not with the sole purpose of power generation (see Subsection 6.2.1). As such, the BIPV sector spans a range of applications across PV market segments (residential, commercial and industrial systems both connected and off-grid) and addresses developments in both the power generation and construction industries. These niches vary not only in their techno-economic characteristics, but also in terms of commercial maturity and disruptiveness with regards to the established configurations in the energy and construction sectors.

Additionally, the empirical research outlined in Chapters 6 to 8 suggests that innovation dynamics within the BIPV sector are affected by developments in multiple levels, including strategic choices within firms, changes in the market and industrial domains, and tensions within the wider socio-economic landscape.

Addressing the horizontal (cross-sectoral) and vertical (multi-level) boundary-spanning character of the BIPV innovation system, this research uses evidence collected through a range of empirical methods, and implements a hybrid analytical methodology adopting features from different literature strands. Although the TIS approach is used as the starting point to provide a structured methodology, it is extended in order to better reflect intra-firm agency, as well as links of the innovation system to its broader environment. This is achieved through the incorporation of conceptual elements from the Business Studies literature and the MLP respectively. The implementation of the extended-TIS framework on the BIPV innovation system will provide not only empirical insight for the sector, but also evidence regarding the compatibility of these elements within a hybrid methodology.

In order to offer a comprehensive account of the BIPV sector, the framework adopts a three-level structure, resonating with the different conceptual levels of TIS dynamics and interactions with its socio-technical environment: firm-level dynamics, sector-level interactions and contextual tensions. Additionally, the analysis synthesises evidence collected using a two-level spatial perspective, taking into consideration global industry dynamics and context, as well as market and policy characteristics at the national level, focusing on the UK national system. Developments at both levels critically affect the evolution of the sector and the potential for diffusion of new applications.

The application-driven, multi-level framing introduced in this thesis challenges the common practice of defining innovation systems according to technological characteristics or sectoral and national boundaries. By focusing on real-world empirical evidence, this research aims to better reflect on the cross-sectoral BIPV innovation system and extend our understanding of how to assess systems with analogous complexity.

The position of the BIPV innovation system within its wider socio-economic context, as well as the tensions at the various levels outlined in this Section are illustrated in Figure 9.1.

9.2 Structural elements of the BIPV innovation system

The TIS literature defines actors, networks and institutions as the structural elements of an innovation system (see Section 2.3). Although the examination of these elements in isolation is not sufficient to provide a comprehensive assessment of the system in focus, it offers a preliminary indication of its nature and development status. This section will outline the characteristics of these elements based on empirical findings, and provide the basis for the consequent functional analysis.

Many of the structural components associated with an innovation system are not exclusive, but rather shared with other TISs. This is particularly relevant to the emerging BIPV sector, since its short history and high affinity to the relatively mature

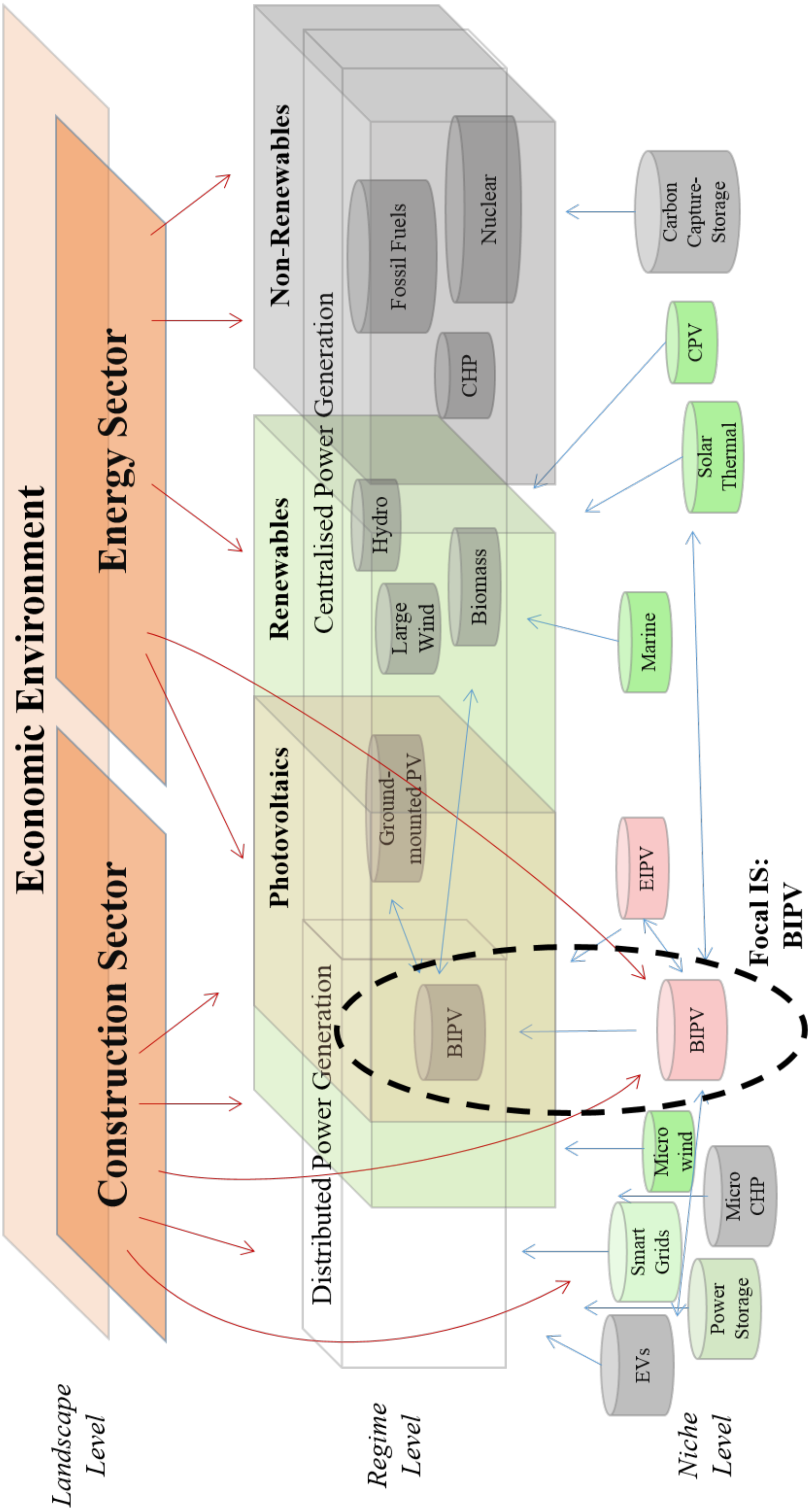

Figure 9.1: The BIPV innovation system within the multi-level conceptual configuration (author's elaboration).

PV industry, have not allowed for the development of an independent entity (see Section 7.2). The nature of this affinity, which has both synergistic and antagonistic characteristics, will be further explored throughout the analysis of the innovation system.

9.2.1 Actors

One of the early activities during the empirical research was the identification of *actors* involved in the development and market deployment of BIPV innovation. BIPV actors are diffused across different sectors at the national and global level. Although the cross-industrial character of the sector and its overall complexity rendered a comprehensive account rather impractical within the scope of this research, the research involved a representative sample of actors within the innovation system, including firms, suppliers, policy-makers, research and other organisations. At the industry level in particular, the cross-firm analysis, which was presented in Section 7.3, investigated the activities of most firms active in the global BIPV sector over a period of three and a half years from January 2011 to August 2014. Alternative approaches may be implemented for the analysis of smaller and more geographically-focused sectors. Vantoch-Wood (2012) for example uses a series of interviews combined with social network analysis for the assessment of the emerging UK wave energy sector.

The sectoral analysis and the case studies revealed that most of the firms involved in the development of BIPV products and applications are incumbent (usually PV) manufacturers that have diversified their production to serve emerging niches, driven by the expectation of market expansion. First Solar, Hanwha and Sharp are some prominent examples of major PV manufacturers active in the established ground-mounted solar industry that have explored building-integrated markets by slightly modifying their products. Other companies supported by strong conglomerates with a diversified portfolio include Ascent Solar, TSMC and Hanergy (see Section 7.3).

New entrants also exist, but are mostly firms at the early stages of deploying their proprietary technology into the BIPV market, and which lack the financial backing that would allow expansion of production and market deployment at high volumes. Konarka, Heliatek, Dyesol and Polysolar are all examples of firms that have stagnated in the absence of resources (see Subsection 8.3.3).

The Polysolar case study revealed the importance of universities and research institutions in the development of new materials and processes. The underlying technology originates in the Cavendish Laboratory, while it was later developed in the University of Sheffield and the Centre for Process Innovation (see Subsection 8.3.2). This example reflects a wider pattern identified throughout the empirical research: the knowledge base behind a range of BIPV products and applications originates in research within public organisations offering incubation spaces for radical innovations, while commercialisation activities are attempted by small-scale entrepreneurial firms.

Sources of public and private financial support were explored in the Solyndra case study. Investment originating in venture capital and government grants is available for disruptive PV technologies; however, the Solyndra experience suggests this support is not sustained unless there is evidence of fast cost reduction realisation. The dramatic reconfiguration of the c-Si supply chain and the rapid growth of low-cost manufacturing in China has put extreme pressure on developers of differentiated products and applications, and has led to an abrupt consolidation process. This ongoing consolidation, combined with the austere economic climate have further impeded experimentation with technologies that are not able to demonstrate accelerated market deployment (see Section 8.2).

A recurring observation throughout the empirical research was that most actors involved in the development and diffusion of BIPV technologies are not confined to the BIPV system, but operate more widely, across the wider PV or construction industries. Particularly, actors involved in the development of new technologies, manufacturing processes and end-products originate in the PV sector, while those involved in the market deployment and installation of BIPV applications are mostly related to the broad construction industry. The underlying reasons and implications of this attribute of the innovation system will be further investigated later in this chapter.

9.2.2 Networks

According to the TIS approach, *networks* for the distribution of knowledge and resources are the second structural component of an innovation system. The existence and functionality of such networks is central for the overall efficient operation of the system (see Subsection 2.3.1).

The extraordinary growth experienced by the PV industry and markets in recent years has created a range of formal and tacit links among sectoral actors, including industry associations, trade networks and political coalitions at an international and predominantly a national level (see Subsection 7.1.1). This system of connections is not explicitly dedicated to the development of the BIPV sector per se, but is rather part of the broader sustainable energy and PV sectors. Consequently, networks often focus on mature renewable energy market segments, diverting resources from disruptive technologies. However, they still collectively facilitate learning and market diffusion processes of BIPV applications. In the UK for example, although most renewable energy networks have focused on the deployment of proven technologies (e.g. wind farms and ground-mounted PV systems), they have also increased awareness and public interest in emerging applications, including BIPV (see Section 7.5).

More dedicated formal knowledge transfer networks have been developed, focusing on certain technological domains including the development of materials and manufacturing processes. These networks tend to form within national boundaries, with examples from the UK being several consortia founded by the Research Councils, as well as the National Solar Centre (NSC) that focuses on creating communication routes along the PV supply chain (see Section 7.5). The empirical research did not reveal any networks specific to BIPV technologies.

The Polysolar case study revealed the importance of establishing partnerships and informal links throughout the supply chain not only for deploying products into the market but also for guiding innovation processes within firms. The experience of incompatibility of sizes between BIPV modules and standard glass panels highlights the necessity of feedback loops and communication throughout the development of new products, especially from the construction and architectural communities (see Subsection 8.3.3).

The case study also outlined the turbulent process of creating industrial and academic consortia within the UK. A series of unsuccessful funding rounds led to consecutive short-term research partnerships, impeding the development of new technologies and production processes, and decelerating the overall intra-firm innovation process (see Subsection 8.3.2). The Solyndra case study on the other hand underlined the significance of developing political affiliations in securing resources and facilitating the scaling of production (see Subsection 8.2.2).

At the international level, the empirical research revealed a small number of industry associations and political coalitions related to the BIPV sector. Despite the globalised nature of supply chains, there is limited evidence regarding the existence and function of formal networks. That said, knowledge transfer is aided to a certain degree through a number of academic consortia, international conferences and trade expositions (see Subsections 7.1.1 and 7.1.2).

9.2.3 Institutions

Institutions within the TIS framework refer to all normative and cognitive structures that shape behaviours and interactions of actors within an innovation system.

With regards to formal rules, a range of renewable energy policy frameworks and low-carbon buildings directives drive the development and deployment of BIPV applications into the market (see Section 7.4). International schemes (e.g. UNFCCC, Kyoto Protocol, Horizon 2020) and more topical mechanisms (e.g. mandates, input and output subsidies) have been set up for the stimulation of research activities and market growth in sustainable energy technologies. The BIPV sector is also shaped by regulations for the decarbonisation of the buildings sector, with the examples of the Energy Performance of Buildings Directive (EPBD) in the EU and the Low Carbon Building Programme (LCBP) schemes in the UK (see Section 7.5).

Specifications of BIPV products are dictated by national standards and requirements relating to all construction materials. Although particular regulations regarding the installation of such products have been created, they are rather limited. The Microgeneration Certification Scheme (MCS) was developed in the UK and has been adopted by several other countries (see Section 7.5). However, the scheme refers to all microgeneration technologies, with no specific emphasis on the standardisation of BIPV products. This lack of institutional attention can be a significant impediment in the diffusion stage of hybrid technologies such as BIPV.

Soft institutions include BIPV practices in the form of entrenched patterns and habits. These are mainly shaped by cognitive rules within the well-established construction sector, which are not always compatible with practices within the wider PV industry. Handling, installation and use of BIPV products are often very different from those of other PV applications, especially the mature ground-mounted sector which imposes the norms within the industry. One example is the module-sizing issues faced by Polysolar, which reveals the difficulties involved in the market deployment of new BIPV products regarding not only manufacturing requirements, but also certain embedded routines within the UK glazing sector (see Section 8.3). It also highlights how a problem in the deployment phase of a new product may be transferred to the development phase, and how this is aggravated by the involvement of different actors in the two processes.

Innovation dynamics within the BIPV sector are also affected by user behaviours. Increasing awareness with regards to environmental sustainability and energy independence is driving the adoption of decentralised energy systems in urban environments, where BIPV is one of the few options (see Subsection 7.1.2). On the other hand, deployment is constrained by individual requirements and preferences on the power performance of the systems as well as their aesthetical characteristics (see Section 6.3).

9.3 Functional analysis of the BIPV innovation system

According to the TIS methodological tradition, the overall performance of an innovation system can be evaluated by assessing the fulfilment of certain functions that capture the dynamics of the system (see Section 2.3). Although this research acknowledges the importance of functional analysis, the empirical study on the BIPV sector revealed that the TIS's established functional set alone does not provide the conceptual tools to sufficiently address the innovation processes within a complex multi-sectoral system.

The extended-TIS functional framework introduced in Section 5.2 broadens the analytical capability of the TIS methodology, by incorporating elements from the MLP and Business Studies literature. Its twelve functions are organised into three groups according to conceptual levels of aggregation, as shown in Table 9.1. This cross-disciplinary approach is designed to better reflect the contribution of intra-firm agency and knowledge development, sector-level dynamics, and interactions with multiple external innovation systems, regimes and landscapes.

Literature and empirical evidence collected through personal communications, semi-structured interviews and in-depth case studies was arranged into the narratives presented in Chapters 6 to 8. The hybrid functional framework provided a structured methodology for the organisation and analysis of the primarily qualitative data, following

Conceptual level	Function	Ref.
Contextual Dynamics		
Landscape	Influence on the direction of search	{F12}
Regime	Tensions in the incumbent configuration	{F11}
	Legitimation	{F10}
Other TISs	Development of positive externalities	{F9}
Sector level	Niche cumulation and dominant designs	{F8}
	Market Formation	{F7}
	Resource Mobilisation	{F6}
	Knowledge diffusion through networks	{F5}
Firm level	Business model innovation	{F4}
	Entrepreneurial experimentation	{F3}
	Materialisation	{F2}
	Development of formal knowledge	{F1}

Table 9.1: Hybrid (extended-TIS) functional framework (author's compilation).

the principles of process theory (see Subsection 5.2.4). The findings that emerged throughout this practice are now synthesised and presented in the following paragraphs, aiming to assess the overall performance of the BIPV innovation system. Many findings of the empirical research relate to more than one functions of the innovation system in different ways and therefore, a certain degree of repetition is inevitable.

At the same time, the analytical strengths and limitations of the framework are highlighted, in order to evaluate its suitability and effectiveness in the study of analogous complex systems. The ability to capture real-world dynamics is assessed, while links and overlaps among individual functions are also identified with the aim to raise potential mutual reinforcement or imperilment patterns[1], and raise potential recommendations.

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[1] Hekkert *et al.* (2007b) refer to these patterns as virtuous and vicious cycles of functional interaction, while Suurs *et al.* (2009) and Hughes (1993) use respectively the concepts of *cumulative causation* and *reverse salients* (see Subsection 2.3.2).

9.3.1 Firm-level dynamics

The functioning of an innovation system relates in part to the accumulation of skills and knowledge within firms [Malerba (1992); Markard and Truffer (2008b)]. A recurring theme throughout this research was the significant number of intra-firm developments contributing to this learning process. However, conventional analytical methodologies tend to underestimate these dynamics, offering a rather myopic perspective on the drivers of innovation.

In accordance with this observation, the first conceptual level of aggregation focuses on innovation processes at the niche level. The functional analysis identifies and assesses not only formal knowledge development within firms, but also indirect learning through the introduction of a function that maps agency in terms of strategic choices and adaptation to contextual processes.

F1: Development of formal knowledge

This first function is used to conceptualise the status and evolution of the knowledge base, and identify formal learning processes within the innovation system (see Subsection 2.3.2). Both tasks are challenging when the innovation system spans multiple technological domains and involves actors across several industries. In this research the function addresses both the characteristics of knowledge and its sources.

The empirical research has revealed that the BIPV sector shares its technological knowledge base with the mature PV industry and, to a much lower extent, with the construction industry. The two industries involve separate communities of actors with different knowledge backgrounds, priorities and capabilities (see Subsection 9.2.1). This was evident throughout the technical domain review, which highlighted the focus of BIPV system manufacturers on the development of new PV technologies rather than their optimisation for integration into buildings, which is a priority for architects and engineers (see Section 6.1 and 6.2). This disjunction of the BIPV development from the diffusion community is one of the recurring themes within this research.

Although most of the intellectual property related to commercial products belongs to private companies, many underlying technologies of the more radical BIPV applications originate in public organisations, including universities and research institutes. Consortia of academic and industrial partners are then developed in order to commercialise the technologies, as was showcased in the Polysolar case study (see Subsection 8.3.2). The inclusion of partners from the construction industry is often pursued to provide feedback with regards to the compatibility of products with building requirements and practices as in the case of Ascent Solar, Dyesol and Oxford PV (see Section 7.3 and Subsection 8.3.3).

With regards to novel technologies and processes, the BIPV knowledge base is very broad and rather fragmented. Section 6.1 outlined a highly diverse technological domain, while the market assessment revealed a large number of universities and early-stage corporations with a range of ongoing BIPV-related R&D activities, especially within the TF and OPV technological families (see Section 8.3). Their operations are usually not sustained by commercialisation of products, but rather through international research programmes in the context of wider renewable energy systems support {F12} (see Section 7.4). The UK in particular is considered to be the leader in the development of third-generation PV materials.

Assessment and certification activities which also facilitate learning processes are carried out in public establishments, including the Fraunhofer TestLab in Germany, the National Renewable Energy Laboratory (NREL) in the USA and the National Solar Centre (NSC) in the UK (see Section 6.3). Consequently, it can be argued that much of the knowledge development process regarding disruptive technologies is undertaken by the public sector, at least initially [Mazzucato (2013)].

Another source of technological learning has been a knowledge spillover from the mature integrated-circuit industry. Wafer-based c-Si technologies have benefited from the mature sector, achieving significant technological breakthroughs and cost reductions and capturing an early dominant position in both ground-mounted and sloped-roof applications {F8, F9} (see Subsection 7.1.2). The significant advancements within the c-Si technological family have driven progress within the wider PV sector. This is evident in the high learning rate, which averages at 20% in the last four decades, reducing the average module price from over \$70/Wp in the mid 1970s to less than \$0.85/Wp currently (see Subsection 6.4.1).

This extraordinary progress of c-Si has also put a high pressure on other PV technologies that do not benefit from a similar learning mechanism, including the TF and OPV technological domains. Despite multiple technological achievements and commercial success of individual companies (e.g. First Solar and Solar Frontier), there is still limited evidence of accelerated learning processes and market deployment in comparison to c-Si. This is confirmed by the relatively slower learning rate and the limited market share of these technologies, which did not exceed the 18% threshold even during the polysilicon feedstock bottleneck in the mid 2000s (see Subsection 6.4.1 and Subsection 7.1.1). Consequently, it can be argued that the association of the PV sector with high-performing first-generation c-Si technologies has had a negative impact on the comparative analysis of the performance of technologies that are inherently more suitable for the development of BIPV products, due to their visual and formal flexibility, including TF and OPV (see Section 6.3.2).

F2: Materialisation

This function concerns knowledge embedded in physical outputs, including products, processes and infrastructure (see Subsection 2.3.2). It is closely related to {F1}, forming the second dimension of knowledge creation within the BIPV sector.

The industry and market assessment revealed that most of the BIPV supply-chain elements are shared with the mature and globalised PV sector. Scaling-up of production during the last decade mainly in East Asia accelerated PV cost reductions, but also contributed to the industrial consolidation process, with a rather negative impact on the BIPV manufacturing base (see Subsection 7.1.2 and Sections 6.4 and 8.2).

PV manufacturing lines, production equipment and processes have been designed for the established market segments and consequently, most developed products are not optimised for integration in the construction sector. The Polysolar case study revealed one such case where the module sizing standards defined by manufacturing equipment designed for the ground-mounted PV segment are not compatible with glazing standards in the UK (see Section 8.3).

Although BIPV is a multi-technology sector, it is mainly associated with the TF and OPV technological families, since these offer the required flexibility with regards to aesthetical characteristics (see Section 6.3.2). The broad and diverse nature of these technologies, which was identified in their knowledge bases {F1}, is also apparent in their respective supply chains. There is still no evidence of an emerging dominant trajectory regarding industrial processes and materials, that would allow the achievement of cost reductions through the development of standardised equipment and large-scale production (see Section 6.1) {F8}. Firms dedicated to the production of BIPV applications remain in a nascent state, with few pilot lines and demonstration projects (see Section 6.3). This is highlighted by the existence of only two PV manufacturers utilising TF technologies (First Solar and Solar Frontier) with GW-scale production lines (see Section 7.3).

With regards to learning-by-using processes, the BIPV sector has benefited from the development of multiple demonstration projects. These have been driven by the willingness of early adopters, as well as companies with an environmentally friendly corporate profile, which use the visual impact of BIPV systems as a marketing tool to communicate this profile to the public. Sainsbury's is one of the companies adopting this strategy in the UK, as was revealed in the Solyndra case study (see Sections 8.2.2 and 8.3.3).

One other process that has aided the development of the BIPV sector is the technological progress achieved by balance-of-system (BoS) PV products. The effect of BoS and other *soft costs* on the overall performance of a system is particularly high in small-scale BIPV applications, reaching 64% in residential systems. Although technological advancements and cost reductions for BoS have been realised at a slower rate than for PV modules, they still have improved the overall performance and price profile of BIPV systems (see Section 6.3 and Subsection 6.4.2).

F3: Entrepreneurial experimentation

Experimentation with new technologies and markets is described in the TIS as a fundamental function of emerging innovation systems that reduces uncertainty through cumulative learning processes. This mechanism of tacit learning is considered to be the third dimension of knowledge development along with formal knowledge development and materialisation (see Subsection 2.3.2). Although this notion implies harmonious dynamics, the empirical research outlined in Chapters 6 and 7, as well as both case studies, revealed a rather conflict-laden process, highlighting the importance of incorporating developments within the wider socio-economic environment in the analysis of an innovation system. The purpose of the function in this framework is to understand the processes that have affected experimentation historically, as well as its cumulative result.

The cross-firm analysis revealed that the vast majority of BIPV companies originate in the PV and semi-conductor industries, with the exception of only a few manufacturers from the glazing and construction sectors (e.g. the firms Schott and Schücco, see Section 7.3). Investment in the wider PV sector was triggered after the introduction of financial incentives to stimulate renewable energy market growth in the 1990s (see Section 7.4). Multiple adjustments to national policy frameworks created short periods of overheated development followed by sharp declines. This has been the case for several countries in Europe, including Spain and the Czech Republic. The market assessment revealed that these policy and market fluctuations, as well as several trade wars and reciprocal litigations at the globalised industry level, have impacted the confidence levels among investors and increased uncertainty within the sector (see Subsections 7.1.1 and 7.1.2).

The breadth of the PV technological domain has allowed for experimentation with a multitude of materials and products with different characteristics (see Subsection 7.1.2). TF and OPV in particular have attracted interest due to their potential techno-economic advantages, especially when the c-Si dominant design was challenged due to concerns regarding long-term feedstock availability and cost in the mid 2000s (see Subsection 7.1.1). The sectoral analysis undertaken during the Solyndra case-study revealed a high number of new entrants during this period including Ascent, Avancis, Heliatek and Stion (see Section 8.2). The existence of an environment that supports entrepreneurial activities at a national level has also been important; the wider analysis undertaken as part of the Polysolar case study revealed the plethora of firms experimenting with novel technologies in the UK during the same period, including GCell, SolarPress, Eight19 and Polysolar itself (see Section 8.3).

The consolidation process within the PV sector that started in 2009 and is still ongoing, has mainly affected firms with technologically diversified manufacturing (see Subsection 7.1.2). The highly antagonistic industrial environment in conjunction with the austere global economic climate have hindered experimentation with disruptive technologies, which usually involves high-risk capital investment {F9} (see Section 7.2). This is particularly relevant to premium products with long-term economic returns, including BIPV materials.

In order to maintain sustainable shipments growth, most PV manufacturers have historically focused on the established and growing utility-scale market segment, rather than experimenting with niche market segments such as BIPV (see Section 6.4). A limited number of new investments on diversified companies still occur, mainly from strong conglomerates with easy access to capital and parallel revenue streams, as in the case of TSMC and most prominently, Hanergy. Both the Solyndra and Polysolar case studies underlined the difficulties involved in market deployment of radical product designs at the international and the UK level (see Sections 8.2 and 8.3).

Despite the recent industrial consolidation, earlier experimentation with technologies and markets in the PV industry created a diverse sector filled with a wide spectrum of applications (see Section 6.2). This experimentation has had a limited impact on the BIPV sector which requires products with different characteristics than the ones that dominate the established PV market segments. The consensus among stakeholders involved in the development and diffusion of BIPV projects is that the market is still missing a product range with the required visual and formal versatility in terms of available colours, shapes and levels of transparency (see Section 6.3). It is still unclear whether entrepreneurial experimentation is the appropriate function within the innovation system to create this versatility, or more fundamental innovation is required for the development of new materials.

F4: Business model innovation

In addition to the activities of new entrepreneurial entrants, the BIPV sector is shaped by strategic actions of incumbent firms within the wider PV, energy and building industries. A range of developments at the wider socio-economic configuration shape the landscape within which companies operate, affecting their operational trajectories.

This function was introduced to the framework in order to counter the suggested tendency toward myopia in TIS, extend the representation of intra-firm innovation dynamics introduced by *entrepreneurial experimentation*, and focus on the strategic responses of actors to adapt to their changing environment. By doing so, the contribution of agency to innovation is further highlighted through the inclusion of analytical elements from the Business Studies literature.

Throughout the empirical research, the dynamic adaptation of PV firms to contextual tensions has been evident. During the polysilicon feedstock bottleneck in the mid 2000s, many companies integrated elements of the upstream value chain in order to be less susceptible to increasing feedstock prices. By internalising materials extraction and handling, leading manufacturers in China and Malaysia were able to ramp up production and achieve significant cost reductions {F9} (see Subsections 7.1.1 and 7.1.2).

Among BIPV firms more specifically, a similar form of corporate resilience was demonstrated throughout the industrial consolidation process during the last five years. Several firms including First Solar, Sharp and Solar Frontier added project development to their operations in order to increase profit margins, i.e. downstream supply-chain integration has emerged as a business model strategy as well as upstream integration (see Section 7.3). Major module manufacturers also responded to international trade wars by outsourcing part of their production to other countries (see Subsection 7.1.2).

The market assessment and the two case studies illustrate some of the different experiences involved here. In spite of recognising the commercial-building sector as its target market, Polysolar diversified its production into the mature domestic-building market segment, in order to establish revenue streams and support ongoing R&D operations (see Subsection 8.3.3). The Solyndra case study and the cross-firm analysis on the other hand outlined the strategic responses of manufacturers to exogenous tensions at times of economic austerity and industrial consolidation {F9}. They also suggested that under the industrial circumstances of the last ten years, the companies with the highest commercial success have been the ones focusing on cost, rather than product and market differentiation (see Subsection 7.3).

In their different ways, these findings highlight the *organisational ambidexterity* (see Section 4.3) required by firms to endure a highly competitive environment. An additional observation that stems from the empirical research is that despite the multitude of business models encountered within the BIPV sector, no clearly defined strategies have emerged as prominent paradigms, as has been the case within other PV market sectors (e.g. First Solar in the ground-mounted sector), indicating that the sector has not yet reached a state of industrial maturity (see Subsection 7.1.2).

9.3.2 Sector-level dynamics

The first four functions were used to identify and assess agency and knowledge development processes within firms. The second level of aggregation extends the analytical boundaries of the framework, offering a higher-level perspective of innovation within the BIPV sector. Its four functions address dynamics associated with aggregate learning, emergence of dominant technological trajectories, cumulation of resources, as well as development and growth of markets.

By opening up and extending the original TIS functions using conceptual insights from the MLP, the analysis aims to better reflect the dynamic nature of the BIPV innovation system, identifying patterns of technological transitions. Such patterns will be further explored in Section 9.4.

F5: Knowledge diffusion through networks

The performance of innovation systems is strengthened by the operation of networks that either accelerate learning processes by facilitating the communication among actors, or by promoting market deployment through political advocacy [Bergek and Jacobsson (2003)]. Although the development of formal and tacit knowledge is conceptualised in the TIS framework in functions F1 to F4, and the existence of such networks is outlined in the structural assessment of the system (see Subsection 9.2.2), there is limited focus on their ability to diffuse knowledge within the innovation system.

The assessment of this systemic function is rather important in sectors where the coexistence of more than one industries impedes the flow of learning outcomes (see Subsection 7.1.1). This is particularly relevant to the BIPV sector, where the analysis up to this point has revealed a rather fragmented knowledge base across a diverse group of stakeholders (see Section 7.2).

The first networks within the PV sector appeared in the USA as public-industrial collaborations for the development of materials and products that could be used in space applications and remote electrification systems in the 1960s and 1970s. Further knowledge development and diffusion networks were created after the introduction of R&D programmes in Europe and Japan during the 1990s (see Subsection 7.1.1). These were mostly academic consortia formed at the national level. The Polysolar case-study outlined the firm's turbulent process of transferring its technology to the market by creating a series of such consortia in the UK (see Subsection 8.3.2).

The widespread implementation of market creation mechanisms in the 2000s accelerated the development of international trade associations and political coalitions (see Section 7.4). Several countries also established public bodies for the assessment and certification of products, that also function as centres for the distribution of accumulated knowledge regarding best practices within the sector, including NREL in the USA and the Fraunhofer Institute in Germany. However, only a few countries including France and Italy have created formal networks that are dedicated to the development of the BIPV sector, rather than the wider PV industry (see Section 7.2). The success of these networks in promoting BIPV innovation could be explored in future research to provide useful insights regarding the role of national systems.

Both case studies highlighted the importance of increased communication of available BIPV materials and product options to the architectural community not only for acquiring feedback that could aid the development of new products, but also for informing and educating stakeholders and users. The Polysolar case study also underlined the difficulties faced by small firms in triggering such communication channels on an individual-firm basis (see Subsection 8.3.3). The Solyndra case study on the other hand revealed the importance of raising political support in the early stages of corporate development, and how this aided its efforts to scale up production and commercialise its products (see Subsection 8.2.2).

F6: Resource mobilisation

This function is used within the TIS methodology to measure financial and other types of resources that are mobilised in order to accelerate the development of the innovation system. This mobilisation can be attributed to processes internal to the system as well as developments in the wider socio-technical landscape. The adoption of a perspective at multiple conceptual levels is therefore deemed appropriate for its evaluation.

The BIPV sector has been receiving financial backing in the context of a wider policy support to sustainable energy systems and low-carbon building design {F12}. Despite the increased interest towards renewables after the two oil crises in the 1970s and the introduction of R&D programmes in the 1990s for the development of solar technologies, substantial mobilisation of resources towards the wider PV sector did not occur until the appearance of fiscal incentives in the 2000s. Since 2010, the sector has been attracting the largest amount of new investments among renewable energy technologies (see Subsection 7.1.1 and Section 7.4).

Certain techno-economic developments within the PV industry have channelled resources towards particular technologies. After a surge in investments on second and third generation technologies (which are arguably more suitable for building-integration as has been discussed earlier) due to a supply chain bottleneck in the mid 2000s, the steep decline of polysilicon feedstock prices in the last ten years has driven major manufacturers towards the capacity expansion of c-Si production lines, as is evident in the historical production capacity trends (see Section 6.4 and Subsection 7.1.2).

As far as contextual processes are concerned, the austere economic landscape has facilitated the development of technologies with a low investment risk {F3}. The production of disruptive applications such as BIPV, requires relatively high capital expenditure, which can be discouraging for investors {F2} (see Subsections 7.1.1 and 7.1.2). As a consequence, the ongoing industrial consolidation has mainly affected differentiated companies, isolating them from both capital and human resources (see Subsection 8.2.4).

Additionally, the high urgency of market deployment of renewable energy systems, which is driven by policy frameworks at the national and international levels, has aided the mobilisation of resources towards technologies that are more advanced in terms of commercial maturity. In the case of the PV sector, the mature ground-mounted market segment has been historically supported as it offers the potential for high-scale deployment, in contrast to the emerging and granular BIPV sector (see Subsection 7.1.2 and Section 7.4).

The Solyndra case study suggested that companies with radical products have a limited opportunity or time window to create a market deployment strategy (see Subsections 8.2.2 and 8.2.5). Despite initial public and private investment that reached $1.5 billion, financial support was retracted when the firm was not able to ramp-up sales and create a sustainable cost-structure (see Subsection 8.2.3). At a smaller scale, the turbulent funding rounds outlined in the Polysolar case study supported this observation regarding the difficulties experienced by differentiating companies to secure long-term financing (see Section 8.3.2).

F7: Market formation

Markets in emerging innovation systems may be significantly underdeveloped, or even non-existent. The creation of spaces where novel products receive technological and institutional protection is often vital, especially in sectors where these products do not demonstrate an obvious short-term advantage that would allow direct competition with incumbent products in real market conditions.

The variety of technological options, as well as the modularity of PV components, have allowed for the development of a multitude of products and potential applications (see Section 6.2 and Subsection 7.1.2). Acting in a similar way to evolutionary natural selection, real market environments have restricted the number of viable products. This process has been accelerated by contextual socio-economic developments, which have limited the degree of experimentation {F3} (see Subsection 7.1.1). The cross-firm analysis presented a broad overview of this selection process at the international firm level. Throughout the last decade, most firms focusing on product and market differentiation have experienced very slow growth, and a high number of them have been driven out of the industry (see Section 7.3).

The development of PV markets has been made possible through policy intervention at different national and international levels (see Sections 6.4 and 7.4). A range of fiscal subsidies, and particularly the fixed-price mechanisms introduced in Europe in the early 1990s, provided protective environments for the relatively high-cost PV products. They also facilitated cost reductions for several technologies, realising the cost-competitiveness of PV-generated electricity with conventional grid power in normal market conditions in regions with a high solar resource (see Subsections 6.4.2 and 7.4.2).

BIPV markets have not been explicitly supported through policy in most national energy systems. BIPV systems are relatively small in their power-generation capacity, and not always replicable, at least not within the current supply chain. High levels of integration (e.g. windows, skylights and glazing) require bespoke system designs, and a long design process. Therefore, the achievable deployment rate is rather slow, and does not comply with the broader imperative for accelerated de-carbonisation of the energy and construction sector. Certain BIPV applications that offer the potential for swift deployment (e.g. building-applied PV on domestic and commercial roofs) have benefited from the widely adopted market-pull policy frameworks, forming growing market niches (see Section 7.5). However, these support mechanisms have not been able to aid the early stages of deployment of more radical BIPV applications that cannot be readily installed, but rather require long-term planning and changes in the *soft institutions*, e.g. entrenched habits within the construction industry (see Subsection 9.2.3).

Building regulations have been an indirect means of BIPV market stimulation. By aiming to reduce the net energy consumption within buildings, these regulations facilitate the deployment of decentralised renewable energy systems, including BIPV (see Subsection 7.4.1). The development of the Energy Performance of Buildings Directive (EPBD) in Europe drove the introduction of incentives for the adoption of BIPV applications in certain countries including France and Italy, allowing the formation and growth of niches. The market share of systems installed in buildings in these countries is currently over 65% of the total PV sector (see Subsection 7.1.2). On the other hand, countries which did not implement similar support mechanisms were not able to create BIPV markets, even in the presence of a substantial PV sector, as in the case of Spain where BIPV systems constitute about 15% of the PV market (see Sections 7.4 and 7.5).

Compared to other European countries, the UK has been rather slow in creating a regulatory framework for the creation of BIPV markets. The wider PV sector has been supported through the Renewable Obligation Certificate (ROC) since 2002 and the feed-in tariff (FIT) schemes since 2010, as part of the country's strategy to increase the share of renewable energy sources in the total energy mix to 15% by 2020. Large scale PV including ground-mounted systems and BAPV on industrial and commercial roofs have been the two market segments benefiting the most from this policy, capturing 47% and 30% of the total PV market respectively (see Subsection 7.1.2).

The introduction of a series of regulations regarding the decarbonisation of buildings in the UK (including the Low Carbon Building Programme (LCBP) in 2006, the Renewable Heat Incentive in 2011 and the zero-carbon standard for new houses from 2016), as well as the shift of policy support towards decentralised power systems, have allowed for the development of niche BIPV markets within the construction sector (see Section 7.5). Nonetheless, the existence of well-established building codes, restrictions and practices are impeding the accelerated growth of the sector (see Subsection 7.4.1).

Further niche markets have been created for BIPV applications that can provide a secondary value proposition to their users, in addition to revenues from power use and sale. The Solyndra case study for example revealed how certain major retailers (including Sainsbury's in the UK) are willing to adopt the technology as part of a marketing strategy regarding a sustainable corporate profile (see Subsection 8.2.2). The Polysolar case study on the other hand discussed unexplored market segments including carport canopies and greenhouses (see Subsection 8.3.3). Finally, the market deployment of smart grid applications, electric vehicles and other power storage options that can increase the economic value of BIPV through self-consumption has created a growing mass of early-adopters of the technology (see Sections 6.4 and 7.2).

F8: Niche cumulation and dominant designs

Although the *market formation* function allows for the identification of market creation processes within an innovation system, it offers limited insights regarding the dynamic state of these markets throughout time. The empirical research on real case studies revealed that mere existence of such protected niches does not always lead to growth and their eventual incorporation into the incumbent socio-economic configuration.

This function was introduced to the analytical framework in order to assess the maturity of niches within the innovation system, and identify their alignment towards certain dominant trajectories. According to the MLP such an alignment, in addition to a certain degree of instability at the regime level, may lead to a technological transition, and accelerated market diffusion. However, this research has revealed a much more multi-faceted, ambiguous and turbulent system transformation process than this essentially bottom-up scenario, with niche markets experiencing significant fluctuations and contextual pressures.

The extraordinary growth of the PV sector over the last ten years has created a substantial industry, and has driven cost-reductions that have rendered PV electricity competitive, in some circumstances, with other types of renewable and fossil-fuel electricity in terms of levelised cost (see Subsection 6.4.2). However, in absolute terms, the sector remains a small market segment, providing a slight fraction of the overall global electricity. This was limited to 0.6% of the global power supply in 2012, while this share in countries with high PV penetration including Germany and Italy has reached 5% and 7% respectively (see Subsection 7.1.1).

The expansion of the sector has also triggered the development of an extensive network downstream the PV value chain, regarding the procurement and installation of systems. However, as the analyses of Solyndra's and Polysolar's business models suggest, there is limited evidence regarding the creation of a comprehensive BIPV supply chain, which would be able to accelerate growth within the sector (see Subsections 8.2.3 and 8.3.3).

The only product type that has emerged as a dominant design within the BIPV sector is the flat-plate glass module installed on roofs. Technological similarities to those within the well-established ground-mounted PV segment, as well as their non-disruptive add-on installation features have facilitated the development of a mature BAPV system-paradigm which offers the potential for fast market deployment (see Section 7.2). More disruptive applications that require deeper changes in behaviours and practices across the supply chain, including fully integrated PV materials, have not yet achieved significant momentum, and remain at the niche level (see Subsection 6.2.1).

As far as technologies are concerned, a range of processes discussed earlier (inter alia knowledge spillovers, low capital expenditure and established interests of equipment providers) have created an early dominant position of c-Si technology within the PV industry (see Section 6.1 and Subsection 7.1.2). The maturity of the c-Si technology is evident in its consistently high market share, the extraordinary learning curve and the involvement of multiple powerful industry actors (see Subsection 6.4.1 and Section 7.3). Despite its current technological and cost advantages, this technology is not considered by the architectural community to be optimal for building integration due to visual and formal limitations of their potential applications (see Subsection 6.3.2).

Thin-film (TF) and organic PV (OPV) technologies on the other hand demonstrate the characteristics that could be considered inherently suitable for BIPV applications (see Section 6.3). As was outlined in the sectoral review, their technological diversity has created a multitude of available materials and applications (see Section 6.2). However, they have not been able to achieve substantial market traction, and their combined PV market share is currently limited to less than 10% (see Subsection 7.1.2).

9.3.3 Contextual dynamics

Technological sectors do not evolve in a vacuum, but are rather interconnected to their environment in different ways and at multiple levels. Consequently, innovation processes are affected not only by internal dynamics, but also developments in other innovation systems, relevant industries and the wider socio-economic configuration. These contextual processes provide the top-down gradients of technological change that shape, along with bottom-up developments at the niche level, potential transition pathways.

The third conceptual level of the analytical framework is designed to address these dynamics by utilising four functions that identify and characterise interactions between the innovation system in focus and other systems, regimes and landscapes. The following paragraphs summarise findings from the empirical research that relate to these four functions.

F9: Development of positive externalities

It has been discussed earlier in this thesis that despite its analytical strengths, the TIS framework provides a rather inward-oriented perspective of innovation dynamics. Although the *development of positive externalities* function is used to connect the innovation system with developments in wider adjacent industries, these externalities are conceptualised as a force assisting growth within the system (see Section 5.2). In this research, the function is opened and extended to address both positive and negative developments in the wider socio-economic configuration and investigate how they affect the development and diffusion of innovation, as well as the strategic choices of actors.

A process that has critically driven growth in the BIPV sector, as part of the wider PV industry, is the increasing support of renewable energy systems based on the manifold rationale of mitigating effects of anthropogenic climate change, increasing security of supply in regions with scarce fossil-fuel resources, stimulating competitiveness within the energy sector and encouraging industry and job creation. Multiple countries have agreed upon international strategies and binding long-term targets, while support has been expressed through a range of regulations and reward schemes for the de-carbonisation of the energy, construction and transport sectors and the increased deployment of sustainable technologies {F12} (see Sections 7.4 and 7.5). The regulatory support has also been accelerated by contextual developments including the nuclear accident in Fukushima and political instability in the Middle East (see Subsection 7.1.2).

This policy shift along a more sustainable path has stimulated the development of multiple renewable energy technologies. The high urgency for their deployment has also created a range of short-term market opportunities. These opportunities are different among countries, and depend not only on local natural resources and policy priorities but also on the characteristics of the respective energy infrastructure. In the UK for example, the highly centralised power grid has been more suitable for the deployment of large-scale technologies, including wind power systems and ground-mounted solar farms. On the other end, countries with strong decentralised power systems including Germany and Denmark have adopted distributed energy systems. The share of PV systems installed in buildings in these countries is respectively 75% and 100% of the entire national PV sector (see Subsection 7.1.2).

The reconfiguration of the power generation system towards a more decentralised paradigm has been observed in many countries as a long-term potential transition (see Subsection 6.2.1). This transformation involves the replacement of large-scale power stations and transmission-grid infrastructure with distributed generation systems located proximally to consumers. Increasing electricity retail prices on the other hand, have made the idea of producing power more appealing to home-owners and businesses (see Section 7.2). Consequently, there is a growing need for technologies that can be integrated in buildings and urban infrastructure more broadly, as well as resources that could facilitate this transition, including power storage facilities, smart grids and electric vehicles (EV).

The empirical research has revealed that this is often viewed by industry actors as a major market opportunity for the BIPV sector (see Sections 6.1 and 6.4). The cross-firm analysis and the case studies investigated how a range of firms (e.g. Ascent, Hanergy and Heliatek) have responded to this development by focusing their strategies on potential synergies with the EV sector (see Section 7.3 and Subsection 8.3.3). In addition to these short-term opportunities, the potential transition to a decentralised power system highlights the long-term significance of the BIPV sector, due to the limited number of renewable energy technologies that can be integrated in urban environments.

The BIPV innovation system has also been shaped by developments within the PV industry and other industries that are not directly related to the BIPV sector. For example, technological breakthroughs in the overlapping semi-conductor industry have offered knowledge spillovers regarding c-Si wafer production and handling. The availability and cost of feedstock materials on the other hand has historically driven the manufacturing paradigm towards either c-Si or TF technologies, also affecting the technological characteristics of available BIPV products. At the industry-level, tensions including international trade regulations and bilateral disputes have shaped the geographical configuration of the globalised PV supply chain, also affecting changes within BIPV end-markets and policy systems (see Subsections 6.4.1, 7.1.1 and 7.1.2). Finally, the current economic downturn has had a detrimental impact on the construction sector, and by extension the integration of PV in both new and retrofit buildings, while increasing electricity prices have made the value proposition of BIPV more widely appealing (see Subsection 7.2).

Overall, markets within the BIPV sector have been affected by developments in the socio-economic environment to a much greater extent than by the techno-economic characteristics of the involved products. In other words, it can be argued that contextual processes have played a more prominent role in the deployment of BIPV innovation than system-internal dynamics, especially in the short term [Candelise *et al.* (2012); Gross *et al.* (2012)].

F10: Legitimation

Social acceptance of a new technological sector is a crucial process driving not only market adoption, but also deeper infrastructural and institutional changes, crucially affecting its integration within the incumbent configuration. In the original TIS framework, the *legitimation* function is used to address not only the level of social legitimacy of the system, but also its compatibility with the socio-economic regime (see Subsection 2.3.2). The dynamic relation of the BIPV innovation system with the established configuration was regarded particularly crucial in this research, and is therefore also reflected in {F8 and F11}, using respectively a niche- and regime-based perspective.

The PV sector has received significant attention within the renewable energy domain, due to technological breakthroughs and policy intervention that have rendered certain applications suitable for wide market diffusion. Although the public image of the sector has been challenged multiple times (e.g. consolidation, trade wars, costs and markets fluctuations), national deployment strategies show that PV is currently regarded as a crucial component of the ongoing sustainable energy transition (see Subsection 7.1.2 and Section 7.4).

The empirical research revealed a consensus among stakeholders along the value chain that BIPV is not recognised as a sector with particular technical and socio-economic characteristics, but rather as a market segment of the PV industry (see Sections 6.3 and 7.5). This is mainly reflected in the regulatory framework developed for the support of PV systems, which usually lacks any explicit provision for adoption of BIPV systems, impeding the development of a common vision for the sector (see Section 6.3 and Subsection 7.1.1).

It has been discussed earlier that the level of attention drawn towards BIPV within policy frameworks is country-specific and depends on a range of national techno-economic processes. This regulatory focus also impacts the profile of the sector within slowly-changing *soft institutions*, including established practices and user preferences. As was suggested by the Polysolar case-study, the relative neglect of BIPV in the renewable energy strategy in the UK until recently, has impeded the development of a supply chain, and has delayed the deployment of otherwise significant R&D activities into the market (see Subsection 8.3.4). On the other hand, early policy support in Germany, France and Italy stimulated not only the development of markets, but also the formation of advocacy coalitions and networks, as well as the involvement of architects, engineers and end-users (see Sections 7.1.2).

On a technological level, the close association of the PV sector with first-generation c-Si technologies has arguably been negative for the BIPV sector. The extraordinary performance of these technologies in terms of efficiency improvement and cost-reduction have created high expectations regarding the potential of the sector, and has laid pressure on technologies with slower learning rates, including TF and OPV (see Subsection 6.1.1). On the other hand, the dominant market position of c-Si glass modules has established a stakeholder perception that PV systems do not have sufficient visual and formal flexibility to be widely integrated in buildings (see Subsection 6.3.2).

In the short term, this negative perception has impacted the attitude of certain societal groups including the construction and the architectural community, as well as their involvement in the BIPV sector. According to stakeholders within the construction sector and end-users, BIPV adoption in the future is expected to depend on the availability of applications in a range of colours and shapes. This will require the development of multiple new materials from manufacturers, as well as the communication of available products to the market-deployment community through demonstration projects, broader involvement of industry and trade associations, education centres and incumbent companies with established supply chains and marketing channels (see Section 7.5).

F11: Tensions in the incumbent configuration

According to the extended-TIS method adopted by this research, the transition of the BIPV innovation system from a niche status to an established sector integrated in the socio-economic regime requires not only a certain level of market cumulation and maturity, but also a degree of instability at the incumbent configuration. This function was introduced to the extended hybrid framework in order to address different tensions at the regime level that may create *windows of opportunity* for accelerated diffusion of certain applications. These are often highly country-specific, relating to both *hard* and *soft* institutions (see Subsection 9.2.3).

The first major tension in the energy system has been the oil crisis in the 1970s which allowed for growth in the PV sector (see Subsection 7.1.1). However, the most prominent tension in the established configuration within the energy and construction sectors has been the aligned support of sustainable energy systems and low-carbon buildings respectively since the late 1990s (see Section 7.4). This trend challenges entrenched practices within both industries, providing space for market deployment of BIPV applications.

In particular, the establishment of binding targets regarding the contribution of renewable resources to the overall energy mix challenges the incumbent energy regime in a direct and explicit way. The achievement of these targets will require the diffusion of a multitude of sustainable power systems with different characteristics, depending on regional techno-economic and social features. A large number of countries have developed prescriptive frameworks that steer this diffusion process (see Section 7.4).

On the other hand, building regulations regarding the decarbonisation of the construction sector have provided a more implicit opportunity for the deployment of BIPV technologies. For example the requirement for near-zero-carbon new buildings in various countries stimulates the adoption of distributed energy systems integrated in urban structures, as well as measures to increase energy efficiency (see Subsections 7.4.1 and 7.4.2). The examination of the UK BIPV sector has shown that the impact of such regulations on market stimulation has been rather limited up to now. The impact of more specific measures that are planned to be introduced in the next few years could provide useful insights in the future (see Section 7.5 and Subsection 8.3.4).

An additional opportunity for deployment of BIPV systems is the development of ancillary distributed energy resources. Electric vehicles and smart grids are able to increase the value of solar electricity through temporal storage of the generated power (see Section 7.2). The increasing adoption of such technologies requires significant reconfiguration of existing infrastructure, and the potential transition towards a decentralised power network. In many countries (including the UK), such a transition is considered to be a rather costly and conflict-laden pathway, and therefore, the nature and timing of this *window of opportunity* is still not clear.

F12: Influence on the direction of search

This TIS function is designed to reflect the level, sources and directionality of influences on the knowledge development processes. It addresses pressures from the socio-economic landscape level to the innovation system, that shape gradients of change in behaviours and practices, and facilitate the emergence of certain technological trajectories. As such, it is highly related and has a significant effect on other functions of the innovation system, e.g. the *development of formal knowledge* {F1}, the *mobilisation of resources* {F6} and the *legitimation* of the sector {F10}. However, in this research, the function is used to reflect more on how these top-down tensions shape technological development within the BIPV sector, rather than market diffusion, which is addressed in the *market formation* function {F7}.

Although several developments in the wider energy and construction industries have indirectly aided the BIPV sector in terms of directing resources and creating markets, the empirical research did not reveal any coordinated support explicitly directed towards knowledge creation within the sector. Nevertheless, research activities related to the BIPV sector have been stimulated and sustained through public funding at the international and most prominently, the national level.

In Europe, R&D investment on efficient, reliable and cost-competitive solar energy systems has been facilitated through the 6^{th} and 7^{th} Framework Programme for Research (FP6 and FP7) from 2003 to 2013, while Horizon 2020 is expected to continue the support through 2020 (see Subsection 7.4.2). Despite this trend towards the support of sustainable energy, fossil-fuel technologies still receive the largest amount of public financial support, which amounted to $548 billion in 2013 worldwide, more than four times the amount invested on renewable energy. In the USA, R&D expenditure on all renewables collectively has been historically lower than the respective expenditure on both nuclear and coal technologies (see Subsection 7.4.3).

The development of TF and OPV technologies, which are more relevant to the BIPV sector, has mainly been supported through academic consortia. However, a high degree of uncertainty with regards to the optimal technological paradigm, and the lack of prevailing product designs, has led to a diverse R&D funding system. In the UK this is evident in the wide scope of the SUPERGEN projects, as well as the National Solar Centre (NSC) (see Section 7.5). The Polysolar case study provided further insights regarding the functioning of industry-academic partnerships in the UK (see Subsection 8.3.2).

On the other hand, the Solyndra case-study revealed the potential dangers involved in the public support of particular firms or technologies. Despite the initial positive effect on the TF PV sector, the overall effect of *picking winners* in the case of Solyndra was detrimental for the public image of the industry after the well-documented bankruptcy of the company. Subsequent state support for radical clean energy innovation in the USA has been rather conservative, contributing to the ongoing consolidation within the PV industry (see Subsection 8.2.2).

Overall, the empirical evidence suggests that the BIPV sector is missing the wide range of materials and applications required by the market diffusion community within the construction sector. Experimentation with novel technologies by firms can be a means of generating variety within the sector {F3}. However, by collectively examining BIPV R&D activities, it can be argued that the coordinated steering of fundamental innovation towards particular paradigms could further aid the product development process.

9.4 BIPV transition dynamics

Sections 9.2 and 9.3 presented an analysis of the BIPV innovation system using an implementation of the extended version of the TIS framework developed for this research. Findings from the literature and empirical research were organised and related to the structural and functional characteristics of the system, in order to reveal the more discreet processes that shape innovation. In the following paragraphs, innovation dynamics identified across the different functions are synthesised, and potential pathways of technological transitions over time are identified, in order to offer a more condensed and higher-level perspective.

Changes at the socio-technical configuration occur when the established *regime* is challenged, and new technological trajectories are formed. The regime may be challenged by internal tensions or contextual pressures from the *landscape* level. The new trajectories on the other hand may come about through the readjustment of activities within the regime, or the incorporation of new elements from emerging niches (see Subsection 3.3.1) [Geels (2002, 2004); Schot and Geels (2008)]. Therefore, in order to identify potential transitions at the BIPV socio-technical system, three separate dynamics need to be assessed: top-down tensions from the energy and construction industries, the level of stability at the regime level, as well as the degree of maturity and cumulation of niches [Geels and Schot (2007); Verbong and Geels (2010)].

Following the application-based framing introduced in Section 9.1, the emerging BIPV innovation system can be seen to encompass market and technological niches within the renewable energy and construction sectors [Markard and Truffer (2008a)]. The assessment of the techno-economic domain outlined in Chapters 6 and 7 revealed that most of these niches are still in a formative phase, not yet able to compete under normal market conditions without institutional protection {F8} [Kemp (1994); Bergek *et al.* (2008a)].

At the technological level, the empirical research revealed a high number of such niches, which can be attributed to the broad knowledge base {F1}, the lack of standardisation {F2} and diverse public research-funding system {F12} that have allowed for experimentation on a wide range of materials and applications {F3}. Most of the technologies (e.g. CIGS, DSSC and OPV) are at the first stages of commercialisation and therefore, compete for institutional support and resources. C-Si is the only technology that has demonstrated a certain degree of maturity in terms of market share and cumulative learning [Geels and Schot (2007)]. Although it is arguably not the optimal technology for building-integration, its prominent position within the PV sector has allowed for significant deployment in certain BIPV market segments {F8}. Additionally, its extra-ordinary techno-economic evolution puts pressure on other technologies with slower learning rates, isolating them from resources and creating tensions at the niche level of the innovation system.

The dominant position of c-Si in the PV sector was challenged in the mid 2000s when fears for a feedstock bottleneck crisis almost *de-aligned* the industrial architecture {F9}. Although manufacturers and developers of emerging TF and OPV technologies and applications attempted to *substitute* the technological paradigm by deploying a range of new products and attempting to ramp-up their production, the level of maturity was not sufficient to establish their presence in the new socio-technical configuration {F3 and F8}. Incumbent manufacturers demonstrated organisational ambidexterity by adjusting their manufacturing capacities and restructuring their supply chains, driving the *transformation* of the sector rather than a more radical transition {F4} [O Reilly and Tushman (2004); Tushman *et al.* (2006); Geels and Schot (2007)].

With respect to markets, a similar level of fragmentation is observed. The construction sector allows for a multitude of BIPV applications (e.g. roofs, facades and glazing), most of which are not easily replicable under the current supply chain configuration and therefore, do not have the potential for high rates of market deployment {F7}. The current dominant design of flat-plate glass modules applied on roofs offers the least disruptive option to building developers and therefore has been able to establish a significant market presence, incorporating within the incumbent socio-technical regime {F8} [Schot and Geels (2008)]. On the other hand, it has also been instituted within industrial practices (e.g. equipment patterns and manufacturing processes), hindering the expansion of other product designs {F2}.

Other technological and market niches associated with the wider socio-economic domain also interact with the BIPV innovation system in an either antagonistic or complementary way [Markard and Truffer (2008a)]. For example, emerging sustainable power systems and energy-efficient technologies compete for the same resources (e.g. investment capital, infrastructure and public funding for R&D), which are allocated for the decarbonisation of the energy and construction sectors {F7 and F12}. In the UK, the regulatory focus on particular technologies that are considered more suitable for the national energy system (e.g. off-shore wind power) has historically impeded the support of the PV and BIPV sectors.

On the other hand, the diffusion of a range of distributed energy applications (e.g. smart grid applications and electric vehicles) expand the economic and social value of BIPV systems by enabling users to better utilise their generated power {F7 and F9}. Distributed technologies also collectively drive the potential transition of national power systems towards a more decentralised paradigm. Drawing upon the typology of Geels and Schot (2007), this transition can be considered to follow a *reconfiguration* pathway, due to the requirement for substantial changes in the power grid architecture, and the adoption of a range of radical technologies. The extent of this socio-technical reconfiguration is a highly debated issue, due to its contested long-term technical and economic implications.

At the landscape level, a range of technology-external processes drive transitions within the socio-technical configuration and collectively shape the evolution of the BIPV innovation system [Geels (2002); Schot and Geels (2008)]. The particularity of the sector is that innovation patterns are affected by dynamics in both the energy and construction industries, as well as developments within the wider economic environment.

Increasing environmental awareness about anthropogenic climate change and concerns over the availability and security of conventional fuel sources have been driving the shift to an energy system with high contribution of renewable energy sources. This long-term *reconfiguration* of the energy sector has been driven by policy interventions at the national and international level {F7 and F12}. Although it is widely accepted that the transition will require the adoption of a range of different technologies, the contribution of each one will depend on their respective techno-economic characteristics, as well as regional features. For example, the adoption of BIPV systems has been much wider in countries with decentralised power networks (e.g. Germany and Denmark) but also in countries with landscape pressures targeted on BIPV growth (e.g. France and Italy) .

A similar, though less disruptive transition in terms of institutional and infrastructural change, is also experienced by the construction industry, where an incremental shift is supported towards a lower-carbon building paradigm {F11}. The identified transition pathway in this case is that of *transformation*. The adopted innovations from the niche level demonstrate more symbiotic characteristics and do not challenge fundamentally the existing socio-technical architecture [Geels and Schot (2007)]. For example, the incorporation of sustainable building materials, or active renewable energy systems including PV in buildings requires moderate changes in the respective supply chains and the cultural patterns embedded in the construction sector.

The empirical research suggests that within the time frame investigated by this research, this transition process has been rather slow. Pressures from the landscape level have been rather mild and not coordinated {F11}, while there has not yet been evidence of mature niches that could be readily adopted in a large scale {F8}. On the other hand, the construction regime demonstrates a high socio-technical stability, with well-established codes, regulations and *soft* institutions that are resistant to change. The introduction of further regulations for the decarbonisation of the construction sector in the next few years might (by some) be expected to eventually trigger architectural adjustments and lead to a more fundamental *reconfiguration* transition, in which BIPV applications could play a substantial role [Geels and Schot (2007)].

Finally, in addition to processes that cause instability at the incumbent socio-technical configuration and create windows of opportunity for adoption of BIPV applications, landscape tensions also affect dynamics directly at the niche level {F9}. Macro-economic processes (e.g. wide economic downturn and international trade competition) have had a significant impact on the formation and growth rate of niches, throughout the last ten years. For example, the ongoing consolidation in the PV industry and the declining construction sector in many countries are driven to a certain extent by exogenous causes. Both processes influence agency within firms, altering their business models and accelerating the selection environment that shapes technological trajectories and bottom-up transitions at the regime level {F3 and F4} [Markard and Truffer (2008b); Geels (2013)].

9.5 Summary and conclusions

The empirical research provided a plethora of (mostly) qualitative data related to innovation processes within the BIPV sector. The structural and functional methodologies outlined in the novel cross-disciplinary framework were implemented here to organise the evidence in a meaningful way from an analytical point of view. This practice provided a broad range of insights regarding particular functionalities within the innovation system, as well as its overall performance.

The main findings were synthesised in order to reveal systemic dynamics at different levels. The MLP approach was then used to assess the dynamics, link them to wider processes within the socio-technical configuration, and identify their role in potential transitions, drawing upon the typology of pathways within the MLP literature.

In the following chapter, overarching themes across this analytical synthesis will be highlighted, with particular emphasis on their research and policy implications.

Chapter 10

Summary and Implications

Introduction

Chapter 9 outlined the analytical synthesis of the empirical evidence regarding innovation dynamics within the BIPV sector. It implemented a hybrid framework for the identification of patterns within the innovation system. This chapter extends this analysis by consolidating these findings into themes that can be generalised to provide empirical and methodological implications.

Section 10.1 outlines overarching themes identified throughout the analytical synthesis, and links them to wider discussions regarding innovation dynamics in hybrid sustainable technologies.

Section 10.2 reflects on the implementation of the hybrid empirical and analytical methodologies, aiming to assess how successful the cross-disciplinary approach has been in practice.

Finally, Section 10.3 discusses the overall theoretical and empirical contribution of this research and identifies potential opportunities for further work.

10.1 Overarching findings and policy implications

The examination of innovation dynamics within the BIPV sector revealed a complex system comprising a multitude of technological and market niches, socio-technical regimes and landscapes. The high level of complexity does not allow for straightforward answers regarding the functionality of the innovation system. However, throughout the analytical synthesis of the multi-level literature and empirical findings, overarching themes and recurrent patterns emerged, which highlighted certain characteristics of the innovation dynamics within the system. The analysis of these dynamics has direct implications to policy design with regards to the support of the development and diffusion of BIPV innovation.

10.1.1 Hybridity

One of the most repeated observations throughout the analysis of the BIPV innovation system, and possibly its most prominent feature, is the co-existence of diverse elements from the PV and the construction industries. The two sectors comprise distinct supply chains and stakeholder communities with different knowledge bases, metrics, priorities and visions for the future of BIPV. Most importantly, they are associated with either of the two fundamental functions of the innovation system, which are the development and diffusion of technology, causing a characteristic disjuncture along the innovation process [Carlsson and Stankiewicz (1991)].

Development of innovation

At the one end is the PV sector which specifies the technological trajectories with regards to materials and manufacturing processes. Most of the industrial actors within the BIPV sector originate in the PV industry which has expanded significantly in the last two decades along with the wider energy reconfiguration to a more sustainable system {F3} (see Subsection 9.2.1). The PV sector also defines to a great extent the upstream supply chain of BIPV, sharing with it production equipment, facilities and certain distribution channels.

The BIPV sector has partially benefited from its high affinity to the relatively mature PV industry. The extra-ordinary growth in mainly the global ground-mounted PV market segment has driven substantial learning processes and cost reductions in modules and other system components {F1 and F2}. It has also increased the collective legitimacy of the technology, allowing for the involvement of major industry actors and the mobilisation of public funding, investment and other resources towards the sector {F6 and F10}.

However, there is empirical evidence that the association of BIPV with the mainstream PV sector has also had several negative implications on the development and support of innovation. For example, the traditional focus of manufacturers on the power performance of the systems favours incremental innovation, rather than the development of radical products with new characteristics, which is a primary concern among architects and building developers {F7 and F8} (see also Subsection 10.1.2). On the other hand, BIPV are disruptive applications, challenging not only the widely established configuration of centralised power grids, but also well-entrenched practices within the construction sector. The traditional paradigm of *market-pull* mechanisms that has been very effective in the development of more incremental technologies (e.g. ground-mounted), has not been able to drive growth in market segments that require significant institutional changes, highlighting the need for more granular policy design {F7} (this issue will be further discussed in Subsection 10.1.3).

Deployment of innovation

At the other end of the innovation process is the construction industry, which defines the rules regarding the diffusion of products into the market. Building regulations, attitudes within the architectural community and well-established empirical routines dictate the required specifications of BIPV applications, as well as the physical and cognitive rules regarding their installation and use. In contrast with the globalised character of the PV industry, these rules are very context-dependent in nature, and depend on national characteristics and cultures, deterring the standardisation of products and practices at an international level {F8}.

Priorities and common practices within the construction and PV communities are often different. Prominent deployment issues include the compatibility of BIPV with other building materials, the seamless integration within urban environments and the replicability of systems. Overall, the construction sector is more interested in the *societal embedding* of BIPV innovation, rather than *technological learning* which is the primary focus of the PV community. Additionally, metrics used in the sizing and costing of applications are often different from the ones used in the energy sector (e.g. system sizing on a basis of either m^2 or kWp). The lack of a common knowledge base and BIPV literature, as well as trade networks and associations specific to the sector, impedes the communication of these issues to PV manufacturers and product developers {F1 and F5}.

Systemic failures

The empirical research and analysis revealed that the composite nature of the BIPV sector could be related to systemic imperfections that block innovation processes within the BIPV sector [Klein Woolthuis *et al.* (2005)].

The disjuncture of the development and deployment phases of innovation prevents the cooperation of different actors, reflecting a type of *interaction failure*. Due to these weak communication networks, complementarities in terms of knowledge and skills are under-utilised, and possibilities for interactive learning are curtailed [Carlsson and Jacobsson (1997)]. Technology developers on the one hand fail to create the product range required for wider adoption, while the construction community is not able to adapt to technological developments. Limited interaction also hinders the development of a common vision for the future of the sector and the coordination of efforts, which is necessary in order to change institutions and stimulate growth [Jacobsson and Bergek (2004)]. Therefore, BIPV policy intervention will only be effective if this interaction is established.

Furthermore, the cross-sectoral character of BIPV innovation causes difficulties with regards to its characterisation and classification, which has direct implications on policy design. Relevant policy frameworks are targeted at either the energy or the construction sectors, overlooking the specific socio-economic characteristics of BIPV applications. This form of *hard institutional failure* impedes the development of differentiated technological capabilities that are essential for further growth in the sector [Klein Woolthuis *et al.* (2005)]. Understanding the complexity of the sector is important in the design of innovation policy, and it is in the interest of the actors, and the research community in particular, to communicate this complexity to the policy community [Watson (2008)].

These findings reflect wider issues related to innovation dynamics in hybrid technological domains. The difficulties in characterising innovation in conventional terms render necessary the use of new methods for its assessment and governance. These methods need to address the high level of inherent complexity, the relative disruptiveness of the associated applications, as well as the additional institutional barriers faced by hybrid technologies. Finally, the separation of the development from the deployment phase of innovation in the BIPV system evokes more linear models of innovation, and contributes to the discussion regarding the need for intellectual renewal within innovation and transition studies, a theme that will be further explored in Subsection 10.2.3.

10.1.2 Diversity

The BIPV sectoral assessment outlined a broad technological domain with a wide range of options and materials being under development {F1}. However, the empirical research also revealed that there is a constant need in the market for a range of products with different visual and formal characteristics, including colours, shapes and textures. Hence, there is evidence that despite extensive experimentation at the primary R&D level, there is a limited number of radical innovations achieving commercialisation, which suggests potential technological and systemic problems {F3 and F7}.

Technological lock-out and accelerated innovation

At the technological level, cSi is the most mature PV technology, benefiting from a long R&D and industrial tradition in both the energy and integrated-circuit sectors [Green (2000); Bagnall and Boreland (2008)]. However, due to their technical characteristics, cSi products have a limited potential for building-integrated applications {F1 and F7} [Hardy *et al.* (2012); SHC (2013b)]. The early dominant position of cSi in the PV industry has triggered a particular *lock-in* phenomenon, where the arguably suboptimal technology has also become the dominant design in the BIPV sector [Unruh (2000); Green (2006)].

Despite the wider flexibility of their applications, thin-film (TF) and organic PV (OPV) technologies have not been able to establish an industrial and market presence. The manufacturing base remains rather fragmented, with no dominant designs in either the technological or the corporate strategy level {F8}. This type of *capabilities failure* from TF and OPV system developers can be attributed to inherent problems of the technologies, which have not been able to demonstrate a learning rate comparable to that of cSi. However, it can be also due to an *interactions failure*, where the very strong network around cSi causes the exclusion of these technologies from investment capital and other resources, and does not allow for scaling-up of production and incremental improvements [Carlsson and Jacobsson (1997); Klein Woolthuis *et al.* (2005)].

The historical analysis of the industrial domain using the *hype-disappointment cycle* notion developed within the 'sociology of expectations' literature provides a similar perspective of this *lock-out* of TF and OPV technologies [Borup *et al.* (2006); Verbong *et al.* (2008)]. The potential for significant cost-reductions and abundance of materials created an initial hype towards the new technologies, which peaked during the cSi feedstock bottleneck in the mid 2000s. A series of high-profile corporate failures (most prominently that of Solyndra), as well as the re-establishment of the cSi technological trajectory triggered the disillusionment of stakeholders and suggested that the technologies where not as market-ready as they were thought to be. The future viability of the technologies will depend on the capability of the remaining industrial actors to demonstrate their applicability and long-term significance in existing and emerging markets (including BIPV). It will also depend on the effectiveness of policy in moving specific technologies from the pre-commercial phase to full commercialisation, and address the danger of *locking-out* more advanced but less well-developed sustainable technologies [Foxon *et al.* (2005); Sandén (2005)].

Consolidation and Strategic adaptation

The assessment of the PV sector outlined a turbulent and conflict-laden environment at both the industrial and the market level. A wide consolidation process has driven over 100 firms to some form of restructuring, bankruptcy or acquisition during the last five years, while international trade wars have impacted the globalised supply chain and the geographical distribution of markets.

The analysis of the industrial consolidation revealed a distinctive dynamic, where the cumulative share of the top 10 manufacturers has dropped significantly, while the share of the top 50 and 100 has increased [Mints (2014c)]. This process of more companies capturing a high share of the market suggests that no clearly defined business models have emerged as dominant paradigms within the sector {F4}. On the other hand, the loss of small companies, which are the main source of diversity in the sector, highlights the negative impact of this process on emerging technologies and market segments {F3}.

The firm-level examination of business strategies revealed a high correlation of corporate success and strategic adaptation (e.g. restructuring operations upstream or downstream along the supply chain). For a firm to sustain growth within this turbulent environment, a high degree of organisational ambidexterity is required, in order to exploit its existing capabilities and form new competences {F4} [O Reilly and Tushman (2004); Tushman *et al.* (2006)]. This strategic ambiguity can be very demanding for small firms which have limited access to resources.

Therefore, there is empirical evidence that in order to achieve technological variety in the BIPV market, differentiation needs to be stimulated through sustained policy intervention not only in the early phases of primary research, but also throughout the formation and growth of markets. This will require the creation of technological and market niches where radical innovations are protected from the cost-reduction imperative and other socio-technical selection tensions [Smith *et al.* (2014)]. Furthermore, a long-term policy support strategy will be able to provide security to investors, and foster diversity [Fuchs and Wassermann (2008)].

10.1.3 Disruptiveness

BIPV systems can be characterised as disruptive applications, challenging the incumbent socio-technical configurations in both the energy and construction sectors. On the one hand, their wide adoption will require the reconfiguration of the power grid towards a more decentralised paradigm, which implies significant infrastructural changes in many energy systems. Additionally, it will require the adaptation of the supply chain and the established practices within the construction sector.

Both the energy and construction sectors are rather conservative and risk-averse industries, where disruptiveness is not welcome. In the absence of significant exogenous tensions, the incumbent configuration would sustain its socio-technical reproduction [Geels and Schot (2007)]. However, environmental and economic processes have driven sustainable transitions in both sectors. These transitions are shaped by policy intervention at different levels {F11}.

In the energy sector, reconfiguration towards a system with high penetration of renewable energy systems has been driven by international directives that define specific targets for their contribution. In the past, innovation in the sustainable energy sector was supported mostly through public R&D investment {F12}. However, the binding character of these targets created an imperative for swift deployment, and led to the implementation of a range of *market-pull* mechanisms at the national level {F7}. This urgency of deployment has historically favoured applications that are scalable and require minimum infrastructural change. Furthermore, market incentives aided the deployment of technologies which demonstrated the highest commercial maturity at the time of introduction.

Both these dynamics have tended not to support the adoption of disruptive technologies, including most BIPV applications, which are neither easily-replicable at the moment (in terms of standardisation of system design and deployment), nor compliant with the incumbent energy and construction systems. Short-term policy design has not allowed for the realisation of the potential long-term significance of BIPV in the decarbonisation of both the energy and the construction, suggesting an *infrastructural failure* of the innovation system [Klein Woolthuis *et al.* (2005)]. Demonstration projects and field trials could play here a crucial role in providing evidence with regards to BIPV potential and benefits, which could in turn inform technology developers, architects, regulators, and policymakers {F2}.

The construction sector is also experiencing a transformation along a more sustainable pathway. International directives have driven the development of policy frameworks around the world at different levels of policy (e.g. regional, national, EU) which reflect an imminent need for low-carbon buildings, and by extension, the integration of distributed renewable energy systems in urban environments. The austere economic environment on the other hand has contracted the mobilisation of resources towards the construction sector, and has imposed stringent investment criteria on sustainable technologies, which are based on the cost structure and calculated risk. Again, this development hinders the adoption of disruptive applications, which complies with the observation that wider framework conditions are often more important than internal developments in shaping innovation dynamics, especially in the short-term [Candelise *et al.* (2012); Gross *et al.* (2012)].

This adds to the ongoing debate regarding the relative regulatory emphasis on either *technology-push* or *market-pull* mechanisms, and their implications for innovation strategy and governance [Winskel *et al.* (2014b); Winskel and Radcliffe (2014)]. Proponents of the former, call for more support on R&D activities which are long-term and globally-relevant, in order to trigger *learning-by-researching* affects [Moselle and Moore (2011);

Helm (2012)]. However, the counter-argument here is that such an approach would have limited impact on system change without sufficiently strong *learning-by-deployment* support mechanisms, which would allow for technology cost reductions [AEIC (2011); Gross *et al.* (2012)].

The development of a more granular, combinatory and long-term policy strategy could be more effective in the support of BIPV innovation. Targeted and customised innovation support that reflects the conditions and latent opportunities of the technology has in the past proven effective in the support of renewable energy applications [Fuchs and Wassermann (2008)]. The design of such a strategy would require the combination of support mechanisms within the energy and construction sectors, and the coordination of interventions at all policy levels. It would also need to take into account synergistic distributed energy resources, including electric vehicles and smart grid applications.

10.2 Reflections on the research methodology

This section reflects on the empirical and analytical methods developed and applied in this thesis, and their effectiveness with regards to capturing dynamics within complex innovation systems. By highlighting its strengths and weaknesses it also explores the potential for implementation of the methodology for the assessment of analogous systems in the future.

10.2.1 Empirical research methods

The multi-layered approach used for the collection of literature and empirical evidence was designed to provide data at different conceptual levels and using different perspectives (see Section 5.3). It involved four distinct methodologies which were not implemented consecutively, but rather intertwined to provide complementary insights.

Academic literature was primarily used for the development of the cross-disciplinary analytical framework. Early on the research design, it was identified that the research problem is complex and open to multiple perspectives and interpretations. Therefore, it was considered more disciplined and scientifically robust to approach it using multiple strands of academic literature. Although the merging of different conceptual and analytical methodologies was often challenging in practice, its implementation for the analysis of the hybrid BIPV sector demonstrates the benefits of combining elements in reducing respective weaknesses of the approaches (e.g. overcoming myopia in the TIS) and the overall added value of the synthesis (see also Subsection 10.2.3).

Academic literature was also used for the understanding of the technical characteristics of the PV domain, as well as different policy frameworks and economic attributes of the socio-economic context. In spite of its breadth and scientific significance in the historic analysis of these aspects, this literature was not able to capture contemporary industrial and market developments within the rapidly changing BIPV sector.

In order to address these dynamics, the *industrial literature* was investigated extensively throughout the time-frame of the empirical research. In addition to trade journal and periodicals, a range of web-based resources were used to inform the research regarding technological advancements, cost and price fluctuations and processes within the globalised supply chain. Although the volume of information from these resources was often overwhelming, it offered the opportunity of triangulating findings and deepening the understanding of the sector. It also helped in overcoming the challenges involved in investigating an emerging and dynamic object.

This understanding was further expanded through *personal communications* and *networking* with academics and industry actors. The SUPERGEN PV21 consortium and the multiple conferences, workshops and seminars attended, provided access to a network of specialists across the BIPV supply chain. The large number of contacts minimised the bias regarding empirical findings, while the temporal distribution of the communications facilitated the assessment of the historical evolution of the sector.

Semi-structured interviews provided a method for more specific, insightful and analytically valuable viewpoints from different stakeholders [Salant and Dillman (1994); Saunders *et al.* (2011)]. Identifying a representative sample and securing sufficient time to conduct the interviews with the identified actors proved to be very time-consuming tasks, involving an iterative process. The design of the generic questionnaire to be used on the diverse sample was also a challenging exercise, which required multiple revisions in order to facilitate the acquisition of the necessary empirical evidence and reflect the analytical framework [Lydeard (1991); Marigo (2009)]. In spite of these challenges, the methodology offered a systematic and analytically robust way of acquiring and coordinating empirical evidence at different levels, while the wide list of interviewees provided multiple insights across the BIPV supply chain.

Finally, *case studies* offered a platform for methodical analysis of agency within firms, which was a central element in this research, and facilitated the establishment of causal relationships among developments in the BIPV sector [Yin (2009)]. The framing of the two case-study clusters was designed to investigate how the dynamic environment affects strategic choices of firms with different characteristics. The Polysolar case on one hand offered the small-firm perspective and provided specific insights regarding the national-UK BIPV innovation system and supply chain. The Solyndra case widened the analysis to address the challenges faced by a large-scale BIPV company and the international developments within a globalised industry.

Solyndra's bankruptcy occurred during the conduct of the case-study and was one of the most significant events during the research. Initially, it was considered to be a rather negative development for the research, that would limit the access to interviewees and alter the overall time-frame of the study. However, the adaptation and redesigning of the case provided a compelling analytical opportunity to investigate the industry consolidation process and reflect on the turbulent evolution of the sector.

Maintaining both a comprehensive (global and national sector level) and a detailed (intra-firm level) perspective throughout the investigation of the BIPV innovation system was a challenging practice, involving multiple methodological tensions. It was often difficult to delineate developments and recognise underlying processes. In order to overcome this obstacle, the twelve indicators of the hybrid analytical framework (which is structured in different conceptual levels) were used throughout the empirical research to provide guidance and relative clarity with respect to the characterisation of innovation dynamics (see Subsection 5.2.3).

An additional challenge was the classification of the BIPV innovation system and the framing of the research problem. Initially, BIPV was approached as a distributed energy application, focusing on its technological characteristics and overlooking the high level of complexity, which is a wider problem in innovation policy [Verbong *et al.* (2008)]. The understanding of the hybrid character of BIPV only fully emerged in the course of the research. Earlier, full appreciation of this hybridity would have allowed for a more balanced treatment of BIPV as both an energy and buildings innovation, providing more empirical attention to the construction sector and the social embedding of innovation.

Nevertheless, the building-development community is still represented throughout the semi-structured interviews and case studies, reflecting its limited engagement in the BIPV sector.

10.2.2 Process Theory

The multi-method literature and empirical research provided a plethora of primarily qualitative data with different characteristics. In order to render this evidence useful from an analytical point of view, methods from the *process theory* approach were implemented. Narrative plots were constructed based on the data, with the aim of interpreting the evidence, and linking emerging patterns to wider analytical themes [Pettigrew (1990); Hekkert *et al.* (2007b)]. However, the development of comprehensive narratives was not possible, due to not only the high number of different stories that were included in the scope of this research (e.g. firm-level case studies, historical evolution of the BIPV sector and industrial diversification), but also the limited literature regarding the sector. Additionally, the aim of the research was not to provide a historical analysis of the BIPV sector, but rather selective analytical focus on its innovation dynamics.

According to this *event history analysis*, instances within the narratives related to the performance of the BIPV innovation system were linked to the analytical framework (see Subsection 10.2.3) [Van de Ven *et al.* (1999); Poole *et al.* (2000)]. Although the focus of the method on reconstructing event-chains could be criticised for neglecting causal factors by giving primary emphasis on output phenomena, the approach offered a practical methodology for the organisation, presentation and functional utilisation of the collected data.

10.2.3 Hybrid analytical framework

One of the aims of this research was to develop a framework that could be used for the analysis of innovation dynamics within the BIPV sector. The hybridity and high complexity of the BIPV innovation system called for the combination of analytical and conceptual elements across disciplines, and the assessment of innovation dynamics at different levels.

The Technological Innovation Systems (TIS) perspective was identified as the conceptual point of departure early on the research design process, due to its rich theoretical basis and well-established empirical base in the analysis of renewable energy technologies (see Subsection 2.3.6).

The approach has demonstrated many analytical strengths, including the ability to identify systemic weaknesses and suggest policy interventions (see Subsection 2.3.7). However, early consideration of the BIPV innovation system revealed a range of dynamics that could not be properly conceptualised and analysed by the standard-TIS framework. These dynamics mainly involve intra-firm agency [Christiansen and Buen (2002); Marigo (2009)] and the changing relation of the innovation system with its multifaceted socio-economic environment [Markard and Truffer (2008a); Winskel *et al.* (2014a)].

Responding to this perceived analytical weak spots, the expansion of the TIS framework using elements from different literature strands was considered, for the development of an original hybrid analytical framework. In order to address contextual processes and better reflect on transitional dynamics, the Multi-Level Perspective (MLP) was incorporated in the framing of the innovation system and the functional framework. MLP uses a nested hierarchy to conceptualise generation and development of niches (micro-level), stability of incumbent regimes (meso-level) and slow-changing contextual processes (macro-level) [Geels (2002); Schot and Geels (2008)]. In spite of its limitations, the approach facilitates the identification of different tensions within the innovation system, and links them to wider transitions in the socio-technical configuration (see Subsections 3.3.1 and 3.3.3).

On the other hand, elements from the Business Studies literature were used to provide a better account of firm-level (and especially firm-internal) dynamics [Porter (1980); Osterwalder and Pigneur (2010)]. These approaches are less reflexive in comparison to the TIS and MLP and were used as analytical tools in order to offer a better comprehension of the micro-economic drivers of innovation. The extended-TIS framework was used to outline the guidelines for the empirical research and the analysis of the BIPV innovation system at the UK and international levels.

The implementation of the original hybrid framework demonstrated a range of analytical strengths. The BIPV innovation system was positioned within its wider socio-economic environment, and dynamic links to the multiple landscapes were drawn and assessed. These links included influences from the construction industry, tensions in the energy sector and developments in the broader economic climate. Additionally, the complex interactions of various technological and market niches within the innovation system with external established and emerging configurations were highlighted (see Section 9.4). Strategic choices within firms were incorporated in the analysis, and were used to better understand their involvement in the development and diffusion of innovation.

The extended-TIS framework used in the functional analysis reflected this multi-layer framing of the system. Twelve indicators provided insights regarding its partial functionalities and interactions across sectors and conceptual levels. Although the co-existence of conventional-TIS functions with novel ones which were designed to reflect dynamics according to the MLP and BS was not homogeneous in formal and analytical terms, they offered complementary findings regarding the performance of the BIPV innovation system. Their combined analysis underlined recurrent patterns, reinforcing interactions and disruptive processes (see Section 10.1)

However, the application of the framework for the assessment of the BIPV system also revealed some weaknesses in the methodology, as well as the overall theoretical proposition to capture real-world innovation dynamics.

From a methodological point of view, although the use of *functions* facilitated significantly the guidance of the empirical research and the organisation of the evidence, it demonstrated some analytical weaknesses. Although the definition of the TIS-framework implies that functions within the innovation systems are delineated, the implementation of the method revealed a compartmentalisation issue when it was used in conjunction with the *event history analysis* method. For example, the knowledge creation function {F1} is used to identify learning processes which may originate in landscape intervention {F12}, developments in complementary innovation systems {F9} or advancements in the manufacturing equipment {F2}. Therefore, the allocation of the events identified in the empirical evidence to each function was sometimes ambiguous and counterproductive.

Although a demarcation of the functions was attempted by better defining their scope, some compartmentalisation problems remain in this research. The repetition of certain developments throughout the functional analysis (e.g. introduction of policy frameworks, diffusion of decentralised resources, industrial consolidation etc.) demonstrates this functionalist problem (see Section 9.3).

Additionally, the implementation of the framework revealed that, in the case of the BIPV innovation system (and potentially other systems as well), certain processes play a much more prominent role in the overall performance of the system than others [Hekkert *et al.* (2007b)]. This research better reflected on these processes through the addition of functions. For example, experimentation is a disruptive notion which is central to the evolution of the BIPV innovation system for creating diversity, not only in the early stages of R&D (as conceptualised by {F3}) but across the supply chain. For this reason, the business model innovation function {F4} was added to the framework, providing more analytical focus on the agency of more mature system actors.

Furthermore, the use of a functional approach in the analysis of innovation dynamics implies a highly systemic character of innovation. However, one of the overarching findings in this research was the separation of the development phase of BIPV innovation from the deployment phase. This particular disjuncture reveals a less systemic behaviour, and suggests more linear approaches for both the assessment of innovation and policy design (see Subsection 10.1.1).

Finally, several concepts within the structural and functional analysis often implied a harmonious innovation process, mainly those related to knowledge development, learning processes and market growth. Despite the conceptual expansion of the framework, the turbulences and conflicts of real-world dynamics revealed by the empirical research were not always appropriately reflected in the methodology. In reality, the emerging BIPV sector is not just a collection of niches trying to grow and be accommodated within the established energy and construction regime [Smith *et al.* (2010)]. This process is affected by many wider socio-economic dynamics and involves a range of disruptive reconfigurations of established rules and practices, forces which develop over different timescales. This research addressed these dynamics by using elements from the transitions typology for the re-assessment of the main findings of the structural and functional analysis (see Section 9.4). In that way, the disruptiveness of BIPV applications was assessed and the significance of BIPV innovation was evaluated in both the short and the long term.

Overall, the complexity of the BIPV sector and the involvement of socio-economic structures with very different characteristics and hierarchies, render the innovation system very difficult to classify, and challenge any analytical presumption that innovation dynamics can be fully understood and predicted. However comprehensive a conceptual framework may be, it remains an abstraction of reality with finite analytical capabilities. Nevertheless, the combination of approaches can help overcome common known respective weaknesses. By better reflecting complexities, tensions and synergies, found in the empirical evidence, the framework developed here offers a promising way forward for innovation studies' analysis of emerging sustainable technologies.

10.3 Contribution and further research

In this section, the overall contribution of this research with respect to both the empirical assessment of BIPV innovation dynamics and the theoretical discussion on methodology will be reviewed, and suggestion for further research will be drawn.

10.3.1 Empirical contribution and further research

With regards to the BIPV innovation system, the first contribution of the thesis is the hybrid framing of the sector. BIPV innovation in the literature is looked at using either the development perspective, which focuses on the incremental technological improvement of PV materials, or the application perspective, which focuses on the deployment of products in the construction sector. For the first time here, BIPV is framed as a hybrid innovation system, and dynamics are assessed with regards to interactions within both socio-technical systems. Future research using this hybrid framing could lead to the emergence of a common knowledge basis that would facilitate the communication among stakeholders, and the development of BIPV-specific policy.

A second major contribution of the thesis is the extensive empirical assessment of the BIPV sector throughout a crucial and turbulent period. The comprehensive coverage of developments at both the sector and the firm level contributes to the understanding of the sources of the consolidation processes within the industry throughout the last decade, as well as its implications on the future of the BIPV market in terms of diversity. Moreover, the investigation of the BIPV sector at both a global and a UK level revealed how national characteristics and policy at different levels affect the early diffusion of innovation. This research could be enhanced by the comparative analysis of multiple national systems, to provide further insights with regards to how international directives and regulations are interpreted in different ways, reflecting national incumbent interests, and what is the impact on innovation dynamics.

Furthermore, the research added to the discussion regarding the relative significance of incremental and disruptive innovation, and revealed the threat which is posed by the urgency for accelerated innovation to more disruptive innovations, including BIPV. This is where long-term transition management meets the hard realities of short-term political and business imperatives. The challenge for policy-makers, innovation sponsors and systems analysts is to keep these longer-term options open and viable, by representing them in scenarios, policy mixes and sustained funding support. Further research could investigate the potential development of a policy framework that will be able to facilitate the support for both types of innovation.

10.3.2 Theoretical contribution and further research

This research has been driven by a theoretical attraction to the analysis of complex innovation, as much as an empirical interest in the BIPV sector. The most prominent methodological contribution of this research is the development of a structured cross-disciplinary framework for the investigation of innovation dynamics in hybrid, emerging innovation systems.

The BIPV sector involves a boundary-spanning innovation system that cannot be easily classified using conventional approaches. The sector spans a range of applications and industries, while innovation dynamics are affected by developments at different levels, including a multitude of firms, markets and socio-economic landscapes. In order to address the complex character of the BIPV innovation system, this research developed and adopted a cross-disciplinary framework for the synthesis and analysis of literature and empirical evidence collected through the implementation of a multi-method approach.

The application of the hybrid framework on empirical evidence demonstrated how the combination of different approaches can facilitate the utilisation of their complementarities, and help overcome respective weaknesses. Although this amalgamation was often challenging due to incompatibilities and tensions among the approaches, the framework offers a realist, integrative perspective that is able to provide a fuller and more robust understanding of complex innovation dynamics. Its application on different empirical cases in the future will evaluate its effectiveness in the analysis of emerging sustainable technologies, and help its incremental improvement.

Along the same way, an emerging theme in innovation studies and sustainability policy-making is looking at spatial framings in a more integrated way, especially at the urban scale. This could be one way of overcoming the persistent divides which have been observed throughout this research between the energy and construction sectors, or the developer and deployment communities. Urban scales may allow greater scope for reconfiguring systems and crossing institutional boundaries than national systems, which tend to be entrenched around dominant vested interests and divides [Markard *et al.* (2012)]. Future research could explore how such a framing could contribute to the discussion regarding innovation in emerging sustainable technologies.

The research also revealed a need to accommodate both linear and network dynamics in conceptual framings within innovation studies. The literature review demonstrated the academic richness in the wider innovation and organisational studies literature (and also business studies) on themes such as the innovation chain, disruptive and incremental innovation, as well as more systematic and architectural innovation. This observation highlights the need to draw on these wider conceptual resources in order to overcome known limitations of current systemic and dynamic framings including the TIS and the MLP, calling for a wider intellectual renewal [Geels (2011); Markard *et al.* (2012)].

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Appendix A

Generic questionnaire for the semi-structured interviews

A.1 Questionnaire for Industry Actor

Generic for whole supply chain - delete parts as appropriate.

(Explanatory remarks and probes in paretheses)

Introduction-Background

- Thanks for agreeing to talk / for your time, ask if OK to record the conversation for own records.
- Introduce self and PV21 (one of the biggest government funded research groups on solar energy in the UK).
- Introduce project (understand the market potential of innovative applications, highlight the role of different groups in innovation processes and their networking).
- Purpose of interview (get informed on the techno-economic characteristics of systems, your views on the market status and the policy framework), your help will be a major contribution to our research.

Company/Organisation and Product Information

- What is your role? (position within company, background, interests)
- What is the organisation history of your company? (development since startup, ownership, financing, future) and size? (manufacturing/shipments)

- What are the specifications of your products? (see attached data sheet: model, technical-system info, environmental challenges, cost)
- Do you have any other parallel activities? (conglomerate, countries of activity, future plans)
- Do you conduct your own R&D? (collaboration with organisations)
- Do you own manufacturing facilities? (location, nominal capacity, annual yield, growth plans and time frame)
- What is the commercialisation status of your product (how much is demonstration/market material, available in Europe?, in the UK?)
- What is the time lag from lab to market?
- What is your corporate strategy? (focus on cost reduction by ramping up, new products, new markets)?
- In a scale where 1 is focus on cost reduction, 5 is focus on new products, or same products in new markets and 10 is new products in new markets, how would you grade the strategic orientation of the company?

Manufacturing, System Development, Deployment and Use

- Where are you positioned in the BIPV supply chain? Where do you source your materials/equipment/cells from and where are they sold to?
- Do you face any certain issues in the manufacturing/product development process? (materials, equipment, storage)
- What technologies and applications are you interested in and why? (current, potential)
- Which are your geographical targets and why? (performance in different environmental/light conditions)
- What are your target markets? (residential, commercial, utility scale) actors? (communities, proprietors) how much each? (%)

- Have you identified certain installation issues? (weight limitations, balance of system, inverter)
- Do you do your own installations? What is the time to complete a project? (domestic, commercial, industrial)
- Could you comment on the number of administrative/bureaucratic processes?
- What is the environmental and social impact of your systems? (local reactions, is it a barrier for deployment, solutions)
- What are the operation and maintenance requirements? (grid, system degradation, maintenance requirements)
- What is the expected product lifetime? Plans for end of life handling? Any recycling plans?
- Do you have performance results from case studies? (location, yield, implementation regulatory problems)
- Where is the potential for performance improvement?

Production and Installation costs

- Could you roughly breakdown the system cost? (% for various module and system components, labour)
- Which elements have a slower cost reduction rate?
- What is the expected ROI/payback time, have you calculated the levelised energy cost in a per kWh basis?
- How easy is to finance a project? Are there any certain investment issues? (cash availability, loans) Do you offer financing solutions to your clients in collaboration with banks?
- Which sector offers the highest profit margins? How much have these margins changed?
- What are further cost implications?

- What do you think drives the investment in BIPV in each sector? ROIs, environmental reasons, marketing tool within 'green' agenda?

Innovation System

- How do you assess the existing R&D in BIPV and the supply chain in general? Have you identified certain problems/potential improvements? Can you comment on the UK supply chain? Are any elements lacking, driving you to international partnerships?
- Is there diversity in the industry? How does the economic climate and policy affect that?
- Where do construction-industry actors (building industry, architects and developers) stand towards BIPV? How do they affect market diffusion?
- How do you assess the existing networks e.g. industry associations/organisations (BPVA, STA, REA, RIBA, BRE, EPIA) what more can be done?
- Where is most of the knowledge development happening across the value chain? Are there any spillovers from other industries? Where is the most potential for learning processes?
- What kind of innovation is needed? (sustaining - improving equipment/processes, or disruptive- new technologies/ materials/ applications)
- Is there competition with other renewable technologies for resources and capital?

International and UK Context

- What is your broad view of the UK energy sector? (conventional power generation, future energy mix, trends towards decentralisation and RES)
- How do you assess the international BIPV market? (current and future share/costs and most successful technologies/markets/applications)
- How does it compare with other emerging and established renewable technologies?

- How does the economic climate, the shift of manufacturing to China, the demand downturn and the bankruptcies in Europe affect the BIPV market and your business in particular?
- What is your view on the UK BIPV market? (maturity, competition, enablers and obstacles for private investment, synergistic/rival industries)
- What are the societal benefits of the BIPV industry (employment, increasing capital productivity) and how do they compare to other power industries?

Policy

- What is the role of policy in creating a knowledge base, in forming new markets and establishing the BIPV industry as a mainstream power sector?
- Should policy focus on helping (by mobilising resources and directing the search) particular technologies, applications or sectors like BIPV?
- How do you assess current market support mechanisms? (ROCs, FiTs, net metering) how do they compare with each other? What is the feedback from users?
- How much do international carbon reduction and renewables-penetration targets and regulations affect the UK policy-making?
- How do fit reductions/policy changes affect the BIPV market in the UK and each sector? (residential, commercial, utility scale) how do users respond?
- How can building regulations help or hinder deployment?
- How do you assess current certification? (in technologies and in training installers designers) Is more needed? Who should carry out actions?
- What is the state of education of consumers and public awareness? Who should carry out further action? (firms, associations)
- Do you see a future where BIPV systems are competitive with other power sources with no subsidies? When?

Thanks for your time. Offer to pass on a copy of the report for comments.

A.2 Product datasheet

Model:		
Technical Information		
Module technology (etc CdTe, CIGS etc):		
Power Rating (at Standard Test Conditions):	*Wp*	
Module efficiency:		
Energy Yield:	*kWh/Wp*	
System Information		
Physical dimensions:	mm^3	
Weight:	*kg(lb)*	
Grid connectivity (connected or standalone):		
Mounting type (eg BIPV, inclined/flat roof, freestanding):		
Connectors:		
Maximum system Voltage:	*V*	
Fuse rating:	*Amps*	
Balance of System Requirements (inverter, batteries etc):		
Environmental Challenges		
Wind tolerance:	*kph(mph)*	
Snow tolerance:		
Hailstone tolerance:	$Pa(lb/ft^2)$	
Temperature tolerance:	$^\circ C$	
Other technical challenges:		

Cost		
Total System Cost:	$\$/Wp$	
Module Cost:	$\$/Wp$	
BoS Cost:	$\$/Wp$	
Electrical Cost (inverter, wiring):	$\$/Wp$	
Structural Cost (site prep, racking):	$\$/Wp$	
Labour Cost:	$hours/Wp$	
O&M Cost:	$\$/kWh$	
Levelized Energy Cost:	$\$/kWh$	
Investment Payback Period:	$years$	
Return on Investment:	$\%/year$	
Power warranty:	$years$	
Product warranty:	$years$	
Cost history:		
Other		

Appendix B

Paper in 28th EUPVSEC 2013

COST LEADERSHIP OR DIVERSIFICATION? ASSESSING THE BUSINESS STRATEGIES OF PV MANUFACTURERS USING CASE STUDIES FROM THE USA AND THE UK

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ABSTRACT: The recent explosive growth of the PV sector combined with the multiple technological advancements have allowed for extensive experimentation in terms of applications and business models.

This paper follows on a previous market assessment and offers a mapping of the various business strategies adopted by PV firms. It investigates real case-studies to analyse the benefits and dangers related to diversification through product and market differentiation. Finally it provides insights for the growth potential of such firms taking into consideration not only the techno-economic characteristics that are intrinsic to each one, but also the wider socio-economic environment.

The analysis combines literature research with original empirical evidence gathered using interviews with PV experts and comparative firm-level case studies. It then draws upon innovation studies, technological transitions and business literature to provide a novel analytical framework for the understanding of the factors facilitating or hindering the successful commercialisation of innovative PV applications.

This work is part of the EPSRC's Supergen PV21 Consortium (PV Materials for the 21st Century) and as such it draws upon leading expertise in TF PV technologies.

Keywords: Strategy, Socio-economic analysis, Building integrated PV (BIPV)

1 INTRODUCTION

The global PV sector has recently experienced not only an explosive market growth driven by declining module prices and national subsidisation policies, but at the same time a significant consolidation of its manufacturing capacity. Companies that use thin-film (TF - aSi, CdTe and CIGS) technologies in particular seem to have suffered the most, despite the apparent techno-economic advantages of these technologies over conventional crystalline silicon (cSi). CdTe modules are the least expensive to manufacture while the conversion efficiency of champion CIGS modules has reached that of polysilicon ones. Another critical technical advantage of thin-films is the capability of deposition not only on glass, but also on a range of materials including metals and plastics, allowing for lightweight flexible modules, integration on building materials and electronic devices etc.

This product differentiation capability, combined with the wide range of manufacturing techniques and the lack of a standardized dominant design, has fuelled the creation of a variety of business models among firms expanding from cost leadership in the established ground-mounted sector to product differentiation through the introduction of new PV system configurations and diversification by introducing novel applications into newly created market segments. Despite their significant technological advancements, as yet these companies have been limited to serving niche market segments, not being able to ramp-up their capacity and benefit from economies of scale. Their growth capacity will depend not only on their aptitude to reduce manufacturing costs and ensure product bankability, but also on the potential of these market segments to either evolve in a sustainable way at the niche level or transform into established mainstream markets. The aim of this work is to evaluate these dynamics and derive insights based on original empirical work.

After an introduction to the basic theoretical concepts and the analytical frameworks used in the empirical research, the paper will reviews previous work on a market assessment of the international thin-film PV sector, including historical trends, market share over time, the evolution of the manufacturing cost and selling price breakdown at the module and the system level. This assessment is then used to identify the main industry actors and evaluate their relative positioning according to size, using their technological maturity and manufacturing capacity as metrics, and corporate strategy, based on their orientation towards cost leadership or product and market differentiation,

After an evaluation of the international value chain the paper focuses on the in-depth analysis of the BIPV sector in the UK, using a socio-economic perspective.

2 CONCEPTUAL REVIEW AND ANALYTICAL FRAMEWORK

The collection of empirical evidence and the subsequent analysis was based on three literature strands: business studies, innovation systems and technological transitions. In this section, the basic concepts and methodological tools from the three theoretical realms are reviewed, and an integrated analytical framework is suggested.

2.1. Business Strategy

Strategic management is the notion of coordinating activities within an organization in order to fulfill their socio-economic purposes and address external developments [1,2]. This coordination is based on a long-term strategy that encompasses all activities and gives structure, focus and direction [3].

Michael Porter developed a typology for generic business strategies that are adopted by firms to create and maintain their competitive advantage. According to that typology, strategies fall into three categories according to their strategic strength (low production cost or differentiation) and strategic scope (narrow markets or broad, industry-wide) [4].

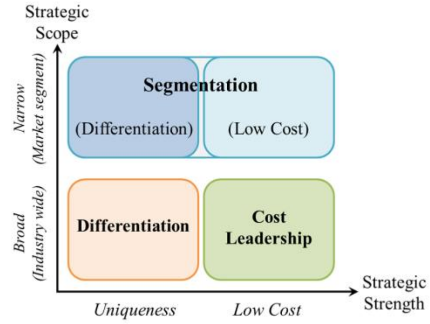

Figure 1: Generic business strategies (adapted from [4])

A *cost leadership* strategy is adopted by companies targeting price-conscious consumers. The firm captures market share by producing at a cost that is lower than average, without significantly compromising quality. Practices that reduce production cost include high turnover (economies of scale and experience curves), lower operational costs (through e.g. standardisation) and control over the supply chain (through e.g. vertical integration).

The *differentiation* strategy involves the development of products or services that have unique attributes different from others available in the market. Potential customers have to recognize the added value brought by these attributes and be willing to pay a premium price for them. Firms that adopt this strategy need to have access to technological expertise, own protected intellectual property, implement successful marketing and have a good reputation for quality.

The *segmentation* strategy involves the narrowing of the firm's focus into serving specific specialized market segments. Within these segments firms may pursue differentiation or market leadership depending on their resources and capabilities. Radical innovations are more crucial when adopting this strategy than incremental efficiency improvements.

2.2. Business Model

The business model is the description of the firm's organizational and financial architecture [5,6]. It is the application of a business strategy in terms of structure and established behaviours that characterize a firm's operations. It represents the firm's perception of what is needed by the market, and outlines its actions to meet that need and generate revenue in return [7].

The business model, as a description of how a firm creates, delivers and captures value, can be a valuable tool for the analysis and comparison of companies and markets in a structured way [8] developed an analytical framework based on nine building blocks of a business model:

- Customer segments define the groups the firm aims to serve
- Value proposition is the product or service the firm offers
- Channels are the ways the firm reaches its customer segments
- Customer relationships are the established links to each customer segment
- Revenue streams refer to the compensation of the firm from the customers
- Key resources include all the firm's assets
- Key activities are the ways the firm creates and delivers value
- Key partnerships refer to the activities and resources that are outsourced
- Cost structure is defined by the elements of the value chain of the firm.

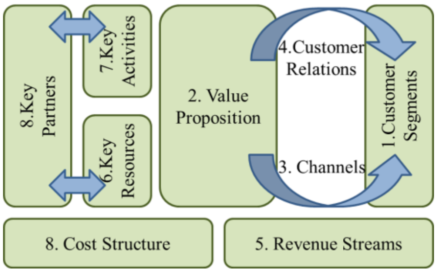

Figure 2: Business model framework (adapted from [8])

2.3. Value and Supply Chains

The value chain concept describes the process of how value is added to a product or service within a firm. This process is considered to be a chain (or system) of activities (or subsystems), each one involving inputs, processes and outputs. Each of the activities adds value to the product/service, and determines its total cost [9].

At the industry level, value chains of several firms are interconnected in a complex and dynamic value-system [9]. This stream of activities from the suppliers to the end-consumer is the supply chain and involves natural resources, materials, components, processes, marketing, sales and delivery of the product or service [10]. Understanding and utilising efficiently the components of the supply chain is crucial for maximizing the returns of a firm.

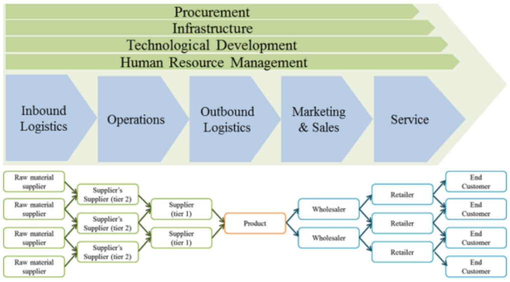

Figure 3: Value chain and supply chain

2.4 Technological Innovation Systems

Innovative activity is considered to be a major component of long-term economic growth [11]. Early theorists located innovation in the middle of a three phase linear process, between invention and diffusion [12]. According to the linear model technological change is stimulated by either scientific advancements (technology-push) or economic developments on the demand-side (market-pull) [13, 14].

Later conceptualizations included approaches from the fields of evolutionary economics [15], learning theory [16] and the path dependency model [17]. The

Technological Innovation Systems (TIS) concept was first developed by [18] to describe innovation as a structured system, comprising of actors, networks and institutions, which work together for the development and diffusion of a new technology.

The TIS framework was developed by [19, 20] and provided a comprehensive methodology including a structural and functional analysis based on 8 functions that assess the performance of the innovation system (see Fig, 4).

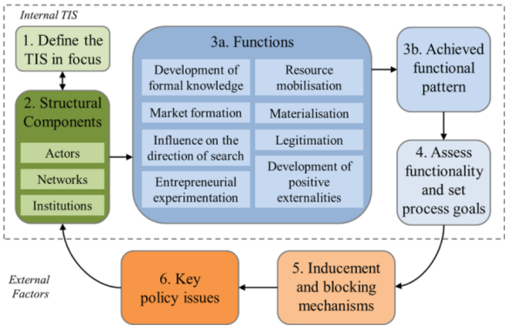

Figure 4: TIS framework (adapted from [19])

The main strength of the systems-perspective is the understanding of innovation as a dynamic process where a network of agents interacts for the development, diffusion and utilization of a new technology. It has also demonstrated the ability to identify various system weaknesses and suggest policy interventions. However, the TIS model has been criticised for being inward-oriented and not paying sufficient attention to the system's environment. As a consequence, the framework is unable to address externalities adequately, ignoring for example strategic intervention from the incumbent actors or emerging technologies outside the system that could work in a complementary way to the system in focus [21]. Furthermore, transitions between different phases of development or even from one system to another are poorly conceptualised and explained [22, 23].

2.5 The Multi-Level Perspective for socio-technical transitions

Another theoretical strand for the study of technological change is the Technological Transitions (TT) approach. If Innovation Systems address the emerging technology perspective, where the focus is on identifying patterns behind the drivers and barriers for the successful deployment of a new technology or product, then the TT approach addresses a wider transitions perspective, investigating the factors that could possibly lead to a reconfiguration or even substitution of the established sectoral set-up [21, 24].

The most prominent approach within TT is Strategic Niche Management (SNM), a form of reflexive governance that involves the deliberate creation, development and controlled phase-out of protective spaces (niches) in order to trigger shifts at the existing sectoral configuration (regime) [25, 26]. A regime shift is the gradual transformation of the existing socio-technical setup and occurs after entrepreneurial experiments (technological niches) stabilize in proto-markets (market niches) and eventually integrate into the sector (see Fig.5). These niches are considered to be crucial for the understanding of the desirability of new technologies and for bridging the `valley of death' between R&D and market diffusion by enhancing their development and rate of application [27, 28, 25].

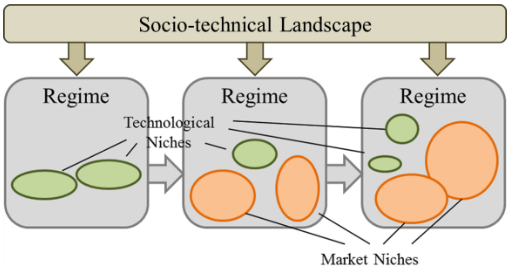

Figure 5: TIS framework (adapted from [25])

The Multi-Level Perspective (MLP) is an analytical framework based on the SNM approach used to study long-term historical transitions. It explains technological transitions as the interplay of dynamics at three different conceptual levels: niche, regime and landscape which can be understood as a nested. As a theoretical framework, MLP can be considered a hybridization of science and technology studies with evolutionary economics [24, 29].

Niches form the micro-level of the hierarchy and are the most unstable configurations. They are responsible for the generation and development of radical innovations; they provide the seeds for change [24]. At their first stages, niches demonstrate low performance [30] and therefore, require protection from external pressures [31, 32].

Regimes are at the meso-level of the hierarchy and account for the stability of technological development through the creation of trajectories [24]. They consist of established technologies, knowledge, rules and practices. From the evolutionary perspective regime could be thought of as the selection environment that hinders the diffusion of radical innovations [21].

The macro-level of the MLP is the landscape, the exogenous environment that provides the gradients for the trajectories [24]. It consists of all those technology-external factors that influence innovation, including macro-economics, macro-politics and cultural patterns. These are hardly affected by lower levels of the hierarchy, and changes take place over long periods of time, in the order of decades [25, 21].

The MLP suggests that regime shifts occur through the interactions at the three conceptual levels of the hierarchy. Regime-internal tensions or pressures from the landscape level may destabilize the incumbent configuration and create a window of opportunity for radical innovations to breakthrough.

In order for this breakthrough to occur a certain level of maturity or accumulation is required at the niche level. Correct timing is essential: unless niches build up sufficient internal momentum, regimes will not shift, and the internal coordination maybe restored [24, 25].

The wide scope and generalizability of the MLP allows for simplification of the analysis of complex structural transformations and reflexive intervention [33, 34]. However it has been criticized for over-emphasizing the niche level as the source of regime shifts [35, 36], for neglecting economic factors [1] and for under-representing human agency [36].

2.6 The integrated framework

The methodology used in this research project is based on a combination of these concepts at three analytical levels:

- At the *firm* level the internal organization of companies is analyzed using the business model and value chain concepts, while the supply chain concept is used to look into the eco-system of the firm
- At the *sector* level (PV), a comparative study of business strategies in an aggregate manner is carried out, and the TIS framework is used to assess the structural and functional performance of the innovation system
- At the *industry* level (energy and construction), the MLP is used to give a more socio-technical perspective.

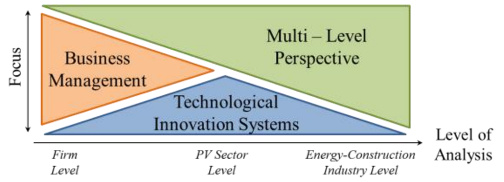

Figure 6: The integrated analytical framework

The same sets of empirical data are analyzed through the different perspectives, providing a more clear understanding of the interplay of dynamics at the three levels.

3 EMPIRICAL METHODS

Throughout the research project, empirical evidence was collected from personal contacts and discussions with actors across the value chain, semi-structured interviews and detailed firm-level case studies.

3.1 Interviews

The method of semi-structured interviews was selected as the most appropriate for empirical data collection, allowing for comparative analysis of the response to standardized questions, and also leaving space for other insights from the respondent.

A series of one-hour interviews was carried out with industry actors across the value chain. These included mainly manufacturers, but also policy makers, regulatory bodies, systems developers, scientists, installers and users.

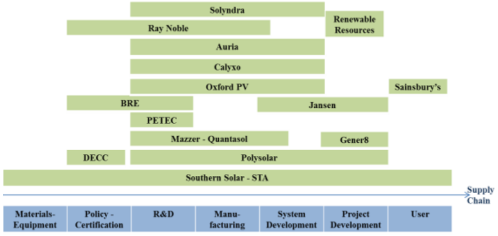

Figure 7: Interviews with industry actors

3.2 Case studies

The case study methodology, just like other research methods (experiments, surveys, histories, archival analyses), is a way of investigating an empirical topic by following a set of pre-specified procedures. However, case studies are distinguished from other methods in the sense that they investigate a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not really evident. The case study inquiry copes with the technically distinctive situation in which there will be many more variables of interest than data points, and as one result it relies on multiple sources of evidence, with data needing to converge in a triangulation fashion, and as another result it benefits from the prior development of theoretical propositions to guide data collection and analysis [37, 38].

For the purposes of this research project two in-depth firm-level business model case studies were carried out, one focusing on the BIPV market in the UK, and the second having an international perspective. Both business models were compared to other models adopted by companies active in the respective technological and market domains.

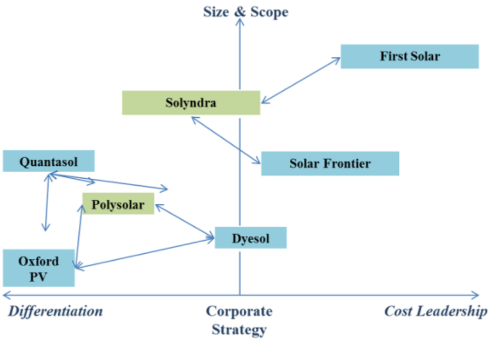

Figure 8: Mapping of case studies

The first case was around Polysolar, a UK-based manufacturing company that is at the first steps of commercialising its products. Based in Cambridge, Polysolar Ltd was established in 2007 and specialized on opaque and semi-transparent glass PV modules that incorporate a-Si technology. These products are mainly used in building integrated systems (BIPV) like facades, windows, roof tiles, canopies, car ports and greenhouses. The company also has an R&D department that focuses on organic polymer photovoltaics (OPV) and is currently in the manufacturing scale-up phase. This case study offered a better understanding of the UK-specific characteristics of the thin-film PV value chain and innovation system.

The second case was Solyndra, a large US-based company that managed to commercialize its innovative thin-film product at an international level. Solyndra's tubular CIGS module is a light-weight system that can be applied on industrial and commercial roofs. Despite the rapid market deployment and production scale-up, the company filed for bankruptcy in August 2011, raising questions related to the factors that affect the commercial success of emerging PV products and the risks involved in the development of market segments beyond the niche level. These factors include not only the techno-economic characteristics of the products, but also business strategies, learning curves, competition with incumbent technologies and the wider economic environment. This case study offered a better understanding of the international context that affects the commercialization potential of emerging PV products and also the risk involved in adopting a business strategy towards differentiation.

4 MARKET ASSESSMENT

The backgound for the empirical research was an extensive techno-economic review of the global PV market. This work was based on both a research on publicly available material and personal interaction with industry experts across the PV value chain. This section draws heavily on previous review work from the authors [39].

4.1 Crystalline-silicon and thin-film PV technologies

C-Si cells are the dominant PV technology and flat-plate modules comprising such cells are used in the vast majority of the installed PV systems. These 'first generation' modules utilise wafers that are cut from polysilicon feedstock, electrically interconnected and enclosed in rigid panels. They are used mainly in ground mounted or building – applied (BAPV) systems, while certain bespoke systems using cells placed between sheets of glass have been used in building integrated (BIPV) systems instead of conventional glazing. The main advantages of wafer-based modules are excellent durability, the highest commercially available conversion efficiency, the relatively low capital cost for capacity expansion and the maturity of the technology and the value chain [40,41].

'Second generation' thin-film technologies utilise amorphous silicon (aSi), cadmium telluride (CdTe) or chalcopyrite (CIGS) compounds to absorb and convert solar radiation into electric current. Instead of interconnected wafers, thin-film modules comprise a uniform active layer deposited on a substrate (or in some cases a superstrate) that is a glass, a plastic or a metallic sheet, usually stainless steel or aluminium. This technique reduces drastically the utilization of active materials, and allows for diverse applications including flexible, lightweight and semi-transparent modules. The potential advantages are low production cost, monolithic module manufacturing allowing for higher capacities and throughput and higher integration of PV in buildings and electronic devices [40,41,42]. On the other hand, thin-films have lower conversion efficiency than c-Si modules, resulting in a lower power output per unit area, and therefore an increased cost of area-related balance-of-system components (mainly mounting structures and cables) [43]. Consequently, they are not preferred in applications where space is limited e.g. domestic rooftops.

Despite the basic functional similarities of both technologies, those technical differences demonstrate their possible complementarity and the potential coexistence of their applications in a range of market segments within the PV sector.

4.2 Evolution of the PV Market

Although the history of the PV market started after introducing silicon based solar cells in space applications in 1954, the real diffusion occurred as a consequence of the oil-price crisis and the invention of the terrestrial module concept in the 1970s. Off-grid rural electrification remained the main PV market segment for 20 years, as it was the least cost option for remote applications. The industry took off after the introduction of capacity based incentives and feed-in tariffs in California, Japan and Europe in late 1990s [44]. Global PV production (production capacity refers to cells in the case of silicon based systems and complete integrated modules in the case of thin-film) has been increasing from 1975 to 2011 at a compound rate (CAGR) of 41.5% per year. The cumulative installed capacity worldwide exceeded 100GWp in 2013 [44, 45, 46].

The global market is expected to stabilize in the next few years showing lower growth rate after the decreasing demand in Europe. However, it is expected to take-off again after 2014 following not only the development of PV markets with domestic module manufacturing including China, India and the USA, but also the increasing occurrence of grid parity effects, i.e. the cost equalization of PV electricity with electricity from the grid [44,45,47].

4.3 Thin film market share

The market share of TF technologies within the rapidly growing PV industry has been fluctuating significantly over the last 30 years. After an impressive 32% of the global market in late 1980s mainly due to off-grid a-Si applications, the share of TF declined. Although it was suggested in 2000 that thin-films would dominate the market since they have no material constraints and the potential to reach very low manufacturing cost [48], their share was restricted to only 5% of the PV market in 2004 [49]. C-Si modules remained the dominant design due to experience build up and knowledge transfer effects from the semiconductor industry [50] and experienced massive deployment as the PV market paradigm shifted to large-scale grid-connected systems.

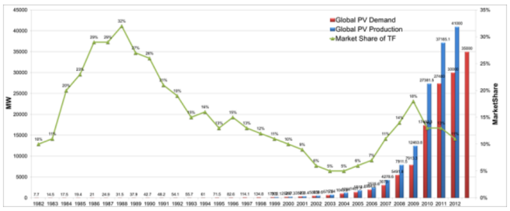

Figure 9: Market review and market share of thin-film technology [49,51]

The high global demand for polysilicon (prime material used in the manufacturing of crystalline silicon cells) between 2004 and 2008 outstripped the semiconductor supply and led to serious concerns over feedstock shortage [52]. The cost of silicon increased rapidly and interest in TF technologies resumed after 20 years because of their use of alternative materials. Although polysilicon manufacturers invested heavily on increasing their feedstock production capacity in order to satisfy the booming demand, these facilities would become fully operational 2-3 years later [53]. This time-lag was seen at the time as a short window of opportunity for thin-film manufacturers to scale-up their production and drive an accelerated breakthrough of their technologies [54]. It was also seen as their chance to gain a critical mass and break through the c-Si technology lock-in barrier [40].

The silicon feedstock production capacity increased and the bottleneck was tackled after 2008. The rapidly declining price of polysilicon feedstock from 475$/kg in early 2008 to 52$/kg in 2010 and 22$/kg in 2012 reduced significantly the cost of c-Si modules [55]. Few TF companies managed to upscale their production and penetrate the PV market that has been experiencing explosive growth after the introduction of financial incentives for PV power generation in key markets including Germany, Spain and Italy. That said, one manufacturer in particular (First Solar) producing CdTe modules achieved high cost reductions by efficiency improvements and production scaling up, being the first company to achieve a production cost of less than 1$/Wp and reaching the first place among PV producers, capturing a 7% share of global cell production in 2011 [45].

5.4 PV System Prices

The PV industry reached a record high in 2012 with over 30GWp of new installations worldwide, while the total production reached 41 GW [45]. This oversupply of mainly flat-plate PV modules (driven by ambitious investments, aggressive business strategies for market penetration and reduction of manufacturing costs) combined with the shift of production to China, caused the average selling price of PV modules to drop by 28% during 2011 [45]. However, this price stabilized in 2012 after the rationalisation of the accumulated module inventories.

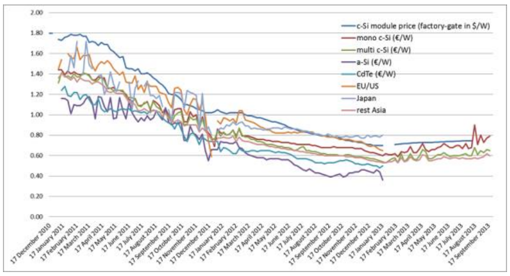

Figure 10: Historic development of factory-gate module prices [57]

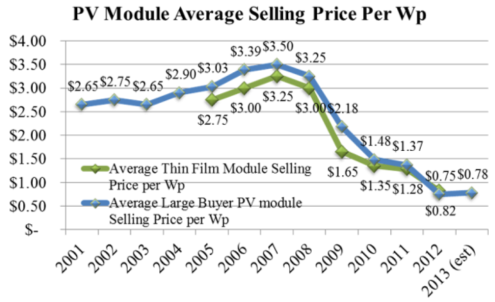

Figure 11: Average module selling prices [44, 56, 57]

The price of an installed PV system depends not only on the price of the module it comprises but also on a range of system components including the inverter, the balance of system (mounting construction, cables, transformers etc.) as well as the installation processes. The contribution of the module to the final system price is expected to decline significantly from 40% that is nowadays to less than 35% in 2020 [43].

According to industry analysts, the average selling price of PV systems is expected to further decline in the next five to ten years, converging to 1.1 $/Wp [55]. These reductions will be driven mainly by production overcapacity and learning effects at the balance of system (BoS) components (mainly inverters and mounting systems) and installation processes [45,55].

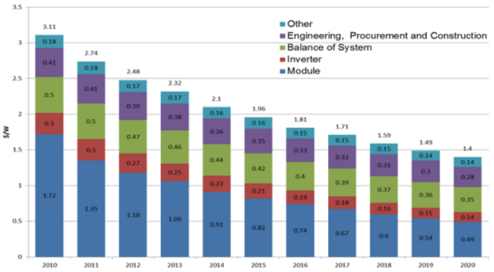

Figure 12: Future Projection of PV System Prices [43]

Thin-film modules have the potential for significantly lower manufacturing costs than c-Si modules, due to low active material utilization and more efficient manufacturing processes not relying on silicon ingot cutting into wafers, such as roll-to-roll deposition. However, the average selling price of TF is now comparable to that of cSi modules which still demonstrate faster cost reduction rates. This is mainly due to the fact that, with the exception of few mature companies, most TF manufacturing plants remain small (less than 100MW of annual capacity) and use custom-made equipment, thus not benefiting from economies of scale [56]. At the system level thin-films suffer from lower conversion efficiencies that implies a cost penalty related to balance of system components. On the other hand, in many cases certain thin-film technologies have demonstrated higher energy yields (kWh/kWp) than cSi, offering an advantage when comparing the levelised cost of energy (LCOE) [42].

Although thin-films (especially CdTe) are expected to continue to be the cheapest among PV technologies, it is uncertain whether they will deliver a sufficient cost margin in order to compete with the established c-Si. The balance between cost competitiveness and efficiency is especially critical in applications where space is limited, such as building applied PV (BAPV – roof or façade-mounted systems). Module manufacturers using thin-film technologies need to utilize and incorporate in their strategies other advantages of their technologies, including application versatility.

5 EMPIRICAL EVIDENCE AND INDICATIVE FINDINGS

In this section some findings from the empirical research and analysis are presented. Since this is an ongoing research project, these are only indicative findings. A more complete overview of the research will be published at a later stage.

5.1 Supply chain analysis

The modeling of the PV value chain revealed that the fewer step required in the manufacturing of thin-film modules allow for easier vertical integration and faster ramping up of manufacturing capacity. It has also revealed that the declining system prices driven mainly by module oversupply is putting pressure and diminishes the profit margins of all players across the value chain.

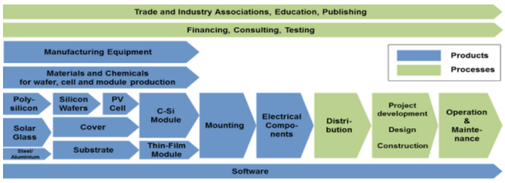

Figure 13: PV supply chain

Under these pressures, many manufacturer have shifted their business model to integrate downstream value chain components in order to capture profit from the higher margins offered by project development.

Another important trend is the internationalization of the value chain. Main R&D activities remain in Europe and the US, as is most of the elaborate manufacturing equipment production. However, the bulk of the manufacturing activities have shifted to Asia, and demand is increasing from emerging markets around the world. Industry players need to adopt this international perspective and incorporate a global vision in their business strategy.

5.2 Mapping of business strategies

In this section we assess the positioning of the main thin-film manufacturers in the PV industry according to their orientation towards cost leadership or differentiation, and the corporate strategies they adopt in order to increase their market share.

Two sectors with high potential for market penetration are large-scale ground-mounted and industrial roof-mounted systems where module area is less restricted [49]. TF manufacturers that obtain a cost leadership business strategy target these markets in order to finance the up-scaling of their manufacturing capacity (for example First Solar, Solar Frontier and Nanosolar). They focus on reducing their manufacturing costs by achieving high asset turnover, offering high volumes of standardized products and integrating parts of the entire PV value chain, both upstream (materials extraction) and downstream (design and installation) [58].

A characteristic example of cost leadership strategy is First Solar, a CdTe modules manufacturer based in the USA with production facilities also in Malaysia and Germany. It was the second largest PV manufacturer in 2011 with a capacity of 2.5 GW/year. It is also the cost leader with an average production cost of 0.74$/W. This cost is expected to drop to 0.70-0.72$/W after a recent restructuring due to low demand in Europe that drove the company to shut down facilities in Germany [59]. A core strategy of the company is designing and developing turn-key systems, including four out of the five world's largest PV projects, currently under construction [59, 60].

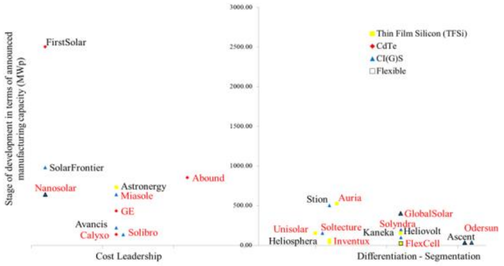

Figure 14: Mapping of business strategies according to strategic focus and manufacturing capacity

Another opportunity for wide deployment of TF technologies will be product differentiation and the creation of new market segments, especially within the building-integrated PV sector where they demonstrate some technological advantages when compared to cSi. These advantages include better temperature coefficient that allows for higher energy yields at high temperatures and the prospect for non-ventilated modules, the possibility of deposition on flexible plastic or metallic substrates and semi-transparent modules that can be used for glazing.

In Figure 14, some major TF companies are mapped according to their manufacturing capacity and their generic business strategy. The horizontal axis represents the focus of a company on gaining cost leadership by having a broad scope and penetrating established large markets (further left) or by differentiating their products and focusing on niche market segments [4].

Manufacturing capacity data were collected from published announcements by the respective companies, and market orientation was assessed based on their commercial products and. These figures provide a trend but not final numbers, since not all companies announce their capacity increases or scale-backs in advance; neither do they disclose information about on-going R&D projects.

The recent developments in the PV industry (modules oversupply, low c-Si cost) resulted in diminishing profit margins for the manufacturers. The main consequence has been the consolidation of the PV industry, forcing the exit of high cost TF manufacturers that could not compete with cheap c-Si and TF producers. The pressure has been greater on firms that focus on product differentiation. These innovation-driven companies use bespoke manufacturing equipment to develop technically-complicated systems (Solyndra, United Solar, Soltecture, Odersun) that usually target niche market applications including roofs that are corrugated or have a weight-bearing limitation. Low uptake and slow development of these market segments do not allow for manufacturing cost reductions, overshadowing the potential technical benefits of such systems.

Investments on differentiated companies are still occurring, with the most proinent examples of TSMC and Hanergy, who acquired the intellectual property of three CIGS firms. However, these investments are backed by strong conglomerates with easy access to capital and parallel revenue streams.

5.3 The BIPV sector in the UK

In this sector we apply the integrated framework presented earlier to look into the BIPV innovation system. As it is still in an immature phase, the TIS shares many structural components with other innovation systems in the renewable energy sector.

Actors include firms across the entire PV value chain including material extractors, cell-module-system manufacturers, project designers and developers, financiers and users, but also organisations involved in the knowledge creation and transfer including universities, research bodies and industry associations.

Many of the learning networks involved are dedicated to the TF TIS including technology platforms and informal links between firms, suppliers, universities and users. Political networks in the form of advocacy coalitions like professional associations, customer interest groups and environmental associations are shared with other renewable energy innovation systems, and indirectly facilitate the development of the TF TIS.

Institutions are also common across energy innovation systems and include formal regulations like international treaties for decarbonisation of the energy supply, fiscal incentives and procurement policies, and informal cultural norms and cognitive rules related to the building sector, power generation and environmental concerns.

The emerging innovation system encompasses market and technological niches within the renewable energy sector. Most of these are in a formative phase; however few market niches have evolved and been integrated into the PV regime.

Taking into consideration that crystalline Silicon BIPV is the established technology, the three main emerging technologies are silicon based thin films (TFSi), cadmium telluride (CdTe) and the CIGS family. These technological niches compete for resources and recognition with each other but also with other technologies from the centralized and the distributed power generation paradigm like organic PV (OPV), fuel cells and concentrator PV (CPV), while they work complementarily to the fuel cells and the smart-grid niches in shifting the power generation regime towards a distributed paradigm.

BIPV market niches include ground-mounted systems, building integrated or applied PV (BIPV and BAPV) and electronics integrated PV (EIPV). They were created by the market pull of renewable energy systems and low carbon buildings, and the technology push of flexible and transparent modules. They compete at the niche level with micro combined heat and power generators (CHP) and market segments that utilize other PV technologies.

A few market niches have already been incorporated in the PV regime. Ground-mounted systems are compatible with the centralized power generation paradigm, and offer competitive cost characteristics, while roof-mounted systems require little changes in the norms within the building sector. These compete at the regime level with the established c-Si PV systems and complement other renewables in the transformation of the power sector.

At the highest (landscape) level, environmental awareness about anthropogenic climate change and concerns over conventional fuel sources availability and security, have steered the energy and construction sectors towards a greener and low carbon path. This trend is driving the transition into a decentralized power system with high contribution of renewable energy sources.

These processes cause instability in the regime level, leaving space for mature niches to grow and achieve market deployment. Apart from maturity, two other factors that will determine the successful development of niches are compatibility with existing paradigms and trends, and solution capability.

PV in the UK market is a rather new market. After the initial unwillingness of the government to adopt the technology, a feed-in-tariff (FiT) was introduced. After the rationalization of the FiT the sector is now at a state of stable growth.

The BIPV sector specifically is very promising in the UK, since it is driven not only by renewable energy generation incentives but mainly by building regulations towards low carbon structures. Another important factor is the existence of an extensive glass industry in the UK, which allows for easy integration of BIPV manufacturing lines to the conventional production lines.

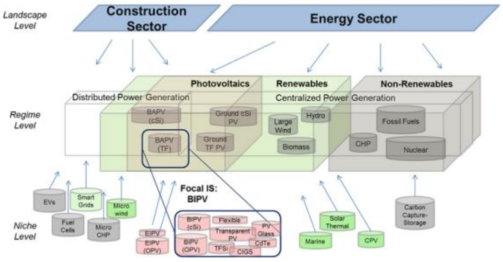

Figure 15: The BIPV innovation system within its environment

The empirical research has revealed that despite the strong PV-related research and development being conducted in the UK and the extensive downstream project development sector, there is still a significant gap in the value chain. This ‘missing middle’ involves equipment, module and components manufacturers as well as system developers. There is evidence showing that the development of the missing value chain elements would facilitate the market deployment of innovative PV products necessary for the booming building-integrated PV sector.

6 CONCLUSSIONS

In order to better understand the innovation dynamics within the emerging BIPV industry, and assess their potential for penetration in the market, a combined analysis is needed of both the internal techno economic characteristics and the external socio-economic factors of the technological innovation system.

This paper uses an integrated framework combining the strengths of three theoretical domains, business management, innovation systems and technological transitions. The research is based on ahistorical market analysis of the PV sector and original empirical research.

Assessment of the international PV sector has revealed a high level of market segmentation and a variety of business models from manufacturers and system developers. Historical hindsight has also revealed that cost leadership through scaling-up production capacity has been the dominant strategy for survival and growth. The expectation for low manufacturing costs has put pressure on firms across the value chain and diminished their profit margins, causing shifts of their business models. Initial experimentation with technologies and markets has been limited to companies with strong parallel revenue streams and easy access to capital. However, this paradigm could be challenged in the future following the stabilisation and establishment of several niche markets, especially those relating to applications integrated in buildings and electronics.

Concerning the BIPV sector, it has been revealed that there is limited understudying of its particularities. Applications are still evaluated based on their power generation performance and not on their performance as building materials. However, the fact that their deployment will be driven mainly by building regulations and not renewable power generation incentives, along with their particular functionality challenges that perspective.

The empirical research has revealed that despite the strong PV-related research and development being conducted in the UK and the extensive downstream project development sector, there is still a significant gap in the value chain. This ‘missing middle’ involves equipment, module and components manufacturers as well as system developers. There is evidence showing that the development of the missing value chain elements would facilitate the market deployment of innovative PV products necessary for the booming building-integrated PV sector.

7 ACKNOWLEDGEMENTS

The authors would like to thank their collaborators within the PV21 consortium for their support and all the interviewees for the provision of data and useful insights.

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