

**Innovation Systems and Regional Governance for the
Development of Low Carbon Building Technologies
in Wales: a *'Functions Approach'***

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Abstract

Having arguably led the world in the transition to a high carbon economy, much of Wales today is economically and socially deprived. Even so, a devolved Welsh Government has set ambitious targets to reduce carbon emissions in the devolved areas, while creating employment and economic opportunities, reducing fuel poverty, thereby helping to solve Wales' entrenched social and economic problems. A low carbon transition in the built environment is critical to achieve such targets.

This PhD study aims to provide theoretically informed and empirically grounded insights into the development of low carbon building technologies in Wales through examining how the functions of the innovation systems of two selected emerging technologies *i.e.* 'Welsh grown timber for construction' (WTC) and 'building integrated solar energy systems' (BISE) have been fulfilled. Having first established a bespoke analytical framework, the functional patterns of the two technological innovation systems (TIS) are documented, assessed and compared. The study further explores how the functional analyses may offer a bottom-up perspective on the policy implications for regional governance in Wales, which might alter the functional patterns, and improve the innovation capability of relevant Welsh organisations.

The functional analyses of the WTC and BISE TIS shows that, although both TISs have reached their formative phases in Wales, there is no guarantee that either system will eventually move onto the phase of market diffusion, due to the inherent system weaknesses and uncertainties likely arising in technology, policy-making, and market. Whereas regional governance in Wales can introduce policy interventions, they matter only when breakouts from certain forms of institutional 'path-dependence' are induced. In this respect, the thesis concludes by discussing four streams of policy-thinking that may instigate different pathways in Wales, namely: technology foresight; the regulation-induced innovation hypothesis; demand-oriented policy measures; and, support for small business innovations through, e.g. R&D consortia.

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Content

<i>List of figures and tables</i>	v
<i>List of abbreviations and acronyms</i>	vii
Chapter 1 Background and Introduction	I
1.1 Wales: an introduction	2
1.2 Buildings and carbon reduction	4
1.3 Evolutionary theory, Innovation Systems and Technological catch-up	7
1.4 Purpose of the research	12
1.5 Methodology	13
1.6 Structure of the thesis	15
Chapter 2 Literature Review	17
2.1 Evolutionary economic theory and innovation	18
2.1.1 Innovation: the definition	20
2.1.2 Innovation process	21
2.2 Innovation Systems	24
2.2.1 <i>National Innovation System (NIS)</i>	26
(a) <i>User-producer linkages</i>	27
(b) <i>Institutions and Social technologies</i>	29
2.2.2 <i>Regional Innovation System (RIS)</i>	31
2.2.3 <i>Sectoral Innovation System (SIS)</i>	35
2.2.4 <i>Technological Innovation System (TIS)</i>	37
2.3 Functions of an Innovation System	41
<i>Function 1: Knowledge development and diffusion</i>	44
<i>Function 2: Entrepreneurial experimentation</i>	45
<i>Function 3: Guidance of the search</i>	46
<i>Function 4: Market formation</i>	46
<i>Function 5: Resource mobilisation</i>	47
<i>Function 6: Legitimation</i>	47
<i>Function 7: Development of positive externalities</i>	48
<i>Identifying the phase of a TIS</i>	49
<i>Assessing the functions</i>	51

2.4	Innovation and Technological catch-up	53
2.4.1	<i>Technological forecasting</i>	56
2.4.2	<i>Catching-up at the industry–firm level</i>	58
2.4.3	<i>The role of domestic demand in the catching-up process</i>	60
2.4.4	<i>Innovation induced by stringent government standards</i>	62
2.5	Concluding remarks	64
Chapter 3 Research Methods, Analytical Framework, and Case Study Selection		67
3.1	Introduction: the choice of research topic	67
3.2	The Functions approach	69
3.3	A bespoke analytical framework for the assessment of the IS Functions	71
3.4	Research Design	78
3.4.1	<i>Case study selection</i>	78
3.4.2	<i>Comparative study</i>	81
3.4.3	<i>Data collection and analysis: semi-structured interviews</i>	82
3.5	Methodological strength, novelty and limitation	85
3.6	Summary	87
Chapter 4 Wales: the Distance Travelled		89
4.1	Transition to a high carbon economy	90
4.2	The British state and the rise of the Welsh manufacturing sector	95
4.3	Welsh devolution	98
4.3.1	<i>Multi-level governance (MLG)</i>	100
4.3.2	<i>Emergence of a Welsh low carbon transition narrative</i>	102
4.4	Innovation policy governance in Wales	105
4.5	Concluding remarks	109
Chapter 5 Case Study: Introducing the Structural Components		111
5.1	Case Study 1: Welsh Grown Timber for Construction (WTC)	111
5.1.1	<i>Technology and Timber construction</i>	117
5.1.2	<i>Actors and networks of the WTC TIS</i>	120
5.2	Case Study 2: Building Integrated Solar Energy Systems (BISE) in Wales	125
5.2.1	<i>Solar technologies and Buildings</i>	130
5.2.2	<i>Actors and networks of the BISE TIS</i>	134
5.3	Summary	135

Chapter 6 Case Study: Mapping the Functional Patterns	137
6.1 Functions of the WTC TIS	139
6.1.1 <i>Function 1: Knowledge development and diffusion</i>	139
6.1.2 <i>Function 2: Entrepreneurial experimentation</i>	144
6.1.3 <i>Function 3: Guidance of the search</i>	146
6.1.4 <i>Function 4: Market formation</i>	148
6.1.5 <i>Function 5: Resource mobilisation</i>	150
6.1.6 <i>Function 6: Legitimation</i>	153
6.1.7 <i>Function 7: Development of positive externalities</i>	155
6.2 Functions of the BISE TIS in Wales	156
6.2.1 <i>Function 1: Knowledge development and diffusion</i>	156
6.2.2 <i>Function 2: Entrepreneurial experimentation</i>	159
6.2.3 <i>Function 3: Guidance of the search</i>	162
6.2.4 <i>Function 4: Market formation</i>	165
6.2.5 <i>Function 5: Resource mobilisation</i>	168
6.2.6 <i>Function 6: Legitimation</i>	171
6.2.7 <i>Function 7: Development of positive externalities</i>	172
6.3 Concluding remarks	173
Chapter 7 Discussion and Conclusion	179
7.1 Assessing the functional patterns	180
7.2 Implication for regional governance in Wales	191
7.2.1 <i>Technology foresight: setting long-term visions</i>	192
7.2.2 <i>Regulation-induces innovation hypothesis: why stringent regulations?</i>	194
7.2.3 <i>Demand-oriented policies for innovation</i>	196
7.2.4 <i>Support for small business innovations</i>	199
7.3 Conclusion	203
7.3.1 <i>Contribution of this study</i>	205
7.3.2 <i>Issues for future research</i>	207
<i>Bibliography</i>	209
<i>Appendix A: Lists of the organisational affiliation of the interviewees</i>	245
<i>Appendix B: An example copy of the interview questions</i>	247

Figures and Tables

Figures

Figure 1.1: The Zero Carbon Hierarchy triangle	6
Figure 2.1: 'Technological push' model	21
Figure 2.2: 'Demand-pull' model	21
Figure 2.3: The trajectory of an individual technology	24
Figure 2.4: Boundaries of innovation systems between NIS, RIS, SIS and TIS	40
Figure 4.1: A historical trend of the coal production in Wales, 1854-2012	92
Figure 4.2: A historical employment pattern among the four major sectors in Wales, 1851-1971	96
Figure 4.3: The impacts of varied governance levels on selected local service areas in Wales	102
Figure 5.1: The development of timber engineering since 1700	118
Figure 5.2: The perceived network map of interactions between actors in a well-functioning WTC TIS	124
Figure 5.3: UK solar radiation maps	127
Figure 5.4: Domestic PV installation in Wales, as of September 2013	127
Figure 5.5: The perceived network map of interactions between actors in a well-functioning BISE TIS	136
Figure 6.1: The Ty Unnos components	141
Figure 6.2: Building projects using the Ty Unnos system	141
Figure 6.3: An innovation pipeline for functionally coated building components: from fundamental research to global market	160
Figure 6.4: The formative phase of the network map of interactions between actors in the WTC TIS	177
Figure 6.5: The formative phase of the network map of interactions between actors in the BISE TIS in Wales	178

Tables

Table 2.1: A comparison of the evolutionary and neo-classical theory	18
Table 2.2: Functions of an Innovation System	43
Table 3.1: A summary of performance indicators for assessing the IS Functions proposed by different scholars	72
Table 3.2: Performance indicators for <i>Knowledge Development and Diffusion</i>	74

Table 3.3: Performance indicators for <i>Entrepreneurial Experimentation</i>	75
Table 3.4: Performance indicators for <i>Guidance of the Search</i>	75
Table 3.5: Performance indicators for <i>Market Formation</i>	76
Table 3.6: Performance indicators for <i>Resource Mobilisation</i>	76
Table 3.7: Performance indicators for <i>Legitimation</i>	77
Table 3.8: Performance indicators for <i>Development of Positive Externalities</i>	77
Table 5.1: A list of EU COST FPS actions on wood technology	120
Table 6.1: A bespoke analytical framework for the assessment of the IS Functions	138
Table 6.2: Varied R&D phases of the Ty Unnos system	139
Table 6.3: Softwood availability forecast for the woodland in Wales, 2013 -2061	152
Table 6.4: An outline of the major BISE related R&D projects in Wales between 2008-2013	156
Table 7.1: A comparison of the functional patterns of the WTC and BISE (in Wales) TIS	181

List of abbreviations and acronyms

1G	the 1 st generation
2G	the 2 nd generation
3G	the 3 rd generation
4G	the 4 th generation
AM	Assembly Member
Arbed	Strategic Energy Performance Investment Programme
BASE	Building Applied (or Adopted) Solar Energy
BBC	British Broadcasting Corporation
BER	Buildings CO ₂ Emissions Rate
BIS	Department for Business Innovation & Skills
BICPV	Building Integrated Concentrating Photovoltaic
BIPV	Building Integrated Photovoltaic
BIPVT	Building Integrated Photovoltaic Thermal
BISE	Building integrated solar energy
BIST	Building Integrated Solar Thermal
BPVA	British Photovoltaic Association
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Methodology
c-Si	Crystalline silicon
C&G	City & Guilds
C24 (or 16)	the strength class of the softwood grades, C stands for Conifer
CAP	Common Agricultural Policy
CCW	Countryside Council for Wales
CO ₂	Carbon Dioxide
COATED	Centre for Doctoral Training in the Field of Functional Coating
COST	the European Co-operation in Science and Technology
CPD	Continuing Professional Development
CPV	Concentrating photovoltaic
CSER	Centre for Solar Energy Research
CZTS	Copper, zinc, tin, sulphur
DCLG	Department for Communities and Local Government
DECC	Department for Energy and Climate Change
DG XVI	the European Commission's Directorate General for Regional Policies
DSSC	Dye sensitised solar cells
EAW	Environment Agency Wales
EE	Element Europe
EngD	Engineering Doctorate
EPIA	European Photovoltaic Industry Association
ERDF	European Regional Development Fund
ESTIF	European Solar Thermal Industry Federation

EU	European Union
EWPs	Engineering wood products
FC	Forestry Commission
FCW	Forestry Commission for Wales
FDI	Foreign direct investment
FIP	Feed-in Premium
FIT	Feed-in Tariff
FP	the Framework Programme for Research and Technological Development
FPS	the COST action on Forests, their Services and Products
FSC	Forest Stewardship Council
FY	Fiscal year
GDP	Gross domestic product
GHG	Greenhouse gas
Glulam	Glued laminated timber
GVA	Gross value added
GW	Gigawatt
GWh	Gigawatt-hours
IEA	International Energy Agency
IKC	Innovation and Knowledge Centres
IKE	Innovation, Knowledge and Economic Dynamic Group, Aalborg University, Denmark
INSEAD	European Institute of Business Administration (in English)
IS	Innovation System
IT	Information technology
ITRI	Industrial Technology Research Institute, Taiwan
KTC	Kilo tons of carbon
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt-hours
LABC	Local Authority Building Control
LCBE	Low Carbon Built Environment
LCRI	Low Carbon Research Institute
LED	Light-emitting diode
MIT	Massachusetts Institute of Technology
MITI	Ministry of International Trade and Industry
MLG	Multi-level governance
MMC	Modern Methods of Construction
MW	Megawatt
MWh	Megawatt-hours
MWp	Megawatt peak
NAW	National Assembly of Wales
NESTA	National Endowment for Science, Technology and the Arts
NGO	Non-governmental Organisation
NIC	Newly industrialising country
NIS	National Innovation System

NISTEP	National Institute of Science and Technology Policy, Japan
NRW	Natural Resources Wales
OBM	Original brand manufacturer
ODM	Original design manufacturer
OECD	Organisation of Economic Co-operation and Development
OEM	Original equipment manufacturer
Ofgem	Office of Gas and Electricity Markets
OPV	Organic Photovoltaic
PC	Personal computer
PEFC	Programme for Endorsement of Forest Certification
PRI	Public sector research institute
PV	Photovoltaic
PVTEAM	PV Technology based on Earth Abundant Materials
Q	Research question
R, D&E	Research, development and engineering
R&D	Research and development
RDP	Rural Development Plan for Wales
RETAS	Regional Technology Strategies
RHI	Renewable Heat Incentive
RiiH	Regulation-induced innovation hypothesis
RIS	Regional Innovation System
RIS3	the European Commission's Research and Innovation Strategy for Smart Specialisation
RO	Renewable Obligation
RTP	Regional Technology Plan
SAPPHO	Scientific Activity Predictor from Pattern with Heuristic Origin
SBEC	Sustainable Building Envelope Centre
SBED	Sustainable Building Envelope Demonstration project
SBEM	Simplified Building Energy Model
Si	Silicon
SIC	Standard Industrial Classification
SIPs	Structural insulated panels
SIS	Sectoral Innovation System
SMEs	Small and medium-sized enterprises
SPARC	Solar Photovoltaic Academic Research Consortium
SPECIFIC	Sustainable Product Engineering Centre for Innovative Functional Industrial Coatings
SPRU	Science Policy Research Unit, University of Sussex, UK
S&T	Science & Technology
STA	Structural Timber Association
STEM	Science, Technology, Engineering and Mathematics
TEP	Techno-economic paradigm
TF	Thin film
TIMs	Territorial innovation models
TIS	Technological Innovation System
TNC	Transnational corporation

TRADA	Timber Research and Development Association (UK)
TSC	Transpired Solar Collector
TWh	Terawatt-hours
UCAS	Universities and Colleges Admissions Services
UN	United Nation
WDA	Welsh Development Agency
WEST	Welsh Energy Sector Training
WFBP	Wales Forest Business Partnership
WFW	Wood Fuel Wales
WG	Welsh Government
WIPO	World Intellectual Property Organisation
WKW	Wood Knowledge Wales
WOF	Welsh Opto-electronics Forum
WP	Work package
WSA	Welsh School of Architecture
WSW	Wood Source Wales
WTC	Welsh grown timber for construction
WWI	the First World War, or the Great War
WWII	the Second World War

Chapter I: Background and Introduction

Buildings encompass virtually every human activity (Gruneberg, 1997). Energy consumed in constructing, occupying (or using), maintaining, retrofitting and demolishing the built environment is a significant contributor to greenhouse gas (GHG) emissions. So, any effort towards a low or zero carbon transition needs to address how we can de-carbonise the built environment (domestic and non-domestic buildings, and infrastructure etc.), through e.g. reducing energy demand (for heating, lighting, ventilation, cooling etc.), improving process efficiency, and generating energy from renewable or low carbon sources. When it has been suggested that it was technically feasible to undergo a low carbon transition in the built environment (The Green Construction Board, 2013; Natarajan and Levermore, 2007; Johnston et al., 2005), such a transition undoubtedly requires significant shifts in current practices. In this sense, this PhD study explores the development and deployment of low carbon building technologies from an evolutionary, socio-technical perspective, using the innovation system and functions approach, as introduced later in the chapter.

This study focuses the level of analysis on the regional level, specifically the development and deployment of low carbon building technologies in Wales. This regional focus partly reflects the acknowledgement that the processes driving innovation and national economic growth are spatially bound (Dawkins, 2003), where localised production systems can benefit from local external economies of scale (Marshall, 1890) and in turn promote local endogenous innovation and productivity growth (Martin and Sunley, 1998). On the other hand, there is also a growing recognition of the importance of the regional context in shaping low carbon innovation and transition pathways, since it constitutes not just the broader institutional, economic and governance dimensions but also the natural and built environment as a potential source of competitive regional advantages (or constraints) (Eames and De Laurentis, 2012). Meanwhile, given that Wales has remained a peripheral region and has been unsuccessful in economically catching-up the rest of the UK for decades, this study sees the need to integrate the technological catch-up strand of research in that it may help to address some gaps in the existing study of innovation systems, as will be discussed later.

This introductory chapter contains six sections. Section 1 provides an overview on Wales' economic and political situation, the emergence of a new Welsh identity since devolution, as well as the Welsh Government's target to reduce greenhouse gas (GHG) emissions by three per cent per year from 2011 in areas of devolved competency. Section 2 explores the role of the built environment in helping to deliver the annual 3% emission reduction target, and some of the institutional and technical challenges facing the development and deployment of low carbon building technologies in Wales. In Section 3, the theoretical basis of this study is introduced; this includes an overview of the literature on evolutionary economic theory, the innovation systems and functions approach, followed by a discussion of the relevance of integrating the literature on technological catch-up in this study. In Section 4, the aim of this PhD study and the related research questions are established, while Section 5 offers an overview of the research methods employed. In the final section the structure of this PhD thesis is outlined.

1.1 Wales: an introduction

With a population of just over three million people, Wales is a relatively small nation located on the western periphery of the United Kingdom. Wales has a long industrial history, once seen as leading the world in the transition to the high carbon economy; the South Wales coal was known as the 'black gold' (Power, 2008) that powered the British Empire during the Industrial Revolution. However, the 'landscape' has changed since the interwar period. The shift of the energy regime from coal to oil, gas and electricity coupled with globalization and neo-liberalism have combined to drive the de-industrialisation of the Welsh economy (Wang and Eames, 2010).

Wales today is relatively poor by both UK and European standards, and lags behind the rest of the UK in both prosperity and productivity terms, with the figures showing that Wales has the lowest level of Gross Value Added (GVA) per head in the UK regions, at 72.2% of the UK average in 2013 (Welsh Government, 2014a). At the European level, West Wales and the valleys (with around two-thirds of the Welsh population) have remained as European Objective One Areas since 1999, which means that the Gross Domestic Product (GDP) of these areas stays at 75% or less of the European average, while the rest of Wales is eligible for European Objective Three support (Jones and Rumbul, 2012). The Welsh economy is described as both a perennial problem and a puzzle in that, for more than 80 years, few other parts of Europe have been subject to such a

prolonged attempt to catch up (Institute of Welsh Affairs, n.d.).

In the meantime, the political landscape in Wales has experienced a sea change, with a progressive process of devolution having taken place since 1999. Wales became a ‘national’ region (Cole and Palmer, 2011), or ‘constitutional’ region (Dickson, 2013), and has wide-ranging legislative powers over twenty devolved areas, defined by the *Government of Wales Act 2006*. Coupled with devolution was a desire to forge a new Welsh identity that, when framed as an explicit acknowledgement of the role that Welsh coal played in the vanguard of the transition to the high carbon economy, is embedded in the National Assembly for Wales’ (NAW) and the Welsh Government’s (WG) commitment to promote sustainability. As described by Davidson (2009), the former Welsh Minister for Environment, Sustainability and Housing,

We are proud to be among the small number of governments worldwide to have sustainable development as one of the core principles within its statute. This distinctive duty gives us an opportunity to develop in ways which meet the social, economic and environmental needs of the Welsh people, now and in the future. Sustainable Development, therefore, is key overarching priority of the Assembly.

This commitment is reinforced by the recent introduction of the *Well-being of Future Generation (Wales) Bill* (previously the *Sustainable Development Bill*), which sets the aim to achieve a prosperous, resilient Wales, with “*an innovative and productive, low carbon emission, economy that makes more efficient and proportionate use of resources; and which generates wealth and provides employment opportunities for a skilled and well-educated population*” (p: 3). More so, this new Welsh identity constitutes part of a distinctive Welsh low carbon transition narrative that emerged during the late 2000s, at the heart of which lies WG’s principal target to reduce greenhouse gas (GHG) emissions by three per cent per year from 2011 in area of devolved competency, first set out in the *One Wales!* document in 2007 (Welsh Government, 2007). In 2010, the *Climate Change Strategy for Wales* formally endorsed the three per cent annual target, along with a 40% reduction target by 2020 on a 1990 baseline, thereby in line with the target set by the UK *Climate Change Act 2008*, i.e. an 80% reduction target for total GHGs by 2050 (Welsh Government, 2010a). The Welsh

¹ The One Wales document was a coalition agreement between the Labour and Plaid Cymru Party that set out a progressive agenda for the government of Wales, following the 2007 National Assembly for Wales election.

housing stock, existing and new builds, is seen as a key sector for helping to deliver these targets, and achieve sustainability.

1.2 Buildings and carbon reduction

A transition from high to low carbon growth has sectoral variations. For Wales to achieve the 3% annual target, the residential sector has been identified as one of the key sectors (in line with the devolved competence) to deliver GHG emissions reductions, whereas 'buildings' are also seen as a cross-cutting theme that underpins emission reduction across the sectors, and ensures effective adaptation. As stated in the *Climate Change Strategy for Wales* (ibid: 45),

Buildings, and energy use in buildings, are responsible for over 60% of the emissions covered by the 3% target. The existing stock of buildings in Wales is our greatest challenge because most of these buildings will still be with us in 15, 20 and even 50 years time and they have not been designed to either minimise their carbon footprint or to maximise their resilience to the impacts of climate change. Encouraging people to make improvements that enhance both these aspects will remain a key priority within our overall approach to climate change.

More importantly, the WG links the goal of reducing carbon emissions in buildings with those of alleviating fuel poverty, creating employment and economic opportunities, encouraging innovation and skills, and improving the health and wellbeing of many poorest communities in Wales (Welsh Government 2010a, 2010b, 2012a), as exemplified by the ongoing Arbed programme – the 'Strategic Energy Performance Investment Programme'. Set up by the WG in 2009, the Arbed (meaning 'to save' in Welsh) programme², with a combined investment of around £113 millions by the WG, EU structural funds and energy companies, is designed to improve the energy efficiency of homes in the regeneration areas across Wales. It is expected that, over the programme period (2009-2015), a range of energy efficiency measures will be installed at more than 12,000 existing Welsh homes, while a minimum of 2.54 KTC (Kilo tons of carbon) of GHG emissions will be saved. The socio-economic benefits that are expected to be generated include the development of local supply chains in the design, manufacture, distribution, installation and maintenance of domestic energy efficiency measures and renewable energy technologies, the creation of

² Information on the Arbed programme is available from <http://wales.gov.uk/topics/environmentcountryside/energy/efficiency/arbed/?lang=en>

jobs for local communities, and various training provided to local workers, etc. (Welsh Government, 2013a).

For new builds, the WG announced in February 2007 that all new buildings in Wales should be zero carbon by 2011, and an intention to seek the devolution of the Building Regulations to Wales (Welsh Government, n.d.). The Building Regulations were eventually devolved to the Welsh Government on 31 December 2011, which thus now gives the WG a wide range of regulatory powers in both planning (devolved since 1999) and building regulations to deliver low carbon built environment in Wales. The consultation on changes to the Part L (Conservation of fuel and power) of the Building Regulations for Wales commenced in July 2012, with the preferred targets for new domestic buildings to achieve a 40% energy efficiency improvement on the 2010 Standards³, and 20% improvement for non-domestic buildings (Welsh Government, 2012b). However, when the new Part L for Wales was finally released in February 2014, it only required all new domestic buildings to achieve an aggregate reduction of a mere eight per cent against the 2010 level, with 20% for non-domestic buildings; all changes have taken effect on 31 July 2014 (Welsh Government, 2013b).

Whereas the decision to adopt the 8% target was justified on the grounds of the tough economic climate caused by the financial crisis of 2007-2008 (Chapman, 2013), and avoiding unintended impacts on the property and employment market while securing building development in Wales (Sargeant, 2013a), it nevertheless dealt a major blow to WG's credibility on sustainable development. Friends of the Earth Cymru (2012) stated that the WG was, in effect, transferring the financial outlay from developers to future householders, and thus contravening the basic tenets of sustainable development. Since all new buildings in Europe need to be nearly zero-energy by 31 December 2020, in conformity to the *Directive 2010/31/EU on the Energy Performance of Buildings (recast)*, it can be argued that an important opportunity slipped away, in terms of encouraging innovation, and enabling Welsh businesses to develop the skills, expertise and experience that can prepare them to be in a good position (Davidson, 2011) once changes come into force elsewhere, thus catching an 'early-mover' advantage (Friend of the Earth Cymru, 2012).

³ In July 2010, the previous Welsh Government issued a policy statement setting out its target for the first changes it planned to make to the Building Regulations following the transfer of powers, *i.e.* for new homes to achieve a 55% improvement in energy efficiency over the 2006 level (40% over 2010 levels), which was subsequently endorsed by the current administration (National Assembly for Wales, 2012).

Furthermore, as argued later in the thesis, the decision to adopt this 8% target may also be an outcome of ‘path-dependence’, relating to a historical ‘way-of-doing-things’ in Wales.

On the technical side, the worldwide oil crisis of 1973-1974 triggered both regulatory requirements for, and research and development (R&D) on, building energy efficiency in many developed countries; this trend has been further accelerated by the universal call for low and zero carbon transition, as an attempt to reduce the rising concentrations of GHGs in the Earth’s atmosphere, especially since the ratification of the *Kyoto Protocol* in 1997 (Geller et al., 2006; IEA, 2008; Awawdeh and Tweed, 2014). By definition, a low or zero carbon building should be designed to have its operational energy demand reduced through more efficient heating, cooling, lighting, ventilation and electrical power use etc., and then the building energy use should be supplied from low or zero carbon sources, mostly from renewable energy, where this renewable energy supply should be part of the development, either through integrated building design or being located ‘near-to’ as part of a community system (Jones, et al., 2012).

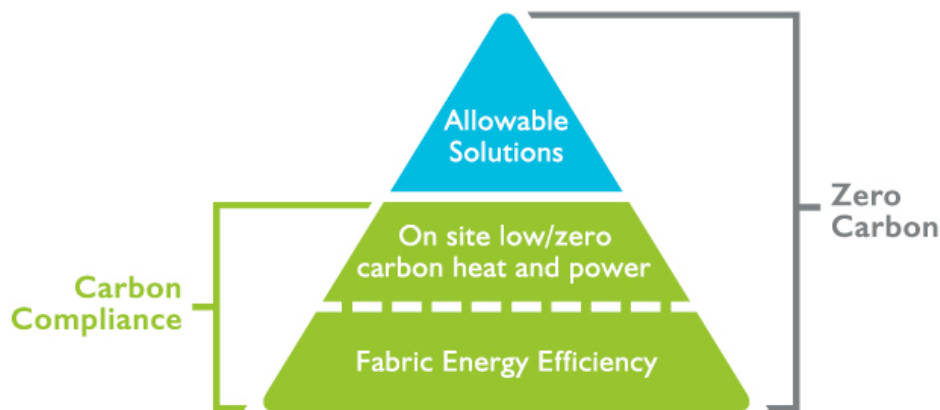


Figure 1.1: the Zero Carbon Hierarchy triangle (Source: Zero Carbon Hub⁴)

Figure 1.1 above illustrates the stepped policy approach required by the UK government to deliver zero carbon buildings, in which ‘Allowable Solutions’ (Step 3) is a term used to blanket any approved carbon-saving measures that are available to mitigate any remaining CO₂ emissions from regulated energy sources⁵, after the requirement for fabric energy

⁴ Source: <http://www.zerocarbonhub.org/zero-carbon-policy/zero-carbon-policy>

⁵ Regulated energy sources include energy used to provide space heating and cooling, hot water and fixed lighting, as outlined in Part L of the Building Regulations (Zero Carbon Hub, 2013)

efficiency (Step 1) and onsite low and zero carbon heat and power (Step 2) are met (Zero Carbon Hub, 2013).

A wide range of energy efficient measures is already available for constructing low or zero carbon buildings, from integrated design approaches to technologically advanced solutions. For example, more than 400 of the low carbon building and construction technologies and materials are currently demonstrated in the BRE Innovation Park (BRE, 2012). However, in practice, the deployment of these technologies is still very limited. So, why have not we seen the wide diffusion of these technologies or solutions in practice? There are already literatures looking into the issue from the perspectives of, e.g. industrial relationships (Anderson and Manseau, 1999; Dubois and Gadde, 2002), organisational studies (Barlow, 2000), economic sociology (Biggart and Lutzenhister, 2007, cited in Emtairah et al., 2008), and social structuring of technical innovation (Shove, 1998), but few have approached it using the innovation system and functions approach (Emtairah et al., 2008) as this study intends to do, thereby providing insights from an evolutionary, socio-technical perspective.

1.3 Evolutionary theory, Innovation Systems and Technological catch-up

Strongly inspired by Schumpeter's works, particularly his emphasis on innovation in '*The Theory of Economic Development*' (Schumpeter, 1934 [in English]), evolutionary economic theory has been developed as an alternative to neoclassical theory after the latter was seen as failing to satisfactorily explain the observed pattern of international trade and long-term technological, economic and social changes (Freeman, 1982a; Fagerberg, 2002; Nelson, 2008a). By focusing on the role of technological change and innovation in economic growth, the evolutionary theory sees economic activities as constantly interacting with, while also being influenced by, various factors (e.g. social, political, cultural and scientific) which are likely beyond the economic domain; meanwhile individual and organisational economic actors often make decisions within the limits imposed by 'bounded rationality' (Simon, 1972), while following the routines that have in the past yielded satisfactory results; nevertheless, when opportunities arise, actors are, at the same time, capable of innovating through 'learning' by doing and interacting (Lundvall, 1988; Nelson, 2008).

Evolutionary studies often involve exploring how economic and non-economic factors interact in affecting technical change and economic growth, which has led to the formation

of several highly influential notions e.g. technological paradigm and trajectory (Dosi, 1982), techno-economic paradigms (Perez, 1983), socio-technical systems (Kline and Rosenberg, 1986), and innovation systems (Freeman, 1987; Lundvall, 1992; Nelson, 1993). The perspective offered by these notions stresses technology, market and institution interacting in a complex and systematic way, exerting strong mutual influences over time, and thus leading to path-dependence; in this respect, the world economy is characterised by incessant changes driven by innovations at firm level that lead up to the process of creative destruction at macro-economic level (Freeman and Soete, 1997; Kattel et al., 2011).

With its theoretical origin in the evolutionary theory of technical change, as well as the theory of interactive learning (Edquist, 1997), the Innovation System (IS) strand of research recognises that individual or organisational actors do not innovate in isolation, whereas the process of innovation may span over time and is influenced by many factors. Lundvall (1992, 2007) defines an IS as constituting elements that interact in shaping innovation processes as well as elements that link innovation to economic performance. Edquist (1997, 2001), on the other hand, gives a much broader definition, *i.e.* an IS consists of all important economic, social, political, organisational and other factors that influence the development, diffusion and use of innovations. To this end, the study of innovation systems essentially involves the identification of determinants that affect the development, diffusion and use of innovations or technologies.

The initial works on innovation systems by Freeman (1987), Lundvall (1992) and Nelson (1993) focus on national levels, *i.e.* the National Innovation System (NIS), which, from different perspectives, explore whether and how institutional-based factors can explain the comparative innovation performance among countries, and the relative status of 'forging-ahead', 'catching-up' and 'falling behind' (Freeman, 1995; Edquist, 1997). Around the same time, Carlsson and colleagues developed the concept of the Technological Innovation System (TIS) and argued that technological changes tended to follow patterns specific to a given technological field, and were thus much likely bounded by techno-industrial features than by national borders (Carlsson and Stankiewicz, 1991). The two concepts were quickly diffused in both academic and political circles, and inspired other variations e.g. Regional Innovation System (RIS) (Cooke 1992, 1998; Asheim and Coenen, 2005), Sectoral Innovation System (SIS) (Breschi and Malerba 1997, Malerba, 2004), while a variety of

international and national bodies, including the European Commission, OECD, the World Bank and various United Nations agencies, adopted the IS approach, to varied extents (Edquist, 1997; Lundvall, 2007).

As a relatively new concept, the IS approach inevitably faces a number of conceptual, analytical and methodological issues (Edquist, 1997; Carlsson et al., 2002), which are seen to prevent ISs from becoming a more 'rigorous' and 'theoretical' concept (Edquist, 2004). One of them is 'conceptual diffuseness'; for instance, there is still no agreement on the definition of ISs, or 'institutions', in literature (Fagerberg and Srholec, 2008), which leads to the vagueness over the boundary of an IS, especially the non-geographic, functional boundary of a system (Edquist, 1997, 2004). Also, there is no agreed methodology for the empirical study of ISs (Fagerberg and Srholec, 2008). A situation is not helped by the fact that innovation systems can differ between countries, regions, sectors or technological fields, whereas organisations (actors) and institutions as the constituting elements of an IS may also vary in different countries, regions, sectors, and technology fields; these differences, as well as the evolutionary nature of innovation systems, make it impossible to define an optimal system of innovation, and therefore the empirical study of ISs has often relied on comparing different systems (Edquist, 1997).

Throughout the years, different attempts have been made to study ISs based on the 'functions' of an IS (Liu and White, 2001; Bergek, 1998; Bergek and Jacobsson, 2001; Hekkert et al., 2007; Bergek et al., 2008a), or 'key activities', as Edquist (2004) prefers. The functions approach postulates that the overall function of an IS is to induce the generation, diffusion and utilisation of innovations, which can then be configured into a number of sub-functions (or 'system functions', hereafter 'functions'). To date, it is widely accepted that there are seven such functions (Bergek et al., 2008; Hekkert et al., 2007): (a) knowledge development and diffusion, (b) entrepreneurial experimentation, (c) guidance on the search, (d) market formation, (e) resource mobilisation, (f) legitimisation, and (g) the development of positive externalities. In this respect, as Edquist (2004) states, given our limited knowledge on the systematic dynamics of innovations, this focus on the functions helps to increase our knowledge of innovation processes, and our capacity to explore the determinants of specific innovation systems.

The emergence of the functions approach has strengthened IS's position as a policy

concept, and an alternative framework to support technological change and innovation. It departs from a narrow concept of market failure, instead focuses on a broader set of system failures (Markard et al., 2012), and thus enables “*policy-makers to identify the processes and components in a system where intervention is likely to matter most*” (Jacobsson and Bergek, 2011: 41). Recently, the Innovation System approach has been identified as one of the four major theoretical frameworks by which sustainability transitions have been studied (ibid; van den Bergh et al., 2011; Markard et al., 2012). More so, in comparison with e.g. the ‘multi-level perspective’ on transition (Rip and Kemp, 1998; Geels, 2002), the IS and functions approach have been praised for providing a better analytical tool with a more elaborated framework that allows the analyses of both niche-level innovations, and the meso-level socio-technical regimes, as well as the interaction between niche-innovation and the surrounding networks and institutions (Negro, 2007; Markard and Truffer, 2008).

Given the aforementioned analytical strengths, this PhD research uses the IS and functions approach to study two emerging low carbon building technologies in Wales. The assumption is that, for an emerging technology to develop and achieve successful market diffusion, it needs to be fostered by a TIS (Suurs et al., 2010); by examining how the functions of a TIS have been fulfilled, it can help to establish whether a TIS has formed. Moreover, it is believed that the function analyses can help to uncover whether system failures or weaknesses have occurred, while offering insights and evidence on how policy intervention should be designed to alter the functional pattern and improve the innovation capability of the relevant actors.

Since this study focuses on the development of low carbon building technologies at regional level, specifically in Wales, this, to a large extent, allows the system boundary of the proposed TISs to be drawn, which is essential for defining the system components (e.g. actors and institutions) of the proposed TISs, their attributes and key relationships within the systems (Carlsson et al., 2002). However, this does not mean that the proposed TISs only operate within the geographic and administrative borders of Wales; rather this regional perspective provides a starting point to facilitate the analyses, as where to draw the boundaries can be circumstance related (Carlsson and Stankiewicz, 1991). On the other hand, this regional focus reflects the growing recognition that innovation and entrepreneurship are essentially spatially embedded and localised processes (Asheim et al.,

2006), while geographical, cultural and political proximity are important for actors to establish intimate and extensive communication, and effectively organise economic activities (Carlsson and Stankiewicz, 1991).

As noted, the post-devolution government of Wales has wide-ranging legislative powers over twenty devolved areas. This is particularly the case with respect to the built environment in that, with the full-fledged competency on both planning and building regulations, the Welsh Government is now in a position to introduce varied policy instruments to help set a Welsh transition to a low carbon built environment in motion. Nevertheless, while it is argued in this thesis that the functions approach can help the Welsh policy-makers to identify where intervention is likely to matter most, factors such as the type of policies adopted, the way that the policies are implemented, the organisational capabilities and the leadership quality of regional administration can also affect the innovation processes and the development of innovation capability within the region. Moreover, these factors are more than likely confined and shaped by what happened in the past.

As indicated, Wales remains a peripheral region that has failed to catch-up for decades. On the other hand, the successful experiences elsewhere have shown that, whereas successful economic or technological catch-ups were attainable, they often required a break from previous familiar practices while learning to master new ways of doing things (Nelson, 2004). This is because economic and technological backwardness is not a mere accident, where the tenacious societal characteristics that are responsible for a country's past failure likely remain to keep it from making the full technological leap (Abramovitz, 1986). An effective way to abandon such 'tenacious societal characteristics' is through developing new 'social capability' (ibid), in terms of e.g. a country's general education system and technical competence, the commercial, industrial and financial institutions which affect a country's capacity to finance and operate modern, large-scale businesses, or the political and social characteristics that influence the risks, the incentives and the personal rewards of economic activity (Abramovitz, 1994). This proposition of a combination of institutional and political factors needed for successful catch-up has generated a certain research tradition with respect to identifying the factors conducive to catch-up, e.g. 'technological capability' (Kim, 1980), 'innovation capability' (Dahlman et al., 1987), 'absorptive capacity' (Cohen and Levinthal, 1990).

In recent years, the literatures on catch-up have increasingly adopted an innovation system perspective (e.g. Sung and Carlsson, 2003; Malerba and Nelson, 2011; Cusmano et al., 2010). On the other hand, this study argues that the gap arising in the existing RIS literature may also make it necessary to integrate the literature on technological catch-up when the study of ISs in peripheral regions is concerned. The existing RIS literature does not seem to separate the study of peripheral (or less favoured) regions from that of high-tech and well-performing regions, while the latter is often the exclusive subject of RIS studies (Markusen 1999; Doloreux and Parto 2005; Uyarra 2010; Asheim et al., 2011). This tendency has led to regional policies indifferently stressing the need to attract high-tech, knowledge based or 'creative' industries, and to stimulate spin-offs etc., without taking into consideration the specific strengths and weaknesses of individual regions (Tödting and Tripl, 2005), particularly in terms of institutional arrangements, knowledge infrastructures and innovation capabilities. In this respect, when good practices in advanced regions may offer inspirations to emulate, the peripheral regions, e.g. Wales, may not have the right social technologies (Nelson and Sampat, 2001) and institutional infrastructure to deliver these good practices. However, by drawing insights from countries and regions who have successfully caught-up, peripheral regions such as Wales may learn how the necessary institutional infrastructure and social technologies may be developed.

1.4 Purpose of the research

The aims of this PhD study are twofold. First, it sets out to develop theoretically informed and empirically grounded insights into the development of low carbon building technologies in Wales through investigating how the functions of innovation systems of two emerging technologies have been fulfilled respectively. The two emerging low carbon building technologies chosen for this study are 'Welsh grown timber for construction' (WTC) and 'building integrated solar energy systems' (BISE). Here, the term 'emerging' is used, in a sense that the development and use of the technologies are new for Wales, even though some elements of these technologies may previously have been deployed elsewhere around the world.

Secondly, having compared the functional patterns of the WTC and BISE TIS and analysed the similarities and differences that have arisen, this study goes on to explore the extent to which the findings of the function analyses offer a bottom-up perspective on how regional governance in Wales might help to alter the functional patterns, in terms of

leading to the successful market diffusion of these low carbon building technologies, while improving the relevant innovation capability in Wales.

The corresponding research questions (Q) are:

- Q1: Can a bespoke analytical framework be developed and used to analyse the emergent WTC and BISE innovation systems in Wales?
- Q2: To what extent have the functions of the WTC and BISE TIS been fulfilled? Based on the results of the function analyses, what conclusion can be drawn with regard to the status of the two TISs?
- Q3: What does the comparative study of functional patterns of the WTC and BISE TISs tell about the relevant innovation capability in Wales?
- Q4: Subsequently, what are the policy implications for regional governance in Wales in terms of altering the functional patterns and improving the innovation capability of relevant Welsh organisations?

1.5 Methodology

This PhD study is linked to the research I conducted for the European Regional Development Fund (ERDF) sponsored project '*Low Carbon Built Environment (LCBE)*' between 2010-2013. The two selected technologies link to two of the Work Packages, and such connection has provided important accesses to data and information, as well as contacts required for the interviews. The main research methods are as follows.

Literature review

This research has involved extensive literature reviews of a number of subject areas: evolutionary economic theory; innovation systems; technological catch-up; Wales since the industrial revolution (with focuses on socio-economical development and changes in policy and governance); the development of timber construction and solar technologies once the case studies were selected. The literature sources include books, journal and research papers, policy documents and technical reports from the Welsh Government, the National Assembly of Wales, the UK government, OECD, the European Union, international organisations in the field of energy and timber, and trade associations e.g. the UK Timber Research And Development Association (TRADA) and the European Photovoltaic Industry Association (EPIA), etc., and news articles, etc.

Case Study

As indicated, two fields of low carbon building technologies were selected for empirical studies, owing to the perceived relevance to the research purpose. The analysis has been carried out using the proposed analytical framework that consists of seven functions of the innovations system with relevant performance indicators selected for each function. Apart from literature review, semi-structured interviews were also carried out in order to advance the understanding, which is supplemented by the attendance of several seminar / conference events for the purpose of gathering information and forging contacts for the interview.

Semi-structured Interviews

Either by face-to-face or through telephone, 34 semi-structured interviews were carried out between May 2012 and July 2013, involving representatives from businesses across the Wales in a number of sectors (e.g. timber, solar technology, steel and construction), government departments, relevant NGOs and research organisations. Interview questions were prepared beforehand in line with the chosen functions of the innovation system. Most interviews lasted between 30 to 100 minutes. All interviews were transcribed by a professional transcription service, and were subsequently coded manually.

The identification of interviewees was based on a mix of recommendations (the 'snowball' method), networking in the seminar / conference events, and Internet search of relevant trade associations e.g. TRADA and EPIA, although two different foci were taken. With regard to the WTC TIS, the selection was most along the supply chain, and therefore the interviewees included forest owners (including the then Forestry Commission for Wales), sawmills, secondary wood processors and architects, as well as related stakeholders e.g. landowner associations, research institutes and relevant government bodies (e.g. the Construction Sector in the WG). For the BISE TIS, as the technological field is still at the early stage of commercialization, a supply-chain perspective is less relevant, and instead the interviews were set to cover as many relevant Wales-based actors as possible; to this end, the representatives of most of the Wales-based solar firms and research institutes were interviewed (with one group missing *i.e.* solar installers, which will be discussed later in Chapter 3).

Comparative study

True to the tradition of empirical study of ISs, the two case studies will also be studied in a comparative manner later in the thesis. It is expected that the similarities and differences arising from the comparison can help to better establish the system strengths and weaknesses with regard to the development of low carbon building technologies in Wales, and offer insights into the relevant innovation capability within the region; subsequently, these findings provide a bottom-up perspective on how regional governance might be more responsive to local circumstances, while helping to alter the functional pattern and enhance the innovation capability of relevant Welsh organisations.

1.6 Structure of the thesis

The remainder of this thesis is sequenced as follows.

Chapter 2 [Literature review] provides the theoretical basis for the analysis carried out in this thesis; it starts with an overview of evolutionary economic theory, and its contribution to the emergence of the innovation system approach, which is followed by an exploration of the definition and process of innovation. Next, the IS strand of literature is critically reviewed, covering the four major IS approaches *i.e.* national, regional, sectoral and technological respectively, and the functions approach, while some gaps in the existing literature are explored. This is then succeeded by the review of the relevant literature on technological catch-up, and the discussion of how insights may be drawn from countries or regions that have successfully caught up.

Chapter 3 [Research methods, analytical framework and case study selection] provides an explanation of why and how this research has been carried out. It explores the methods used in the study of the IS functions, and explains the broad approach taken in this research; subsequently, the proposed analytical framework is developed. The chapter then goes on to elucidate how case studies were chosen, the interviewees selected, and data collection and processing carried out, followed by the discussion of the methodological strengths, novelty and limitations of the research.

As history matters, Chapter 4 [Wales: the distance travelled] is set to study why Wales has lagged behind from a historical perspective, and explores the extent to which the past may have impacted on the economic, institutional and technological performances of

Wales at present. It includes a historical review of socio-economic development in Wales since the industrial revolution, the regional policy interventions by the British State before devolution, changes in the regional governance since devolution, and the emergence of a Welsh low carbon transition narrative, etc.

Chapter 5 [Case study: introducing the structural components] commences the proposed case studies. It focuses on establishing the structural components of the two selected technological systems, *i.e.* ‘Welsh grown timber for construction (WTC)’ and ‘building integrated solar energy systems (BISE)’ in Wales, so to set up the context for the examination of the functions of the two TISs in the following chapter.

Chapter 6 [Case study: mapping the functional patterns] is dedicated to investigating the extent to which the functions of the WTC and BISE TISs have been fulfilled respectively; this is followed by a discussion on whether the two TISs have been formed in Wales, and how likely they may move onto a stage of successful market diffusion.

Chapter 7 [Discussion and conclusion] mainly addresses Research Question Three and Four, *i.e.* by assessing the functional patterns of the WTC and BISE TIS in a comparative manner, the ‘system strengths’ and ‘system weaknesses’ will be explored in relations to the relevant innovation capability in Wales; this subsequently leads to the postulation of possible policy measures at the regional level that might alter the functional patterns, and improve the relevant innovation capability within the region. The chapter then draws a conclusion to this PhD study, which includes an evaluation of the contribution of this PhD study, and suggestion for future research.

Chapter 2: Literature Review

*“Refuge from crises can only be found in social and technological innovation.”
(Mensch, 1979:3)*

This ‘literature review’ chapter establishes and examines the theoretical framework within which this PhD study has been carried out. It also identifies and discusses some gaps arising in the existing literature and the extent to which this research may help to address these gaps. This chapter contains five sections.

Section 1 explores how the emergence of evolutionary economic theory has led to the development of the innovation system (IS) approach. This is followed by a review of the concept of innovation, and how our understanding on innovation processes has evolved from early linear models to a more complex, integrated system perspective, in particular Dosi’s technological paradigm and trajectory.

Section 2 is dedicated to the IS strand of literature. Four main IS approaches, *i.e.* national, regional, sectoral and technological, are critically reviewed individually, while some of the analytical and methodological gaps emerging in the current literature are explored. In Section 3, the functions approach is examined, which includes a brief account of the important literatures that have contributed to the development of the functions approach. Then, the seven IS functions that are deployed in this study are explored respectively, followed by the discussion of the issues that may affect the use of the functions approach.

Section 4 is not in the original frame of this study, however, as this research was progressing, especially further into the empirical study stage, it became clear that the nature of economic and technological advances in Wales often involves catch-up, in terms of not only the development of technology *per se*, but also the development of social technologies and institutional infrastructures that facilitate these changes. To this end, this section explores the literature on technological catch-up, with intention to draw insights from countries and regions that have successfully caught up.

In Section 5, I draw a conclusion to this literature review chapter.

2.1 Evolutionary economic theory and innovation

It is now commonly accepted that technological change is a main determinant of economic growth, and innovation is an essential condition of economic and social changes. However, it was not until 1960s that academic interests on innovation and the relationship between technical change and economic growth revived, after the prevailing neo-classical economics seemed to fail to satisfactorily explain the observed pattern of international trade and long-term technological, economic and social changes (Fagerberg, 2002; Freeman, 1982a). Explicitly influenced by Schumpeter's works e.g. *The Theory of Economic Development* (Schumpeter, 1934 [in English]), the next two decades saw the emergence of evolutionary economic theory. As outlined in Table 2.1, the evolutionary theory fundamentally differs from the neo-classical theory; it views economic activities interacting with, and being influenced by, various factors (e.g. social, political, cultural and scientific) that are likely beyond the economic domain; thus the economic process is often characterised by uncertainties that are not always perfectly known or understood by both individual and organisational economic actors (Nelson, 2008a; Verspagen, 2001).

Table 2.1: A comparison of the evolutionary and neo-classical theory

Neo-Classical Theory	Evolutionary Theory
<ul style="list-style-type: none"> ▪ Use of physical metaphors ▪ 'Equilibrium' as a central feature ▪ Static / comparative statics ▪ High degree of precision ▪ Assumes perfect information ▪ Time not an issue ▪ Entrepreneurship unimportant ▪ All economic activities are equal (potato chips, wood chips, computer chips) ▪ The 'representative firm' ▪ The market as price setter ▪ Technology as a free good 	<ul style="list-style-type: none"> ▪ Use of biological metaphors ▪ Emphasis on factors causing disequilibrium ▪ Dynamic ▪ Less precise, open to non-quantifiable factors ▪ Operate under uncertainty ▪ 'History matters' ▪ Entrepreneurship central factor ▪ Economic activities are different because there are innovation 'foci' at any point in time ▪ The 'representative firm' does not exist ▪ The market also as selection mechanism among firms ▪ Technology as an important factor in wealth creation and distribution
Source: Kattel et al., 2011 (based on Reinert and Riiser 1994)	

One central theme of the evolutionary study is the exploration of interactions between economic and non-economic factors, and their impacts on technological changes and economic development. This has led to the introduction of a number of highly influential concepts or notions, including technological paradigm and trajectory (Dosi, 1982), techno-economic paradigms (Perez, 1983), socio-technical system (Kline and Rosenberg, 1986), and, of course, innovation systems (Freeman, 1987b; Lundvall, 1992; Nelson, 1993). Edquist (1997: 14) has gone so far to define an IS⁶ as constituting “*all important economic, social, political, organizational, institutional and other factors that influence the development, diffusion, and use of innovations*”, and thus the mission of the IS approach is to identify all these important factors, or the determinants of innovations.

At the micro-economic level, the evolutionary theory explains the behaviours of individual and organisational actors through concepts such as skills, routines, imitation, selection, ‘bounded rationality’, and path dependence within firms and industries, using approaches e.g. ‘appreciative theory’ (which is like storytelling with the aim of capturing the basics of what actually is going on) (Nelson and Winter, 1982; Nelson, 1998, 2008a). The ‘rationality’ of the actors is viewed as being bounded, but, at the same time, potentially creative and innovative. Through the process of ‘learning’ by doing and interacting, the actors are capable of developing new skills, knowledge, and new management attitudes and structures (Lundvall, 1988).

The evolutionary theory of technological change is identified as one of the underlying theoretical origins of the IS approach (Edquist, 1997). This does not say that other theoretical constructs have not influenced the development of the varied IS approaches, as will be explored later. Rather, the evolutionary theory is seen to provide an underlying analytical structure for apprehending the behaviours of individual and organisational economic actors, and exploring the complex and changing network of interactions and cooperation among a variety of agents, which contributes to the generation, diffusion and utilisation of innovations and technologies. Although before I move onto the IS strand of literature, I next theoretically explore the important concept and process of innovation.

⁶ As indicated in Section 1.3, Chapter 1, Lundvall has defined the IS differently, with a more restricted view (Godin, 2009).

2.1.1 Innovation: the definition

Schumpeter (1934: 65) defined innovation as the '*new combination*' of the materials and forces within our reach in form of new products, processes, raw materials, organisation or market which is carried out within the economic sphere with a commercial purpose. He particularly distinguished innovation from invention. As Freeman (1987a; Freeman and Soete, 1997) explains, invention normally means a novel idea, sketch or model for a new or improved product, process or system, which may be patented but does not necessarily lead to technological innovations; innovation, on the other hand, is only accomplished with the first commercial transaction involving new products, processes, methods or systems; so, there is an immense difference between 'working' under laboratory conditions and under market conditions. Such distinctness has now become a generally accepted notion in the study of technological change.

Moreover, Freeman (ibid) points out the 'diffusion' dimension of technical changes in the Schumpeterian framework. In other words, through a population of potential adopters (imitators), the diffusion of innovation generates multiplier effects in generating additional demand and in turn induces a further wave of innovations (clusters of innovations) in certain sectors and over certain time periods, which combine creating expansionary effects in the economy. The interdependence between economic and technological elements suggests a strong systemic character of the innovation process, and gives rise to the 'lock-in' and 'path-dependence' effects of each dominant style in technology (Freeman and Soete, 1997; Dosi, 1988). Subsequently, this systemic aspect of innovation-diffusion dimension as well as its relationship to social, institutional and political factors becomes a central theme of the innovation system approach (Fagerberg, 2002).

While the aforementioned discussions seem to suggest that individual and organisational economic actors are the main enablers of innovation, in recent years, the notion of 'social innovation' has gained ground in academic, non-for-profits and public service sectors. The examples of social innovations include microcredit, self-build housing, the Open University, distance learning, and community wind farms etc. The main difference separating social innovation from commercial innovation is its motivation, i.e. social innovation is not driven by profit maximization but by social purposes, e.g. inequalities, health and education; but the borderline can sometimes become blurry when individual social innovations are adopted by businesses, e.g. the model of distance learning (Mulgan et al., 2007). While this

research mainly looks into the innovation developed for commercialisation, it recognises that social innovation has a role to play in capacity building with regard to e.g. networking and regional governance (Howaldt and Schwarz, 2010).

2.1.2 Innovation process

An ever-present inquiry in innovation studies is the search for the factors that influence both the rate and direction of innovation, with questions such as ‘What causes innovation?’ ‘Why do certain technologies emerge instead of others?’ As Mowery and Rosenberg (1979) point out, an understanding of the innovation process at this level is essential if government intervention is to be successful in promoting innovations in specific areas. The linear models of ‘market-demand pull’ and ‘technology push’ dominated early debates. As illustrated in figure 2.1 and 2.2, the ‘market-demand pull’ reckons that demand (or market force) is the leading force in determining the direction and magnitude of inventive activities over the business cycle, whereas the ‘technology push’ model suggests that developments in science and technology are the essential force behind the social-economic advance as firms spot economic opportunities in new technological possibilities (Rothwell, 1994). However, the linear models have been criticised for their oversimplified assumptions, methodological flaws, and conceptual confounding (Mowery and Rosenberg, 1979; Freeman, 1979; Dosi, 1982). For instance, it was suggested that the linear models have ignored the nature of process innovations during a production stage, which often involve learning processes through cumulated experiences (Kline and Rosenberg, 1986).

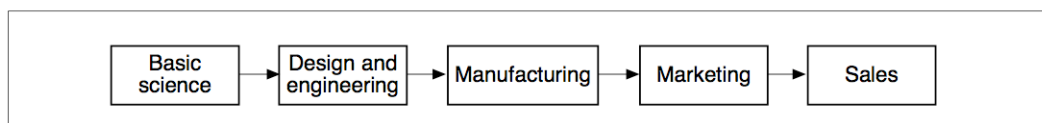


Figure 2.1: ‘Technology push’ model (Source: Rothwell, 1994)

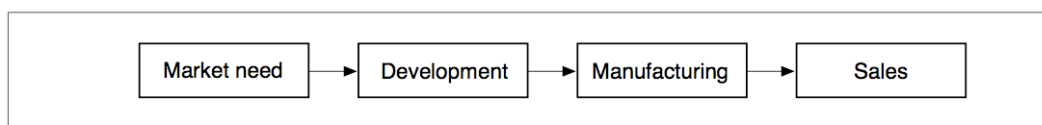


Figure 2.2: ‘Demand-pull’ model (Source: Rothwell, 1994)

In turn, the scholars of the evolutionary study argue that the innovation process is

complex, uncertain and often disorderly, which normally involves periods of research, experimental design and development that require iterative learning and feedback mechanisms, while operating at the ever-changing interface between science, technology and the market. Kline and Rosenberg (1986) proposed to consider the process of innovation as an exercise in the management and reduction of uncertainties; the greater the changes introduced, the greater the uncertainties, in terms of not only technical performance but also the market response and the ability of organisations to absorb and take advantage of the requisite changes effectively. This strong correlation between the degree of change and the level of uncertainty implies a complex nature of the innovation process, with various forms of knowledge involved at different stages of the life cycle of a given product. This becomes evident in some empirical studies of innovations at firm levels. For instance, the SAPPHO⁷ project indicated a changing pattern of causalities, i.e. at the birth and early stages of development of new industries, major new developments in science appeared to trigger waves of invention and in turn led to the recognition of big new business opportunities; however, once such new industries were maturing, the shifting patterns of consumer demand and the requirements for process improvements seemed to become the principal determinants of the direction and scale of innovations, thus producing classical demand-led innovations (Freeman, 1979; Rothwell et al., 1974; Bernal, 1953).

Dosi (1982, 1988) postulates an alternative explanation in the notions of 'technological paradigm'⁸ and 'technological trajectory'. He sees innovation as a problem-solving process, which involves both 'discovery' and 'creation' aspects. The information inputs, knowledge and capabilities from which innovators draw for the development of new technologies or innovative solutions assemble a 'knowledge base'. The knowledge base in a specific field and the common patterns of problem solving activities that base on highly selected principles derived from natural sciences jointly create a 'technological paradigm' or a 'dominant design' (Arthur, 1988). The development made along the path created by a technological paradigm form 'technological trajectory' that tends to lead to the 'normal' problem-solving activities. The paradigm generates cumulative effects and becomes highly

⁷ SAPPHO (Scientific Activity Predictor from Pattern with Heuristic Origin) was a three-year research project funded by the UK Science Research Council and carried out by the Science Policy Research Unit (SPRU) at the University of Sussex (Cumow and Moring, 1968). Christopher Freeman was the founder and the first Director of the SPRU

⁸ Dosi defines 'technological paradigm' in analogy with Kuhn's (1962) 'scientific paradigm'.

selective. As it grows more powerfully, a switch from one trajectory to an alternative one becomes extremely difficult, creating a 'lock-in' effect.

A technological paradigm could generate a cluster of possible technological directions. Given the intrinsic uncertainty associated with the innovation process, it is hardly possible to compare and rank the technological and economic successes of all possible trajectories *ex ante*. Subsequently, other more specific variables come into play, e.g. economic (market), institutional and social factors, including those so-called 'selective disadvantages' e.g. hostile climate or geographic conditions, high labour cost or lack of raw materials (Vernon, 1966; Porter, 1990, 1998a). They operate as a selecting device at each level of research and development, on the grounds of some rather obvious and broad criteria e.g. feasibility, marketability, profitability or/and cost-saving capability, while exerting influence on the selected trajectories, in terms of the direction and magnitude of technical progress.

Dosi particularly stresses the role of market (economic factors) as an *ex post* selecting device at the final stage of innovation, which contrasts with its role in the previous stages acting as *a priori* directing device in choosing the technological path among the possible choices. This final market selection is considered to be similar to the effect of environmental selection on mutation, *i.e.* an 'evolutionary' mechanism within the economic environment. In all, Dosi considers economic factors performing "*as selective criteria, as final (market) checking, and as a continuous form of incentives, constraints and 'feed-back' stimuli*" (Dosi, 1982: 159).

Meanwhile, Dosi (1988) sees that scientific and technological knowledge is the major if not the sole source in defining technological paradigms. However, empirical studies on information technology (IT) innovations have challenged this proposition. For instance, it has been pointed out that an intense dialogue between the provider and the user was an essential condition of the successful implementation of IT innovations (Lockett, 1987), whereas demand or more precisely latent demand may be a main instigator of a new technological paradigm (Ende and Dolfsma, 2005). That being said, Dosi's technological paradigm and trajectory highlight how incremental innovations follow each radical innovation in the growth path, and postulate that process innovations drive most of the scaling-up investment once production volume and productivity become crucial for market expansion, as illustrated in Figure 2.3 (Perez, 2009).

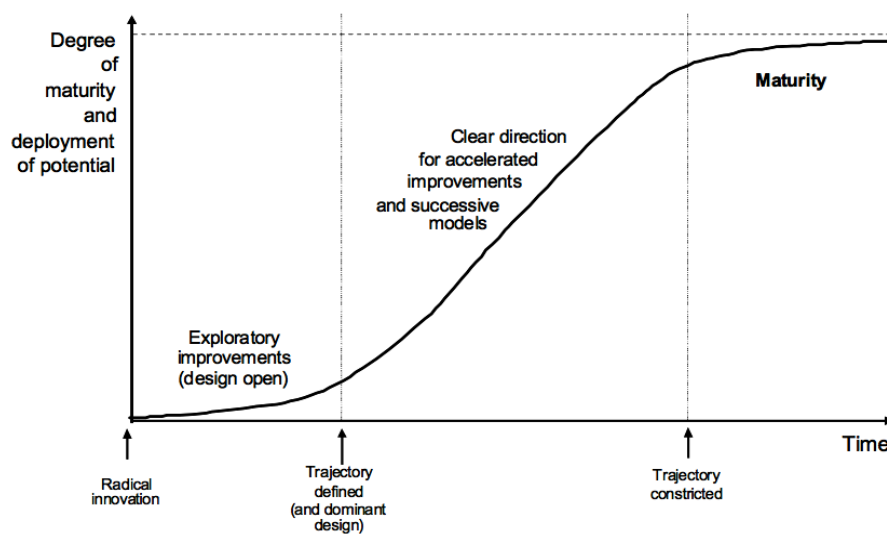


Figure 2.3: The trajectory of an individual technology (Source: Perez, 2009:5, based on Nelson and Winter, Dosi, Metcalfe, Wolf, Utterback and Abernathy, Arthur, etc.)

Dosi's technological paradigm and trajectory have since become one of the core concepts in evolutionary and innovation studies (Teece, 2008; Kattel et al., 2011). They help to explain 'path-dependence', *i.e.* past developments lead to present resource configurations, which determine future actions (Arthur, 1994). In the case of the high carbon economy, the concepts of technological paradigm and trajectory helped to establish the close linkage between our current development model and the fossil-fuel based energy systems (Kemp 1994); thereby, the inertial force of the dominant fossil-fuels based technological paradigm has limited changes to incremental developments, with the related technological trajectory generating the 'lock-in' effect (Unruh, 2000). In this respect, a low carbon transition requires the emergence of different sets of technological paradigms and trajectories which can lead to not only the innovations of disruptive nature at the firm level but widespread creative destruction to the broader social, institutional, economic and technical systems that are supporting the existing energy infrastructure.

2.2 Innovation Systems

In the 1960s, Europeans became increasingly concerned about the disparities emerged in the technological and economic performances between Europe and the United States (Freeman and Soete, 1997, Godin 2002). A number of studies were commissioned by the then newly established OECD seeking to explain these gaps. The findings from these studies indicated that the gap was not in R&D *per se*, *i.e.* scientific and technological

capacity, but rather in other factors e.g. capital availability, management, competence, attitude, entrepreneurship, marketing skills, labour relations, education and culture. It was suggested that Europe had failed to develop adequate research organisations and effective entrepreneurship in the exploitation of science for practical purposes, whereas European universities were not sufficiently oriented toward economic and social needs; therefore, long-term policies involving structural changes were required (Ben-David, 1968; Godin, 2009). Between the 1960s and the early 1990s, OECD published a series of publications and advocated member states to adopt a system approach towards research. These publications were considered to be one of the early sources for the idea of the innovation system (Godin, 2009).

Freeman's book "*Technology Policy and Economic Performance: lesson from Japan*" (Freeman, 1987b) is widely cited as the first publication⁹ to formally introduce the innovation system (or the system of innovation) approach, in the form of the National Innovation System. Together with the seminal works by Lundvall (1992) and Nelson (1993), they, from different perspectives, explore whether and how institution-based factors may determine the comparative innovation performance among countries, and affect the processes of forging-ahead, catching-up, and falling-behind by countries (Freeman 1995; Edquist 1997). Around the same time, Carlsson and colleagues developed the concept of the Technological Innovation System (Carlsson and Stankiewicz, 1991), which suggests that technological changes often follow patterns specific to a given technological field, and are thus more likely bounded by techno-industrial characteristics than by national borders.

The two concepts were quickly diffused in academic circles, and inspired other forms of the IS, namely Regional Innovation Systems (Cooke, 1992, 1998; Asheim and Coenen, 2005), and Sectoral Innovation Systems (Breschi and Malerba, 1997; Malerba, 2004), as well as some conceptual works at firm levels. Whilst differing in system boundaries and emphases, these concepts are seen to complement rather than compete with each other (Edquist 1997; Lundvall et al., 2009). As follows, I will explore the four main IS approaches individually.

⁹ At the beginning of the 1980s, Freeman was working closely with Lundvall and colleagues at Aalborg University in Denmark. This collaboration contributed to the early conceptual development of NIS. Lundvall is regarded by Freeman (1995) to be the first person to use the expression of NIS. Lundvall (et al., 2009), on the other hand, suggests an unpublished 1982 OECD report from Freeman (1982b) to be the first written contribution to the concept.

2.2.1 National Innovation System (NIS)

Freeman (1995) stated that the idea of National Innovation System could be traced back to Friedrich List's conception of '*The National System of Political Economy*' (List, 1841), which was seen to have helped Germany overtake England in the late 19th century. At the time, List was concerned that, if adopted Adam Smith's invisible hand and his cosmopolitan strategy, Germany (and other underdeveloped countries) would have permanently and increasingly lagged behind England; he subsequently advocated that national governments should be active in coordinating and carrying out long-term industrial and economic policies, protecting infant industries, building infrastructure for science and education, etc. In particular, List viewed 'intellectual' capital being more important than physical and financial capitals (Lundvall et al., 2009); together with other like-minded economists, they helped Germany develop one of the best technical education and training systems in the world, and laid the foundation for the superior skills and higher productivity of the German labour force (Prais, 1981, cited in Freeman, 1995). It was suggested that Japan has learnt from List's model in its successful post-WWII catch-up (Fallows, 1993).

In his 1987 book on Japan's national system of innovation, Freeman defined the NIS as "*the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies*" (Freeman, 1987b: 1). He particularly looked into four institutional aspects of the Japanese system, which were: (a) the role of the Ministry of International Trade and Industry (MITI); (b) the role of company research and development strategy in relation to imported technology and 'reverse engineering'; (c) the role of education and training, and related social innovations, and (d) the conglomerate structure of industry. Freeman stated that the NIS has enabled Japan, a country with rather limited natural resources, to rapidly progress, not only overtaking those leading countries but also opening up a technology gap in some industrial sectors (ibid). I shall discuss some key features of the Japanese system later in Section 2.4.

Following Freeman's book, more works were published on the NIS, where two 'schools' of thinking arose (Edquist, 1997; Lundvall, 2007): the Aalborg-school¹⁰ led by Lundvall, and the institution-based perspective represented by Nelson's works. Such difference is clearly reflected upon their respective definitions of the NIS, as follows.

¹⁰ This mainly includes the researches conducted by the IKE (Innovation, Knowledge and Economic Dynamics) Group based at Aalborg University in Denmark with Lundvall as a leading figure.

A NIS constitutes -

Elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge, ...and are either located within or rooted inside the borders of a nation state (Lundvall 2010a: 2).

A set of institutions whose interactions determine the innovative performance of national firms (Nelson and Rosenberg, 1993: 4).

For this study, two lines of inquiry, i.e. the 'user-producer' linkages relating to the works of the Aalborg-school, and the concept of 'social technologies' linked to Nelson's works on institutions, have emerged to be particularly relevant. The former is relevant to the debate that is already discussed in the previous section, i.e. what causes innovation, demand or technology? An understanding of the 'user-producer' linkage is seen to offer a different aspect for devising relevant policy instruments, e.g. demand-oriented policies, if policy intervention is required. Meanwhile, even though institutions are universally considered to be an essential component of ISs, in the IS literature the term 'institution' is often used without clear clarification on what 'institution' actually mean; in other words, the term 'institution' is often interpreted in different contexts, for instance, as a substitution to 'organisation' or 'market' (Edquist and Johnson, 1997; Cooke et al., 1998; Nelson, 2008b). To this end, Nelson's interpretation of institution, with the introduction of the term 'social technologies', appears to provide a better-defined framework for developing our understanding on how institutions and institutional changes relate to technological advances and economic growth.

(a) User- producer linkages

Essentially, the Aalborg-school bases its conception on two sets of assumption: (a) "the most fundamental resource in the modern economy is knowledge and accordingly the most important process is learning", and (b) "learning is predominantly an interactive and thus a socially embedded process that cannot be understood without taking into consideration its institutional and cultural context" (Lundvall 2010a: 1). In this respect, technical change is seen as a learning process of gradual and cumulative in character. This notion of interactive learning is seen by Edquist (1997) to constitute one of the two theoretical origins of the IS approach (the other being the evolutionary theory, as discussed), and has since led to the

concept of 'knowledge-based economy' or 'learning economy' (Lundvall and Johnson 1994; Godin 2009), and of 'learning regions' (Morgan, 1997).

Lundvall (1988, 2010b) particularly stresses the importance of the interactive learning experience between users and producers in producing successful product innovation, for it provides a single mechanism that is able to automatically select the optimal combination of markets and organisations (in terms of innovative producers and potential users). In this sense, a close interaction between competent users and producers may have contributed to the patterns of specialisation in many small open economies, e.g. dairy technology in Denmark, and wood-cutting and metal working technologies in Sweden.

The user-producer linkage constitutes part of vertically integrated networks in an IS, with a number of inherent characteristics (ibid): it is often durable over time; the effectiveness of interaction between producers and users is affected by not only the geographical-physical proximity but cultural distance, and thus it works more effective if users and producers are close to each other, especially when user needs are complex and ever-changing; meanwhile, this interaction is more important for incremental innovations than for radical innovations. However, in a negative term, the user-producer interaction also likely yields adverse impacts and lead to 'unsatisfactory' innovations, due to the inertia incurred in the relationship, or a lack of competent and demanding local users; this causes firms to be captivated in the established technological trajectories and miss out truly new and better technological opportunities (Christensen, 1997).

A limited number of empirical studies designed to test this user-producer linkage have been carried out. For instance, upon examining Danish manufacturing and service firms, Laursen (2011) attests the presence of positive correlation between customers' knowledge and firms' innovations. He argues that using customers as a source of innovation is justified by the ample positive association with higher levels of innovative sales; however over-dependence on customers' knowledge can prevent firms from searching in new direction, given that firms are unable to widen their search breadth e.g. external knowledge sources; while there is clear difference between firms' interactions with local customers and with international customers for incremental innovations, such difference diminishes for more radical innovation (new to the firms' market).

In recent years there are increasing calls for demand-oriented policies for innovation (EU, 2012a; Edler, 2009; NESTA, 2010; Edquist and Zabala-Iturriagoitia, 2012). This emphasis on the user-producer linkage certainly provides much-needed theoretical support. On the other hand, as already discussed, this recognition of the importance of firm's attention to users' needs and knowledge is not new, although Lundvall's postulation shifts the attention onto the 'quality of user needs' by pointing out the likely adverse impacts caused by the inadequate user-producer linkage. In this respect, certain parallel can be drawn between the theory on the user-producer linkage and Porter's 'home demand conditions' that is seen as one of the key sources of firms' competitiveness (Porter, 1990, 1998a). It will be interesting to see whether some synergy can be generated between them. This may help to address the gap in the current IS literature, as few of which are interested in analysing the linkage between users and producers theoretically and empirically (Laursen, 2011).

(b) *Institutions and Social technologies*

Nelson's 1993 book on the national systems of technical innovation comprises a comparative study of fifteen countries, *i.e.* large market-oriented industrialised countries (USA, Britain, Japan, Germany, France and Italy), small high-income countries (Sweden, Denmark, Canada and Australia) and newly industrialising (low-income) countries (Korea, Taiwan, Brazil, Argentina and Israel) (Nelson, 1993). The key purpose was to illuminate the institutions and mechanisms that have supported the technical innovation in these countries, and influenced national technological capabilities, through exploring the similarities and differences emerged (*ibid.*). This emphasis on the role of institutions is furthered by Nelson's subsequent works, with the introduction of the term 'social technologies', as differentiated to 'physical technologies' (Nelson and Sampat, 2001).

Nelson and Sampat (2001) point out that there are varied interpretations of 'institutions' in literature: *e.g.* 'rules of the game' that includes the broad legal regime and the way it is enforced (*cf.* North, 1990); customs, standards and expected patterns of behaviour in particular contexts (Veblen, 1899); or in association with 'governing structures' moulding aspects of economic activity, like financial 'institutions', or the way firms tend to be organised and managed (*cf.* Williamson, 1975, 1985). Meanwhile, in the writings on ISs, 'institutions' have been sometimes referred to relatively concrete entities *e.g.* universities, industry-university links, public programmes.

To this end, they argue that, by employing the concept of 'social technologies', all these different lines of thinking can be coalesced coherently. In other words, the conception of social technologies is able to encompass both the ways of organising activity within specific organisations (*i.e.* the multidivisional form of organisation [the M form]), and the ways of transacting across organisational borders (the way the game is played) (Nelson and Nelson, 2002). In the meantime, the term 'institutions' is used explicitly for the structures and forces which support and hold in place prevalent social technologies, and thus tends to be used in association with broad economy-wide context conditions, including *e.g.* the legal system of a nation, a financial system capable of funding new enterprises, labour markets, and strong university research system (Nelson, 2008b).

Nelson and Sampat (2001) postulate that virtually all economic activities involve the use of both physical and social technologies, which combined determine the productivity or effectiveness of the activities. As physical technologies advance, they open possibilities for the emergence of new 'social technologies', in terms of *e.g.* a new mode of organising and managing businesses. Some of them can be implemented by firms on their own volition, while others require cooperation, or even government actions, which subsequently generate new 'institutions' *e.g.* new government programme or laws.

Whereas social technologies are seen to intertwine with physical technologies, the evolution of social technologies and their supporting institutions is perceived to be much more erratic and slow than that of physical technologies. Moreover, the ability to devise institutions that work as planned is much more limited than the ability to design new physical technologies, as the latter tends to be relatively tightly constrained by the physical inputs and processing equipment used in their operation (Nelson, 2008b), as well as by the given technological paradigms. Social technologies, on the other hand, are much more open to the vagaries of human motivations and bounded rationality, which can seldom be controlled effectively (*ibid.*).

Accordingly, for a nation seeking to catch-up, it often appears that physical technologies are much easier to learn about and acquire than social technologies, which include *e.g.* an effective firm organisation and management structure to operate imported physical technologies, or an effective set of technique for acquiring inputs, or for marketing. When the reform of particular institutions is required, such as the educational and financial

systems, it is likely far easier to advocate institutional reform, or to mount programmes aimed at reform, than actually to achieve a system that successfully drives the catch-up in that effective social technologies are almost impossible to copy, or to establish (Nelson, 2004).

Although it is still challenging to develop a solid understanding on how institutions affect ISs, the adoption of the concept 'social technologies', while seeing institutions as structures and forces that support and hold social technologies in place, makes it possible to explain how institutions and institutional changes link to technological changes. To this end, they also sit well with the IS approach, and provide a concrete theoretical base for its further development and articulation (Nelson and Nelson, 2002; Nelson, 2008b).

2.2.2 Regional Innovation System (RIS)

In the late 1970s and throughout the 1980s, academic interests in economic geography were reignited with a growing recognition of geographic proximity or agglomeration (Pyke and Sengenberger, 1992; Becattini, 2002, Maillat, 1998). This followed a number of regions in the United States, and in parts of Europe and Japan exhibiting remarkable resilience and even growth, whilst economies elsewhere set into recession and stagnation. These regions were homes of a variety of industries, including both technology-intensive sectors e.g. IT technology, automobile, pharmaceuticals, and more traditional and labour-intensive ones e.g. ceramic tiles, textile, footwear, wood furniture. Meanwhile, the literature on the relationship between technological change and regional development began to emerge, e.g. Meyer (1963), Thomas (1975), Oakey (1979) and Rees (1979), whereas policies designed to stimulate regional economic growth have been increasingly directed towards the promotion of innovativeness at the firm level (Hassink 1992). Against such backdrop, the concept of regional innovation system was introduced in the early 1990s.

Cooke¹¹ (1992) is widely credited for coining the term 'regional innovation system' in his *Geoforum* paper, although it was then interpreted in the context of competitive regulations. The concept has since been further developed, with a more multidisciplinary approach adopted. Meanwhile, together with 'industrial districts' (Bagnasco, 1977; Brusco, 1982; Becattini, 2002; Pyke and Sengenberger, 1992), 'innovative milieu' (Aydalot, 1986),

¹¹ Cooke (2001) explained that the low innovativeness and poor economic performance in Wales has initiated his research interest in RIS. Cooke is a professor based in Cardiff University.

'clusters' (Porter, 1990; 1998ab), and 'learning regions' (Morgan, 1997), they form the so-called 'territorial innovation models' (TIMs) that embrace the value of local and regional development potentials, and are seen as an alternative to national-state led regional economic policy (Moulaert and Sekia, 2003; Lagendijk, 1998).

At the centre of this group of TIMs lies a revival of the academic interests in Marshall's work on industrial district. Characterised by the notion of external economies of localised specialisation, Marshall (1890) argued that external economies of scale could be secured by the concentration of many small businesses of a similar character in particular localities, where small firms benefitted from the advantage of collective efficiency as a result of clustering. Three, by now well-known, drivers for such clustering or localisation were postulated by Marshall: (a) providing a pooled market for workers with specialized skills; (b) facilitating the development of specialized inputs and services, and (c) allowing firms to benefit from technological spill-overs (Marshall, 1890; Malmberg and Maskell, 1997).

As for its relationship to the other TIMs, the development of the RIS has been influenced by the literature on the social-territorial dimension of the industrial districts, mostly regarding the analysis of cooperation, trust, networking, institutions, and knowledge transfer (Cooke, 1998; Ashiem et al. 2011, Ashiem, 2000). Meanwhile, the literature on RIS has been developed more or less in parallel with Porter's works on 'clusters', (1990, 1998a,b). One common aspect shared by the two concepts is that they have emerged from similar conceptual path, *i.e.* it started with observations made at higher spatial levels (*i.e.* nation), from which a regional dimension was derived (Lagendijk, 1998). It was suggested that economic geographers and regional scientists were attracted to Porter's view on proximity and the 'home base' of firms as the main driver of competitiveness, and his short prayer to localised processes, which laid the ground for the exploration of clusters at regional or local levels. Subsequently, cluster is seen as an important component of a RIS (Cooke, 2001; Asheim and Coenen, 2005; Asheim et al. 2011), or "*an effect of the interaction of a functioning innovation system*" (Simmie, 2006: 183).

The emergence of the NIS literature provided a unifying framework for a large group of related research on regional innovation (Moulaert and Sekia, 2003, Asheim et al., 2011). By the late 1990s, two strands of interpretations of the RIS were observed in literature: (a) RIS as a subsystem of a national, sector-based systems, in the form of local clusters

operating along specific technological or sectoral trajectories, and (b) RIS as a mini version of a NIS (Lagendijk, 1999; Uyarra, 2010). The former interpretation is seen to focus on bottom-up, localised knowledge spill-overs and their impacts on local innovation processes. The latter is considered to be a top-down approach that conforms to Cooke's (1998) original postulation of a RIS, *i.e.* a “*geographically defined, administratively supported arrangement of innovative networks and institutions that interact regularly and strongly to enhance the innovative outputs of firms in the region*” (Cooke and Schienstock, 2000: 273-274). In this sense, regions are required to feature strong autonomous governments (or with ambitions to achieve similar levels of autonomy) and institutional density, and are able to coordinate economic processes at the meso-level, between the national (even super-national *e.g.* EU) level and the cluster level of firms (Uyarra, 2010, 2011).

The different interpretations of the RIS have led to the question of how one ‘knows’ a RIS when one sees one (Doloreux and Parto, 2005). Some scholars suggest that all regions have some sort of the RIS (Bunnell and Coe, 2001), while others argue that a RIS is a rare case, with only three regions being considered to have a true RIS, *i.e.* Baden Württemberg in Germany, Silicon Valley in the USA and Emilia-Romagna in north Italy (Cooks and Morgan, 1998). This disagreement over the presence or absence of a RIS is seen to increase confusion in the policy realm, with policy-makers at regional levels pointlessly questioning whether their regions are truly systems of innovation, and how, why, when and where policy interventions can take place (Uyarra, 2010).

The conceptual vagueness also gives rise to the concern over the study of the innovation performance of less-favoured regions, or peripheral regions, or rural areas etc. This is not helped by the fact that the existing studies often exclusively centre on high-tech and well-performing regions and clusters (Markusen 1999; Doloreux and Parto 2005; Uyarra 2010; Asheim et al., 2011). As Tödting and Trippl (2005) argue, this tendency has led to regional policies indifferently stressing the need to attract high-tech, knowledge based or ‘creative’ industries, to build up research excellence, to stimulate spin-offs, without taking into consideration the specific strengths and weaknesses of individual regions, in terms of their existing industries, institutional set-up and innovation potentials. There is no one ‘best practice’ policy model for innovation that can apply to all regions, whereas policy solutions drawn from ‘successful stories’ are likely only of limited use for less-favoured regions.

Moreover, the methods developed to study RISs has largely confined to a top-down, macro-to-micro perspective (Iammarino, 2005). For instance, Cooke and colleagues adopt a framework that constitutes five key and linked attributes (*i.e.* region, innovation, network, learning and interaction), supplemented by the organizational and institutional dimensions of infrastructural issues (e.g. regional financial competency) and super-structural issues (e.g. the degree of embeddedness of a region, its institutions and organisations) to decide the extent to which a RIS exists in a region (Cooke et al., 1998; Cooke, 1998, 2001).

Often, the attention is placed on the structural elements of a region (e.g. the role of the public sector and public policy, and the industrial structure etc.), and their contribution to regional innovations (Werker and Athreye, 2004), whereas firms are treated as an 'abstract' and 'homogeneous' entity, mere demanders of support, automatically respondents of incentives from the supply side (Uyarra, 2007, 2010). This lack of bottom-up, micro-to-macro perspectives of RIS on e.g. actors and localised patterns of learning and communication has led regional institutional configurations and policy-making to replicating that of the national level, rather than reflecting local circumstance (Iammarino, 2005). To this end, as this study argues, the use of the functions approach allows insights into micro-firm activities, and subsequently offers a bottom-up perspective, which may help regional governance to better respond to local needs and reflect local circumstance.

In terms of the system boundary of a RIS, a growing number of scholars have argued that, in an increasingly globalising economy, regions can not remain competitive on their own, where firms that primarily rely on knowledge generated locally could risk technological stagnation and 'cognitive lock-in' (Asheim and Gertler, 2004; Ter Wal and Boschma, 2011). So, the boundary of a RIS could travel beyond its own spatial or administrative sphere through a process of economic integration and globalisation (Asheim and Gertler, 2004). After all, regions are not "*isolated islands in a wider economy*" (Staber, 1996: 301).

In recent years, there is an increasing theoretical and empirical exploration of the openness of RIS. This line of inquiry can be seen to be partly influenced by Chesbrough's (2003) works on 'open innovation', except shifting the inquiry from firm levels to network levels. In an 'Open Regional Innovation System' model, local innovation processes cross not only firms' boundaries but also regional borders; that sees firms establishing research

collaborations with actors located both in and outside their home regions, and build linkages with national, super-national (e.g. EU) and global circuits of knowledge creation and diffusion, partly to compensate the relatively lower level of internal R&D investment (Belussi et al., 2010). But, the effectiveness of an open innovation model could vary, depending on firms' absorptive capacity as well as their abilities to renew such capacity over time (Ter Wal and Boschma, 2011).

On the other hand, due to varied devolution processes and the establishment of the European Union, a multi-level governance (MLG) framework is seen to operate in many European regions (Marks, 1993), including Wales. This inevitably adds complication to the understanding of the RIS boundary and regional innovation governance, since local innovation processes can be affected by the institutional settings at national and EU levels, e.g. European structural funds, or EU's Science and Technology Framework Programme. MLG can also cause conflicts between regional and national or supra-national (EU) governance, due to e.g. different priority settings (Koschatzky and Kroll, 2009). MLG may also operate differently among member states, because of their distinguished constitutional and political traditions (Cooke, 2002). In practice, it has shown that this multi-actor and multi-level governance model has turned political actions into complex bargaining processes between several levels and different actor groups (Koschatzky and Kroll, 2009). Nevertheless, more studies are required for advancing our understanding on the extent to which MLG may affect RIS.

2.2.3 Sectoral Innovation System (SIS)

Both Sectoral and Technological Innovation System recognise the patterns of innovation activities and innovation processes differ across industrial sectors, and technologic fields. Between the two concepts, TIS was first introduced, which has promoted the scholars of the SIS to consciously draw a line to differentiate SIS from TIS. They argued that, when TIS took a network view by emphasising how a network of firms and organisations was interacted in generating, diffusing and utilising specific technologies, SIS primarily studied the pattern of innovation activities from a microeconomic perspective by focusing on the dynamic processes of competition and selection involving firms and products in relatively homogeneous sectors (Breschi and Malerba, 1997). However, the literature on SIS has since been further developed, with a network perspective being incorporated into the approach. Therefore, the borderline between the TIS and the SIS becomes ever nebulous.

In some literatures, the SIS and the TIS are studied in a same context (e.g. Bergek et al., 2005).

A SIS is defined¹² as a system composing of “a set of agents carrying out market and non-market interactions for the creation, development and diffusion of new sectoral products” (Malerba, 2005: 65), while a ‘sector’ means “a set of activities which are unified by some related product groups for a given or emerging demand and which share some basic knowledge” (ibid.). Meanwhile, an analytical framework is also postulated for the study of SIS, which contains key building blocks¹³ (or elements) of a SIS that can affect the generation and adoption of new technologies, and the organisation of innovation and production at the sectoral level.

Three main building blocks are particularly chosen for their respective influences in defining the ‘structure’ of a sector, which are: (a) ‘knowledge and technology’ that determine the knowledge base of a given SIS and define the sectoral boundary of an IS; (b) ‘actors and networks’ that involve both firms and non-firm organisations (e.g. universities, and government agencies), and heterogeneous agents (i.e. individuals and organisations, including users and suppliers); they interact through processes of learning, communication, cooperation, competition and command, and are connected by both market and non-market relationships; and (c) ‘institutions’ that, from binding to less binding, formal to informal, shape actors’ cognition, actions and interactions; it is argued that the relationship between national institutions and sectoral systems is particularly important in that; for instance, national institutions such as patent system or regulations can have different effects on innovation across sectors, which may lead to one national institution favouring one sector over others, to the extent that the institutions of one sector become so dominant nationally that effectively affect the innovation activities of other sectors

¹² When the concept of Sectoral Innovation System (SIS) was first introduced in the late 1990s, it was defined as “a system (group) of firms active in developing and making a sector’s products and in generating and utilizing a sector’s technologies”; such a system of firms is related in two different ways: “through processes of interaction and cooperation in artefact-technology development and through processes of competition and selection in innovative and market activities” (Breschi and Malerba, 1997: 131). Private firms were seen as the central actors of a SIS, while the overall dynamics among the firms that compete within a sector was a primary concern of the SIS approach. However, the approach has since evolved to incorporate the elements of relationships and networks.

¹³ In an earlier paper by Malerba (2002), seven elements were identified to be the basic components of a SIS: ‘products’, ‘agents’, ‘knowledge and learning processes’, ‘basic technologies’, ‘inputs’, ‘demand and the related links and complementarities’, ‘mechanism of interactions both within firms and outside firms’, ‘processes of competition and selection’, and ‘institutions’.

(Malerba, 2004, 2005).

‘Demand’ is seen as a key part of a sectoral system, although in the SIS literature ‘demand’ seems to be used in the same context as ‘users’. For instance, Malerba (2005: 67) refers ‘demand’ as being “*made up of individual consumers, firms and public agencies, each characterised by knowledge, learning processes, competencies and goals, and affected by social factors and institutions*”. Whereas the way that ‘demand’ is perceived here shares certain similarity with Lundvall’s interpretation of the ‘users-producers’ linkage, the use of term ‘demand’, rather than ‘user needs’, may cause some confusion. As Mowery and Rosenberg (1979) point out, demand is a precise concept, denoting a systematic relationship between prices and quantities and devolving from the consumer preferences and incomes, whereas the notion of needs is rather shapeless and elusive. Therefore, it could significantly weaken one’s argument to confound the need recognition with market demand as a motivating or controlling influence in the innovation process.

Empirically, several SIS types have been identified and studied, e.g. ‘traditional sectors’, ‘machinery and the industrial district’, ‘the auto industry and local system of component suppliers’, ‘software’, ‘pharmaceuticals and biotechnology’, and ‘chemicals’ (Breschi and Malerba, 1997; Malerba, 2002, 2004). However, the emergence of new ‘clusters’ that span over several sectors, e.g. Internet – software – telecom, biotechnology – pharmaceutical or new materials, has posed new challenges for the SIS study (Malerba, 2002; 2005). In addition, it was suggested that the SIS current literature overly focused on the development of technology but paid less attention to the latter stage of innovation processes, *i.e.* the diffusion and utilisation of technology, and its impact on the economic performance of a sector (Geels, 2004; Reinstaller, 2003; Malerba, 2005).

2.2.4 Technological Innovation System (TIS) ¹⁴

The Technological Innovation System approach was developed in the early 1990s, within the framework of a five-year research programme ‘*Sweden’s Technological Systems and Future Development Potentials*’ led by Carlsson (Carlsson and Stankiewicz, 1991; Edquist,

¹⁴ The technological innovation system was initially termed as ‘technological system’ in the paper by Carlsson and Stankiewicz (1991). However, because of its conceptual similarity to the NIS (Edquist, 1997), the two concepts were grouped together as part of a broad IS approach. In the subsequent literature the term ‘technological innovation system’ started to be used, or ‘technological specific innovation system’ in some literature (Jacobsson and Johnson, 2000; Hekkert et al., 2007).

1997). The research adopted an evolutionary approach, and involved the empirical study of specific technical systems e.g. pharmaceuticals and powder technology, electronics and computers, and factory automation. Carlsson and colleagues postulated that the ability for a country to grow its economy was determined by its development potentials; this, in turn, was a function of a TIS in which a variety of economic agents participated. Meanwhile, because of the increasing globalisation and inter-relatedness of world market, a TIS may or may not be bound by national borders, and may differ from one techno-industrial area to another (Carlsson and Stankiewicz, 1991).

By definition, a TIS constitutes “*a dynamic network of agents interacting in a specific economic / industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilisation of technology*” (ibid: 111). A TIS contains mainly knowledge and competence flows, rather than the flow of ordinary goods and service. With the presence of entrepreneurs and sufficient critical mass, the dynamic networks of knowledge and competence could be transformed into synergistic clusters of firms and technologies within an industry or a group of industries, and give rise to new business opportunities.

The TIS approach can be applied to at least three levels of analysis: (a) a technology in the sense of a knowledge field, (b) a product or an artefact, or (c) a set of related products and artefacts aiming at satisfying a particular societal function (Carlsson et al., 2002). Since the TIS focuses on a given technological field, it somehow reduces the system complexity, in comparison to the NIS, RIS and SIS, and subsequently permits the mapping of system dynamics (Negro, 2007; Hekkert et al., 2007). This leads to one of the key strengths that differentiates the TIS from the other IS approaches, i.e. its capacity to facilitate the analysis of emerging technologies, rather than only mature systems (Carlsson, 1997; Negro, 2007). The TIS has been widely used for explaining why and how emerging technologies, especially sustainable energy technologies (e.g. biomass technology, solar cells, wind turbine), have developed and diffused into a society, or have failed to do so (e.g. Bergek, 2002; Jacobsson et al., 2004; Negro et al., 2008; Hekkert and Negro, 2009; Truffer et al., 2012).

A TIS contains a number of structural components that are essential for the operation of a TIS. These structural components are relatively stable over time, and include: (a) ‘actors

(and their competence)' involve both individuals and organisations that possess specific technological, financial and/or political capabilities and are able to contribute to the development, diffusion and use of technology; (b) 'institutions' include both formal and informal, normative and cognitive ones; (c) 'networks' contain linkages within a particular group of actors that facilitate learning processes, especially the transfer of tacit knowledge, while compensating the limitations in firms' searching efforts due to both bounded-rationality and bounded-vision (Carlsson and Jacobsson, 1997); and (d) 'technology'¹⁵ includes artefacts and technological infrastructure, in the form of knowledge, skills and technological rules (Suurs, 2009).

Postulated by Suurs (2009; et al., 2010), the fourth component 'technology' was not in the original line-up of the structural components recognised by Carlsson and Stankiewicz (1991), and Jacobsson and Bergek (2000). Suurs argues that, like institutions, technologies also enforce rules (in terms of technical know-how and know-what etc.) upon actors, however technological rules differ greatly from institutional rules and are often executed by different sets of actors; while institutions inevitably affect the material and economic domain of technology, the reverse also holds true; the two represent very different aspects of a TIS and therefore should be studied separately. In a way, Suurs' interpretation of the difference as well as the relationship between institutions and technology draws some parallel to Nelson's view on social and physical technologies. In the meantime, by including 'technology', the structure of a TIS resembles that of a SIS. As a matter of fact, Bergek et al. (2008b) adopts all four elements as the structure of a TIS, so does this study.

A TIS is spatially correlated. Where to draw the system boundary is circumstance-related, resulting from e.g. institutional infrastructure, technological and market requirements, the capabilities of various agents, or the interactions among actors. While the knowledge base of a given TIS becomes increasingly international, the geographical, cultural and political proximity continue to be important for actors to establish intimate and extensive communication, and effectively organise economic activities. Thereby, "*the nation-state constitutes a natural boundary of many technological systems. Sometimes, however, it may make more sense to talk about a regional or local technological system than about a national one: Route*

¹⁵ In Suurs (2009), 'networks' is replaced by 'technology' as the third structural component of a TIS. Suurs argues that technology, actors and institutions are merely elements if they do not interact with one another, whereas, in an actual TIS, they often link with one another and thus form networks. In this regard, 'networks' are seen not to exist on the same ontological level as the other elements.

128 and Silicon Valley are regional, not national system. In yet other cases, the technological systems are international, even global” (Carlsson and Stankiewicz, 1991: 111). Figure 2.4 illustrates the relationship between different ISs and their embeddedness, although the challenge of how to define the boundary of an IS remain. One of the attempts is to define the system boundary of an IS according to the functions of ISs, as will be discussed in the next section.

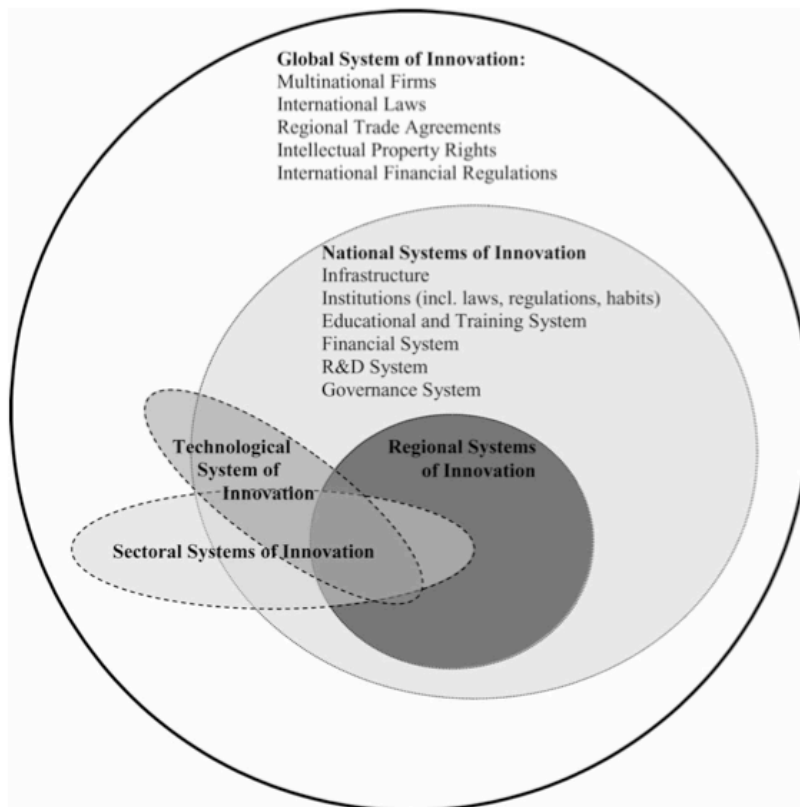


Figure 2.4: Boundaries of innovation systems between NIS, RIS, SIS and TIS
(Source: Frenz and Oughton, 2005)

Just as the other IS approaches, the TIS has difficulty to provide practical enough guidance for policy makers (Edquist 2006; Woolthuis et al. 2005; Bergek et al. 2008a), due to a number of conceptual, analytical and methodological issues (Edquist, 1997; Carlsson et al., 2002). One of them is ‘conceptual diffuseness’; as noted, in the current literature there is a lack of general agreement on e.g. what constitutes an IS, NIS or RIS or TIS, or how ‘institutions’ should be defined, which has led to vagueness over the boundary of a given IS, especially the non-geographic, functional boundaries of a system (Edquist, 1997, 2006). Also, there is no agreed methodology for the empirical study of ISs (Fagerberg and

Srholec, 2008); especially since ISs can differ between countries, regions, sectors or technological fields, while actors and institutions as constituting elements of an IS may also vary in different countries, regions, sectors, and technology fields, these differences, as well as the evolutionary and learning natures of ISs, make it impossible to define an optimal IS; this thus results in the empirical study of ISs often relying on the comparative study of different systems (Edquist, 1997). Nevertheless, the emergence of the functions approach (Liu and White, 2001; Edquist, 2006; Hekkert et al., 2007; Bergek et al., 2008a) is seen to likely help to address some of the aforementioned issues, while providing a holistic framework for the empirical study of ISs.

2.3 Functions of an Innovation System

The early IS literature has been dominated by the analyses of system components (e.g. actors, institutions and policies) and the relations between them, with few explanations on how fundamental activities (or functions) of an innovation process are organised, distributed and interacted in a systemic manner. As Liu and White (2001: 1092)¹⁶ states, *“although proposing to be analysing “system”, most scholars have actually focuses on the roles of specific actors and the impact of specific policies and institutions to explain system-level outcomes. They have proceeded from a generalised, organisationally-defined typology of actors and the generic, disembodied institutions that influence them. The ironic result is that we have no nomenclature to describe alternative system-level structures of which actors and institutions are only elements, and hence no way to make comparisons among alternative systems, a shortcoming also identified by Edquist (1997, p20)”*. Subsequently, they developed a generalisable framework based on the different organisational boundaries around an essential set of activities, linking to the creation, diffusion and exploitation of technological innovations in a system, resulting in the identification of five fundamental activities:

- (a) Research (basic, developmental and engineering),
- (b) Implementation (manufacturing),
- (c) End-use (customers of products or process outputs),
- (d) Linkage (for facilitating complementary knowledge), and

¹⁶ After the first foreign studies of China's national innovation system by the International Development Research Centre, Liu and White argued that, without a system-level description of the system's structure, dynamics or performance, the report reflected implicit assumptions about the role of the actors and policies based on the foreign researchers' experiences and knowledge; they were formed on the basis of the economic principles and industrial organisation which were fundamentally differed from the state central planning system and the Soviet-style of industrial organisation prevailed in China (cf. Liu and White, 2000).

(e) Education

Edquist (2001), on the other hand, states that the determinants (economic, social, political, and organisational etc.) influencing the development, diffusion and use of innovation may be traced through identifying activities that take place within an IS. He proposed ten activities to be important in most ISs, which are, in an order based on the hierarchy of causes (Edquist, 2006: 190-191):

- (a) Provision of R&D, contributing to creating new knowledge (primarily in engineering, medicine and the natural sciences);
- (b) Competence building, contributing to creating human capital through the provision of education and training;
- (c) Formation of new product market;
- (d) Articulation of quality requirements emanating from the demand side with regard to new products;
- (e) Creating and changing organisations needed for development of new fields of innovation;
- (f) Networking through markets and other mechanisms;
- (g) Creating and changing institutions that influence innovating organisation and innovation processes by providing incentives or obstacles to innovation;
- (h) Incubating activities for new innovative efforts;
- (i) Financing of innovation processes and other activities that can facilitate commercialisation of knowledge and its adoption, and
- (j) Provision of consultancy services of relevance for innovation processes.

However, it is the works of Bergek (1998, 2002; and Jacobson, 2001; et al. 2008a) that help the functions approach truly left its imprint in the academic circle (Suurs, 2009); a process also saw the important inputs from the researchers based at Utrecht University (the Netherlands), resulting from numerous discussions between them and Bergek and Jacobson (Hekket et al., 2007; Suurs, 2009).

Having drawn insights from literature on e.g. political science, sociology of technology and organisation theory, Bergek (1998) adopted a 'functional dynamic' approach in identifying the basic functions of the ISs. As she puts it, inherently "*all system components contribute to the 'goal' of the system or they would not be considered part of that system. The contribution of a*

component or a set of components to the goal is what is here called a function” (ibid: 2-3). Whereas the prime goal of an IS is to induce innovation processes, all activities that contribute to the development, diffusion and utilisation of innovations are considered as ‘system functions’, or as Edquist prefers ‘key activities’. They act as an intermediary level between the structure components of an IS and the system performance (Jacobsson and Bergek, 2004), so successful innovations occur only after these functions are properly fulfilled (Hekkert et al., 2007).

The interactions between the various functions define the internal dynamics of an IS, and form cumulative and circular causation. By studying the functions, it is possible to get a picture of present status of the system (Bergek, 1998). Moreover, by separating structure from content, the functions approach is able to identify ‘system failures’, and express them in functional terms, *i.e.* what is (actually) achieved in the system, and what performs poorly or is missing. In this regard, policy-makers can define the process goal of policy intervention that aims to alter the functional pattern through adding (or reinforcing) inducement mechanism, or offsetting (or removing) blocking mechanism (Bergek et al. 2008a).

Table 2.2: Functions of an Innovation System

Hekket et al.	Bergek et al.	This PhD study
<ul style="list-style-type: none"> ▪ Entrepreneurial activities; ▪ Knowledge development; ▪ Knowledge diffusion; ▪ Guidance of the search; ▪ Market formation; ▪ Resource mobilization; ▪ Support from advocacy; 	<ul style="list-style-type: none"> ▪ Entrepreneurial experimentation; ▪ Knowledge development and diffusion; ▪ Influence on the direction of search; ▪ Market formation; ▪ Resource mobilization; ▪ Legitimation; ▪ Development of positive externalities 	<ul style="list-style-type: none"> ▪ Knowledge development and diffusion; ▪ Entrepreneurial experimentation; ▪ Guidance of the search; ▪ Market formation; ▪ Resource mobilization; ▪ Legitimation; ▪ Development of positive externalities

As outlined in Table 2.2, seven functions have been respectively proposed by Bergek et al. (2008a) and Hekkert et al. (2007), which are seen as key processes that contribute to the generation, diffusion and utilisation of innovations and technologies. The main deviation

between them is that Bergek et al. include ‘development of positive externalities’ as the seventh function of an innovation system, whereas Hekkert et al. exclude it. While this study draws insights from both Bergek et al. and Hekkert et al., the functions employed in this study are mainly in line with those developed by Bergek et al, as shown in the third column of Table 2.2; I will explain the reason later in Chapter 3. As follows, the seven functions that are employed in this study will be explored individually in more details, in the context of a TIS.

Function 1: Knowledge development and diffusion

This function is central to any ISs. It concerns not only the knowledge base of a specific innovation system at global level, but also the extent to which the knowledge base of the relevant local IS performs and evolves over time (Bergek et al., 2008a). The process to build up a knowledge base requires considerable interactions among different actors, e.g. firms, laboratories, academic institutions and consumers, as well as feedback between different knowledge fields, and encompasses ‘learning by searching’ and ‘learning by doing’ (Hekket et al., 2007).

Knowledge diffusion involves the transferring of knowledge and the exchange of information. It is argued that knowledge diffusion is completed only when the knowledge and information transferred are internalized and translated into the capability of the receivers (Ernst and Kim, 2002). The existence of network is essential for information exchange and a precondition for diffusion. Depending on the natures of knowledge, different mechanisms may be used to transfer knowledge, e.g. through market between knowledge suppliers and knowledge buyers with payment involved; or through the so-called ‘embodied technology diffusion’ which includes the utilisation of new equipment and machinery (as a major source of process innovation) (OECD, 1996); or through personnel mobility, personal contacts, formal or informal face-to-face interaction, sometimes involving commitment and action in a specific context and locality e.g. apprentice-type training (Ernst and Kim, 2002). The latter is particularly a case for tacit knowledge that is so deeply rooted in human body and mind, and becomes hard to codify and communicate.

Both knowledge development and diffusion processes rely heavily on human capital, and the competence of actors. “*Knowledge is abundant but the ability to use it is scarce*” (Lundvall

and Johnson, 1994: 25). To this end, firms need to be able to recruit, develop and retain skilled labour forces (linking to *F4: Resource mobilisation*), while showing willingness to invest in R&D, education and training (linking to *F2: Entrepreneurial experimentation*).

Function 2: Entrepreneurial experimentation

At the core of innovation systems are entrepreneurs who take on uncertainties and exploit business opportunities. Entrepreneurs can be new entrants, or incumbent firms who diversify their business strategies to take advantage of new development (Hekket et al., 2007; Bergek et al, 2008a). As a function of ISs, the mere presence of active entrepreneurs may be a first and prime indication of the performance of an innovation system (Hekket et al., 2007).

On the other hand, this function is also about entrepreneurs experimenting with new technologies and making new 'combination' (Bergek et al., 2008a), a direct reflection of their 'economic competence' (Carlsson and Stankiewicz, 1991). By definition, economic competence constitutes the inclination and ability of firms to identify, expand and exploit business opportunities (ibid), a quality that is seen to set entrepreneurs from the rest. Carlsson and Eliasson (1994) further divide such a quality into four aspects: (a) selective (strategic) capability – firms' ability to make innovative choices, similar to what Cohen and Levintghal (1990) call 'absorptive capacity'; (b) organizational capability – the abilities of firms to integrate and coordinate their functional activities, e.g. production, marketing, R&D, finance; (c) technical (functional) capability – relating to the management of everyday operations of a firm; and (d) learning capability – a form of adaptive ability which shows that firms are able to learn from success as well as failure, to identify and correct mistakes, to read and interpret market signals and take appropriate actions.

It is believed that entrepreneurs can directly influence the other functions, one way or another, through their decision on how much effort they would dedicate to in-firm processes, and in which way they can influence the system around them (Van de Ven, 1993; cited in Hekket et al., 2007). In this respect, 'entrepreneurial experimentation' is seen by some as a 'motor of innovation', as will be explored later in this chapter.

Function 3: Guidance of the search

This function addresses how events or factors emerging in political, regulatory and social arenas as well as market can influence the direction of technology development. As Dosi's technological paradigm postulates, economic, institutional and social factors are crucial in the selection of technological paths, based on criteria such as feasibility, marketability and profitability. These factors may act as either incentives or pressures, and influence the direction of search, between different competing technologies, applications, markets, or business models etc. These factors may act in combination or individually, which include (Bergek et al., 2008a):

- Visions and expectations in growth potentials;
- Regulations and policy;
- Articulation of demand by leading customers;
- Technical bottleneck or reverse salient;
- Actor's tacit knowledge, or their interpretation of knowledge leading to seeing 'possibilities', and
- Industrial or social crisis

Function 4: Market formation

This function involves activities that contribute to the creation of market demand for a 'new' technology (Suurs, 2009). This 'new' technology may be new to the world in general, or may only be new for a given country (or region) in the process of catching up, during which considerable risks are still involved and a lot of trial and error are required for learning to be effective (Malerba and Nelson, 2011). By and large, a new technology cannot be expected to compete with incumbent technologies (Rosenberg, 1976). This 'liability of newness' may be ascribed to that market does not yet exist for the new technology; potential customers may not yet articulate their demands or be able to do so; or, the cost (or performance) of the new technology is too high (inconsistent) to be marketable. Therefore, it is important to have a protected space created for new technologies, e.g. to form 'niche market' for specific applications of a technology.

Meanwhile, in the usual business management term, '*market formation*' also involves activities taken by firms to sell actual products or service, and decisions made by firms on e.g. what to sell, who to sell and how to sell. This requires firms to invest in market

research. As NESTA (2009) indicates, firms must anticipate future demand at the outset, whereas market research or brand development is the 'strategic' element of an innovation process, in terms of identifying the market potential for new products and service, and exploiting them commercially.

Function 5: Resource mobilisation

This function represents a basic economic variable (Suurs, 2009), and involves the allocation of human, financial and material resources. The ability of a TIS to mobilise these resources reflects how the system is able to facilitate the integration in term of synergies, technological complementarities and critical mass, and lead to the development of cluster dynamic. In this sense, the scope of this function includes the deployment of 'competence/human capital' through education programmes created in specific scientific and technological fields, entrepreneurship, and management etc., the access to 'financial capital' (in the form of seed and venture capital, etc.), and the availability of 'complementary assets' such as complementary products, services, network infrastructure, etc. (Bergek et al., 2008a).

Function 6: Legitimation

Legitimacy is a matter of social acceptance and compliance with relevant institutions, as new technology often encounters parties with vested interests who do not want this force of 'creative destruction'. Therefore, it is crucial to attain legitimacy in order for resources to be mobilised, market to form, and actors to innovate, so that the new technology can become part of an incumbent regime, or formulate a new regime that is eventually able to replace the incumbent one (Bergek et al., 2008a; Hekket et al., 2007)

In the early formative phase of an emerging TIS, the legitimation mainly involves to help the new technology to be accepted as a desirable and realistic alternative to incumbent technologies, through articulation of expectations and visions as well as regulative alignment with regard to industrial standards, market regulations, tax policies etc. (Bergek et al., 2008a). However, it is often that existing institutions are inclined to block the development of new technological options, as happened to many low-carbon technologies and solutions (Unruh 2000). To this end, legitimation is at its most difficult, *i.e.* to influence the institutional framework in order to achieve institutional alignments (Oliver 1991;

Zucker 1987, both cited in Bergek et al., 2008b). For an emerging TIS, legitimation often involves 'expert' legitimation, in terms of technology assessments and 'rational' arguments, to kick start the process. On the other hand, advocacy coalitions, *i.e.* forming coalition with politically powerful public or private groups, has also proved to be central to the process of acquiring legitimacy, *e.g.* lobby actions (Hekkert et al., 2007). Moreover, the formation of a market space for the new innovation may lead to legitimation in the form of an increasing number of entrepreneurs who are able to form 'packs' and engage in changing the regulatory framework (Kemp, Schot, and Hoogma 1998). However, a bottom up evolutionary process to gain legitimacy can work if only well orchestrated.

Legitimation is not a given, but conscious actions of various actors during the process, which may take considerable time and be complicated by actions taken by the defenders of incumbent technologies and the associated institutional infrastructure (Bergek et al., 2008b).

Function 7: Development of positive externalities

As noted, this function is proposed by Bergek et al. (2008a), not Hekkert et al. (2007). Its inclusion as a key function of an IS demonstrates clear influence of Marshall's works on the external economies of scale and Porter's clusters (Bergek et al., 2008a, b). As already elucidated, Marshall's concept of external economies is characterised by three sources of the economy: (a) the emergence of pooled labour markets; (b) the emergence of specialized intermediate goods and service providers; and (c) information flows and knowledge spill-overs; they thus also become the positive externalities of an IS. One way or another, the emergence of these positive externalities is seen to show the strength of the collective dimension of innovation and diffusion processes, and indicate the dynamics of the system since externalities magnify the strength of the other functions. For instance, the emergence of these externalities would contribute to '*F1: Knowledge development and diffusion*'; the entry of new firms, resulting from knowledge spill-overs, can strengthen '*F2: Entrepreneurial experimentation*' and '*F4: Market formation*', which may subsequently positively influence '*F6: Legitimation*' (ibid).

Identifying the phase of a TIS

As stated, by studying the functions, it is possible to tell the status of a TIS. Whereas a TIS does not come to existence overnight, it is expected that positive interactions between the functions reinforce each other over time, and lead a TIS to reach a 'formative' phase, before it can be propelled into a phase of 'market growth' (Jacobsson and Bergek, 2004; Bergek et al., 2008a). But, how can one tell that an emerging TIS has reached its formative phase (as this study sets out to address, i.e. Q2), or a market growth phase? While there is no straightforward answer, two different interpretations have been provided in the existing literature.

On the one hand, Bergek et al. (2008a) propose the use of indicators to decide whether or not a new TIS is in a formative phase; accordingly, it is suggested that a TIS reaching a formative phase is normally characterised by the indication of the "*entry of some firms and other organisations, the beginning of an institutional alignment and formation of networks, so a rudimentary structure is formed*" (Bergek et al., 2008a: 419). They further point out that a TIS in this phase also exhibits a certain level of high uncertainties associated with technologies, markets and the price-performance of relevant products etc., while many experimentations are taking place; meanwhile, demand may not be fully articulated, whereas positive externalities may yet emerge, or perform weakly, etc. In this regard, it is sensible to use separate sets of criteria to assess the IS functions when one tries to decide whether an emerging TIS is in its formative phase or the growth phase. Otherwise, the analysis may send out wrong indication, especially in the case of policy-makers who may be discouraged. For instance, 'the volume or level of relevant economic activities' is less suitable for assessing the formative phase than the growth phase, since the former is more likely associated with experimentation and variety creation (ibid), subject to e.g. ongoing demand articulation.

As the functions continuously evolve, especially following a process of positive cumulative causation (Bergek, et al., 2008b), there is a genuine prospect that the TIS moves onto the 'market growth' phase during which the TIS is able to develop in a self-sustaining way, resulting from a significant and persistent increase in demand. Meanwhile, the system focus shifts towards "*system expansion and large-scale technology diffusion through the formation of bridging market and subsequently mass market*" (Bergek, et al., 2008a: 420). That said, there is no guarantee that a TIS once reaching the formative phase would continuously evolve and

lead the emerging technology towards successful market diffusion eventually, as some may never do.

On the other hand, different from Bergek et al.'s proposition that relies on the changing status of the IS structural components (i.e. actors, network, institution and technology), Hekkert et al. (2007), Suurs (2009) and Suurs et al. (2010) postulate the concept of 'motors of innovation', which focuses on the performance of individual IS functions. Essentially, it centres on the notion of 'cumulative causation', i.e. "*the build-up of a TIS accelerates due to system functions interacting and reinforcing each other over time*" (Suurs et al., 2010: 419). They argue that the positive (or negative) fulfilment of certain functions likely has determinant impacts on the other functions, and triggered a virtuous (or vicious) cycle. Based on a number of empirical studies, three such functions, i.e. the 'motors of innovation', are identified as follows. In this regard, the assessment of whether a TIS has reached its formative phase is closely associated with the identification of the presence of the 'motors of innovation'.

Accordingly, one common trigger for a virtuous cycle in the field of sustainable technologies is 'F3: *Guidance of the Search*', in the form of government policies and targets that are designed to mitigate environmental damages, e.g. GHG emissions reduction targets. This function can subsequently lead to resources (F5) being mobilised, new knowledge (FI) being developed, and subsequently increasingly positive expectation about technological options (F3) (Hekkert et al., 2007; Suurs et al., 2010).

The second 'motor of innovation' lies with 'F2: *Entrepreneurial Experimentation*', in terms of a group of enactors who lobby for better economic conditions (F6). This may involve two possible routes, by: (a) lobbying for more resource (F5) to be allocated for R&D which may lead to new knowledge being developed (FI), and subsequently higher technological expectation (F3); (b) lobbying for market formation (F4) to create a level playing field for new technologies, which can lead to more entrepreneurial experimentation and the emergence of related industries (F2 and F7), subsequently contribute to more knowledge development and diffusion (FI), increased legitimation (F6) for more favourable conditions that guide further search (F3) (ibid; Suurs, 2009).

The third 'motor of innovation' is likely fuelled directly by 'F4: Market Formation', similar to the above route (b). Since a market environment is already created, the development of a given technological innovation system is no longer an issue of politics, but part of regular business activities (Suurs, 2009); new business possibilities likely lead to an increase in entrepreneurial activities (F2 and F7), while resources are mobilised (F5) through normal business functional activities, which likely contributes to more knowledge development and diffusion (F1), and lead to increased legitimisation (F6) for more favourable conditions that guide further search (F3) (ibid; Hekkert et al., 2007; Suurs et al., 2010).

Both interpretations can be used to help to establish the status of a TIS, in term of e.g. whether or not an emerging TIS has reached the formative phase, or entered a virtuous or vicious cycle. It may be even more sensible to combine them when assessing the status of an emerging TIS, as this study will do, because, to a large extent, they complement each other, and lend insights respectively into how the structural components of the TIS and its functions may behave and progress as the TIS evolves.

That being said, it may be pointed out that it could become problematic if the analysis overly relies on the conception of 'motors of innovation', especially while studying a TIS at its early stage. This is because it may give rise to a perception that the three proposed 'motors of innovation' are more important than the other functions; subsequently it may result in the study of an emerging TIS in a less coherent and comprehensive manner, while failing to take all uncertainties (e.g. technologies) into consideration, thus misleading the focus of policy-making. In addition, the empirical studies that were used to help generalise this concept are limited in terms of both the technological fields involved (i.e. mainly renewable energy technologies) and social-cultural-institutional-economic heterogeneity (all case studies taken place in a small group of countries), which likely leave the whole conception as well as the proposed motors of innovation open to doubt.

Assessing the functions

The central idea of the Functions approach is that the proposed functions constitute an intermediate level between the structural components of an IS and the overall system performance. Only when the functions are properly fulfilled, can successful innovations occur. However, how can we know whether and the extent to which functions have been fulfilled? Different attempts have been carried out, including e.g. the so-called 'Historical

Event Analysis' (Hekkert et al., 2007; Negro, 2007; Hekkert and Negro, 2009; Suurs et al., 2010), which perceives development and changes as sequences of events, and thus the assessment of the functions mainly involves the collection, categorisation and allocation of archive events to the functions of IS.

The other is to assess the functions using performance indicators, which is not something new. For decades, incessant efforts have been made to quantify, evaluate and benchmark innovation competence and practice of nations, regions and sectors, most notably, *the Oslo Manual*¹⁷, jointly developed by OECD and the European Commission since 1992, and the *Global Innovation Index* co-published by Cornell University, INSEAD, and the UN World Intellectual Property Organization (WIPO) since 2007 (Dutta and Lanvin, 2013). However, the selection of performance measurement is complicated, and likely depends on the level of analysis applied, as well as the maturity of the system (Carlsson et al., 2002). To date, there is no widely agreed combination of indicators that has been developed for measuring the functions (Truffer et al., 2012). That being said, this study will use performance indicators to assess the functions of two selected emerging technological systems. I shall further explain and discuss it in Chapter 3, when I develop the bespoke analytical framework for the assessment of the IS functions (*i.e.* to address Research Question 1).

By and large, the functions approach represents one step at the right direction, and is one major innovation of the TIS concept (Truffer et al., 2012). It permits a more systematic method of mapping the determinants of innovation processes, and thus increase the analytical power of the IS approach. Meanwhile, by analysing the functions of an IS, it adds a new dimension to how the boundary of an IS can be defined, in addition to the delimitation by spatial, administrative or sectoral boundaries. In other words, within certain geographical area, and perhaps also limited to a specific technological / product field, the actual institutional set-ups that support and influence the development, diffusion and utilisation of innovations and technologies can be identified, through *e.g.* understanding the boundaries of the knowledge field studied (Carlsson et al., 2002). This may particularly be useful for studying a TIS at the regional level, as the administrative boundaries of regions can sometime be irrelevant in term of the degree of economic and political coherence or inward orientation, or in terms of knowledge network or localised learning

¹⁷ The official title of the *Oslo Manual* is "The Measurement of Scientific and Technological Activities, Guidelines for Collecting and Interpreting Technological Innovation Data" (OECD/ Eurostat, 2005).

spill-overs (Edquist, 2006). However, it is not going to be a straightforward exercise in that new system boundary may emerge as functions evolve.

On the other hand, despite its obvious analytical strength, the functions approach is not considered to be a fully established theoretical framework yet (Hekkert and Negro, 2009), due to some obvious weaknesses. For instance, as shown, there are different sets of functions existing in literature, even though there is the presence of considerable overlaps between them; different scholars also show different understanding of what each function mean, while there is the question over whether we have come up with a sufficient set of functions (Truffer et al., 2012). All in all, our understanding on the linkages and interactions between different functions, as well as between TIS structural components and functions, needs to be further advanced.

2.4 Innovation and Technological catch-up

As explained at the beginning of this chapter, this section is not in the original frame of this study, however, as the research was progressing, especially further into the empirical study stage, it became obvious that, as a peripheral region, the nature of the technological and economic development in Wales often involves a process of catching-up. This not just reflects upon the development of technology *per se*, but also on the formulation of social technologies and institutional set-up that are necessary for facilitating the technological and economic catch-up in Wales. There is already an extensive literature on the economic and technological catch-up that can provide different perspectives and useful examples for studying why some nations (regions) are able to catch up while others fail.

Ever since Adam Smith's (1776) *magnum opus* "*The Wealth of Nations*", concerns over why some countries (or regions) made significant economic progresses while others seemed to be stagnant have remained central in economic analyses, which often involve the searching of factors that likely simulate progress, as well as those likely limiting it (Nelson, 2008a; Grant, 2011). Early works by Veblen (1915) and Gerschenkron (1966) exclusively studied the catch-up process in the context of industrialisation, especially Germany's caught-up of England; together with the contributions by e.g. Abramovitz (1979, 1986), they gave rise to the proposition that the difference in countries' economic development is mostly caused by technological differences, with technology being the driving force of growth and development (Freeman and Soete, 1997; Fagerberg and Srholec, 2009). This has led to the

so-called 'technology gap theory of economic growth' (Fagerberg and Srholec, 2009), and has since been further backed by a series of empirical studies of successful catch-ups achieved by Japan and newly industrialising countries (NICs) in Asia.

Abramovitz (1986) is first to introduce the distinction between 'forging ahead', 'catching-up' and 'falling-behind' in economic growth (Freeman and Soete, 1997). Accordingly, there are only two major examples of 'forging-ahead' at the country level, *i.e.* the UK in the 19th century and USA in the 20th century (*ibid*), while more examples of 'forging-ahead' can be found at the industry level, *e.g.* Japan's consumer electronics, German chemical industry, and Italian footwear and textiles (Porter, 1990, 1998a). Meanwhile, there are even more instances of 'catching-up' at both country, *e.g.* Germany in the late 19th Century, Japan and other NICs in Asia (*e.g.* South Korea, Taiwan, Hong Kong and Singapore) since WWII (*e.g.* Johnson, 1982; Freeman, 1987b; Kim; 1980; Fishlow et al. 1994), and sectoral levels, *e.g.* semiconductors and telecommunication in Taiwan and South Korea (Song, 2000; Whang and Hobday, 2011; Malerba and Nelson, 2011) and the wine industry in Chile, South African and Australia (Giuliani et al., 2011).

It is now commonly accepted that technological catch-up often involves technology borrowing by latecomers, through the process of *e.g.* from implementation of imported technology, to assimilation, and to eventual innovation (Kim, 1980), following a reverse order of the usual research, development and engineering (R, D&E) model. To this end, catching up was, in early debates, considered to be a question of relative speed in a race along a fixed path, whereas differences in productivity levels created a strong potentiality for latecomers to grow quickly and reduce productivity and income gaps, and thus, in the long run, convergence took place between leaders and followers (Abramovitz, 1986; Fagerberg and Srholec, 2009).

However, such view does not seem to satisfactorily explain why some countries or regions (mainly Japan, South Korea and NICs in Asia) succeeded, whilst, during the same period, others (*e.g.* countries or regions in Africa and South America) achieved little success, despite that they have adopted similar procedures of adopting imported technology (Perez, 2001). The causes for such different outcomes were sought in the particular conditions of each country, in terms of how social, cultural, economic and institutional factors have affected technological changes in 'forging ahead' and 'catching-up'

(Fagerberg and Srholec, 2009). As Abramovitz (1986) stated, economic and technological backwardness was not a mere accident, where the tenacious societal characteristics that were responsible for a country's past failure likely remained to keep it from making the full technological leap; he subsequently interpreted such tenacious societal characteristics in the context of 'social capability' (Abramovitz, 1986). This proposition has since promoted a certain research tradition, with similar interpretative frameworks being postulated to include 'technological capability' (Kim, 1980), 'innovation capability' (Dahlman et al., 1987), 'absorptive capacity' (Cohen and Levinthal, 1990), and innovation systems, as discussed.

Furthermore, it is argued that the spectacular performance and progress made by Japan and NICs in Asia may have been linked to the 'window of opportunity' created by the emergence of a new techno-economic paradigm in leading countries, where the follower countries were able to either consciously or intuitively take advantage of it (Perez, 2001). To do so, not only are these followers able to acquire packaged foreign technologies and assimilate them, but also to build on existing knowledge and create their own trajectory of development. As Perez and Soete (1988: pp.462-3) put it:

There is every reason to expect that the vast majority of new technologies will originate primarily with the technologically most advanced countries. There are also, however, good reason to expect that diffusion of such major new technologies will be hampered in some of those countries by the heavy investment outlays in the more established technologies, the commitment of management and the skilled labour force to them and even by the research geared towards improving them. This could mean that the new technology might diffuse more quickly elsewhere, in a country less committed to the old technology in terms of actual production, investment and skills. ..., as diffusion proceeds, some of the crucial, incremental innovations, resulting from user-feedback information and other dynamic factors, could tend to shift further the technological advantage to the country in which the new technology is diffusing more rapidly.

It is not within the scope of this study to fully explore how a Welsh catch-up may take place, or to discuss whether the transition from high to low carbon growth may present a 'window of opportunity' (Matthews, 2013) for a Welsh catch-up. However, as will be discussed in Chapter 4, the emergence of a distinctive low carbon transition narrative in Wales indicates that the Welsh Government (WG) has seen a low carbon transition as an opportunity to create jobs and new businesses, with the building sector to play an

important role. In this regard, a Welsh catch-up in the course of a transition to a low carbon economy could learn from the countries and regions that have successfully caught-up at either country or industrial level. This, in a way, may help to address some gap in the existing RIS literature which, as already discussed, does not seem to provide sufficient guidance on how peripheral regions such as Wales may improve their regional innovation capability, and economic performance.

As stated, technological catch up is often rare and not guaranteed. It depends on not only the presence of certain conditions and capabilities which can facilitate a catch-up, but also on whether the latecomers are able to break out of the tenacious social, economic and institutional characteristics ascribed to their past failure. Chapters 4, 5 and 6 of this thesis will explore why Wales has lagged behind from a historical perspective, whereas the functional analyses of the two selected technological systems, and their comparison, would help to expose the system weaknesses in Wales' current institutional-social-economic structure. In this sense, I next look into the successful catch-up in countries or regions such as Japan or Taiwan, and explore the conditions and capabilities that likely facilitate a successful catch-up, and how they may be created by the relevant policy intervention.

As follows, this contains four aspects: 'technological forecasting', 'catching-up at the industrial-firm level', 'the role of domestic demand in the catching up process', and 'innovation induced by stringent government standards'. The last aspect is triggered by the recent development with the amendments to the Part L (Conservation of fuel and power) of the Building Regulations for Wales, which saw the WG abandoning its original target of 40% energy efficiency improvement for new domestic buildings, opting for a much lower target of 8%. Whereas I will speculate the reason behind this change of the stand by the WG later in the thesis, Japan's experience, following the two oil crises of 1970s, has showed that tough energy efficient regulations could promote technological innovations, and contributed to the technological catch-up process. Moreover, I will discuss Japan's experience in relation to the 'regulation-induced innovation hypothesis', postulated by Ashford and Hall (2011).

2.4.1 Technological forecasting

As mentioned, Freeman's 1987 book "*Technology Policy and Economic Performance: lessons from Japan*" formally introduced the concept of innovation system. He stated that the

Japanese system of innovation was the reason behind the exceptional Japanese progress in catching-up, and one of the most notable features of the Japanese innovation system was the “*Japanese system of technological forecasting*” (Freeman, 1987b: 4-5). He credited the Japanese technological forecasting system for identifying the main elements of the emerging ICT paradigm¹⁸ much earlier than elsewhere; this allowed Japanese policy-makers and firms to exploit the potentials of this new paradigm, and embark on the measures to diffuse this new technology very rapidly to a great variety of industries, including e.g. machinery and automobiles in the form of robotics, computer numerically controlled machine tools, and flexible manufacturing systems etc. (ibid).

In functional terms, the technological forecasting system fits as an effective mechanism to provide long-term visions (*F3: Guidance of the search*) through a systemic identification and exploitation of future trends and potentials in technology, world market and societal needs. For catching-up economies, the forecasting exercise can serve as a complementary solution to their lack of a sound national infrastructure in science and technology, while helping to define the strategic direction for selective and indigenous science and technology development that can facilitate a nation’s economic and social progress (Shin et al., 1999). More importantly, it would enable policy-makers to frame technological and industrial policies “*not so much on the basis of existing industrial statistics and the weight of established firms and industries, as on the basis of those new technologies which are likely to transform the established existing systems*” (Freeman 1987b: 78).

By the 1990s, similar technological forecasting or foresight exercises have been observed, to varied extents, in many emerging economies that tried to close technological gap (Shin et al., 1999), as well as in many Western European countries that wished to optimise resource allocation in science and technology (S&T) policy (Brandes, 2009; Meissner, 2012). For instance, UK embarked on its first foresight exercise in 1994, covering 15 expert panels involving an overall 2585 responses (out of 8384 experts contacted) aiming at generating estimation of future S&T areas with a time horizon of 2015 or beyond (Brandes, 2009). In recent years, more studies have been conducted on how technology foresight can serve as a regional governance tool to build up regional innovation potentials,

¹⁸ Freeman (1987b) saw information and computer technology (ICT) representing a new techno-economic paradigm in which ICT, as a generic technology, has a major influence on the behaviour of the entire economy, and affects the structure and the conditions of production and distribution for almost every branch of the economy.

while developing common visions about the future, enhancing cohesion among regional actors and enabling coordinated action towards common goals (Koschatzky, 2005; Hanssen et al., 2009; Keller et al., 2014; Vecchiato and Roveda, 2014).

2.4.2 *Catching-up at the industry-firm level*

As noted, a catch-up process often involves technological borrowing by latecomers, and involves certain forms of 'reverse engineering'. In practice, two different patterns that were seen to yield satisfactory results have been observed, based on insights into the micro dynamics of Asia's catch-ups. They are the East Asian 'local firms'-led catch-up, and the Southeast Asian TNC (transnational corporation)- or FDI (foreign direct investment)-based growth (Hobday, 2011).

As will be reviewed in Chapter 4, Wales' catch-up effort has more or less followed the Southeast Asian FDI-based growth pattern¹⁹, under which governments look to FDI, and TNC subsidiaries, to jump start industrial development through offering TNCs favourable conditions and policy incentives (ibid; Wong, 1999). But, where innovation is concerned, this approach largely relies on the global strategies of individual TNCs, and thus does not necessarily automatically generate important externalities, e.g. improved technological capabilities of indigenous firms. Thereby, specific policy intervention is often required, e.g. by imposing requirements on TNCs to increase the local content of their products through the links to local supply chain and other intermediate inputs, as adopted in Brazil (Dahlman et al., 1987), or restrict FDI to the form of local-based joint ventures between TNCs and local firms, as implemented in China (Nam, 2011). However, as Dahlman et al. (1987) indicate, such policy intervention likely only works in countries with large domestic markets; in smaller markets, TNCs would be unlikely to make the extra effort required to increase local content unless components could be produced at competitive costs. To date, this FDI- and TNC- based approach has failed to generate a successful Welsh catch-up, although more causes may have contributed to this continuous lagging-behind status in Wales, as I will try to explore in the following chapters.

¹⁹ This TNC- or FDI- based growth pattern was initiated in Singapore in the 1960s, with subsidised economic zones built to attract TNCs to lead export growth. It proved highly successful, and was imitated by other countries in the regions, and around the world. At the time, this was a major policy innovation (Hobday, 2011).

On the other hand, the East Asian 'local firms'-based pattern, as suggested by the term itself, primarily relies on domestic enterprises to import and implement, assimilate, and improve foreign technologies in response to the changing competitive environment (Kim, 1980). It started in Japan. As Freeman (1987b) stated, the Japanese approach to the import of technology has been putting the full responsibility for assimilating and improving imported technology upon Japanese enterprises; this has led to Japanese management, engineers and workers growing accustomed to 'system' thinking in an integrated way about product design and process design; thus, whereas Japanese firms made few original radical product innovations, they have made many incremental innovations, and redesign many processes in such a way as to improve productivity and raise quality. Following in Japan's footsteps, South Korea (hereafter Korea) and Taiwan adopted a similar pattern, but with different formulas.

In the case of Korea, it, to certain extent, imitated the Japanese model, and let large firms to lead the catch-up process (Hobday, 2011; Lee, 2005, 2009). With the direct policy and financial support from the Korean government, large domestic firms, *i.e.* the so-called '*chaebols*'²⁰ such as Samsung and Hyundai, have been able to diverge into high-valued goods *e.g.* electronics goods, telecommunication and automobiles, through investment in (following a sequence of) *e.g.* technological licenses, in-house R&D, public-private R&D consortia, and overseas R&D posts. This resulted in the rapid accumulation of technological capability by Korean firms (Lee, 2009), and subsequently, in Samsung's case, a world leader in semiconductors, mobile phones and laptop computers etc. (Hobday, 2011).

By contrast, Taiwan has, to a high degree, depended on small and medium-size Chinese-owned family businesses to proliferate and grow, which led to a dispersed and pluralistic industrial structure with some large firms and many SMEs (*ibid*, Wong, 1999; Mathews, 2002; Lee, 2005). Ernst (2000: 223) views Taiwan's successful technological catching-up as a "puzzle" in that it defied "a vicious circle of size-related disadvantages: a) *The small domestic market places tight restrictions on the ability to function as a buffer against heavy fluctuations in international demand; b) It constrains the development of sophisticated 'lead users' that could*

²⁰ The term 'Chaebol' literally means 'money clan' in Korean, and represents a South Korean form of business conglomerate, typically family-owned (Apple Dictionary), emphasising scale and high degrees of vertical integration; to some extent, it imitated the Japanese *keiretsu*, (Hobday, 2011).

stimulate innovation; c) It also limits the scope for technological spill-overs; and d) the limited size of the national knowledge and capital base restricts the choice of industries in which such small nations might successfully specialise.”

Against these odds, by the early 2000s, Taiwan emerged as the world’s most capable and agile supply base for the design, manufacture, and delivery of PCs and related products, ranging from computer monitors, to various components and subsystems, to complete desktop and laptop PC systems (Sturgeon and Kawakami, 2010). As Taiwan-based firms gained new competencies and accumulated technological capabilities, they also began to produce their own branded products²¹, and in recent years established their leading places in a few niche segments of electronics sectors. For instance, AsusTek and Acer are two of the biggest producers of ‘netbook’ computers (*i.e.* the ultra-low cost portable PCs), while HTC has been selling its own branded Android-based smartphones since 2009 (*ibid.*).

The key to Taiwan’s success is seen to lie with its unique ‘*knowledge development and diffusion*’ mechanism, based on the cooperation forged between public and private sectors, in the form of R&D consortia (Mathews, 2002; Jan and Chen, 2006; Dodgson et al., 2006), or, as Wong (1995, 1999) called it, a SME-Public Research Institute (SME-PRI) Innovation Network model. It involves the use of PRIs, namely the Industrial Technology Research Institute (ITRI), to facilitate technology assimilation and transfer, and cooperative R&D promotion in support of indigenous SMEs. Wong (1999: 17) argues that, among the NICs, “*Taiwan has probably been most successful in using PRIs to promote the diffusion of industrially-relevant technologies.*” In this regard, given the industrial structure in Wales, *i.e.* predominated by small businesses (Welsh Government, 2014c), Taiwan’s experience may offer some insight into how to improve the innovation capabilities of Welsh SMEs, and organise relevant institutional set-ups. I shall further discuss this later when I address Q4.

2.4.3 The role of domestic demand in the catching-up process

As reviewed, from an evolutionary perspective, an innovation process is driven by both ‘technology push’ and ‘market-demand pull’; whereas the development of science and technology opens possibilities for new products, processes or modes of organisation, the

²¹ This therefore saw Taiwan firms completing the catch-up cycle, *i.e.* from OEM (original equipment manufacturer), to ODM (original design manufacturer), to eventual OBM (original brand manufacturer). By contrast, it is suggested that Korean firms have followed the stage of OEM, OBM and then ODM (Lee, 2005).

market demand plays an important part in e.g. enriching the knowledge base, selecting technological trajectories, and accelerating development processes. However, the existing literature on technologic catch-up has largely focused on 'technology push', and the role of government policy in promoting the development of technologies, and has comparatively overlooked the role of 'market-demand pull', especially the linkage between domestic demand and the innovation capability and competitiveness of local firms in the catching-up processes. This being said, among the limited number of studies that have looked into this linkage, certain correlations have been suggested.

The studies on technological catch-up by Japan and Korea have both indicated that, during the early catch-up period, both governments introduced policies to protect their infant industries, e.g. high tariff and import quota, or being a purchaser; this in turn created a protected domestic market so that indigenous firms and entrepreneurs were able to grow and exploit new business opportunities while lowering cost and improving quality through scale economies (Kim, 1980; Kagami, 1995; Odagiri and Goto, 1993). In Japan's case, there is the further proposition that domestic rivalry that saw Japanese firms competing fiercely for the domestic market has stimulated innovation and improvement in productivity and quality, and contributed to their international competitiveness (Porter, 1990, 1998a; Okuno-Fujiwara, 1991; Tezuka, 1997; Sakakibara and Porter, 2001). However, in a reversal of fortune, this over-emphasis on domestic markets and rivalry has been accused, in recent years, of turning Japanese industries towards in-ward thinking and contributing to their declines in the global market in industries such as consumer electronics (The Economist, 2011) and mobile phone handsets (Tabuchi, 2009; Marukawa, 2009). As *The Economist* (ibid) summarises, "they focused on satisfying domestic consumers with advanced features that didn't matter to customers elsewhere." This thus resonates with what Lundvall calls the adverse impact of the user-producer linkage, if firms fail to broaden their network with and access to the global knowledge base.

On the other hand, a recent empirical study on the Korean mobile handset industry indicates that the emergence of demanding domestic users, despite its small size, has served as a 'test bed' for experimental user-producer learning, which subsequently has not only stimulated innovations but also led to the development of a new technological trajectory, resulting in the industry's leaping from a follower to an industrial leader within a decade (Whang and Hobday, 2011). Here, the notion of 'test bed' may be interpreted in

the context of ‘lead market’ which assumes “*that particular characteristics of local demand increase the probability that local innovations can also be commercialised on the world market*” (Beise, 2004: 1015). This line of thinking draws a considerable parallel to Porter’s Diamond model (Porter, 1990, 1998a), in which demand in a home market is seen as one of the four determinants influencing the innovativeness of local firms, resulting from sophisticated or stringent local buyers pressuring firms to innovate faster and develop more advanced products. The concept of lead market was initially only linked with economically advanced countries due to its emphasis on customer sophistication and affluence as the inducers of innovation, but the theory was later extended to include the ‘lead market for frugal innovations’ in emerging economies, most notably small cars in India etc., where innovations are characterised by high affordability, robustness, and ‘good enough’ quality in a volume-driven market (Tiwari and Herstatt, 2012).

2.4.4 Innovation induced by stringent government standards

Porter and Takeuchi (1999; Porter and van der Linde, 1995a,b) have argued that the tough energy efficiency law introduced by the Japanese government in the 1970s has triggered a flurry of innovations in industries such as air-conditioners and automobiles; as a result, these industries were able to establish first-mover advantage, and subsequently to become the global leaders in their respective sectors. It is well-documented that the two oil crises of the 1970s (together with the adoption of a flexible exchange rate system in 1973 that caused major appreciations of the Japanese yen²²) compelled the Japanese government to turn its policy focus to energy conservation, subsequently shifting the industrial structure towards an energy-saving, knowledge-intensive, and high value-added one (Kagami, 1975; Odagiri and Goto, 1993; Fukasaku, 1995; Geller et al., 2006). The government implemented a 5% oil consumption reduction program in 1979, a 7% reduction program in 1980, and another one in 1981, and achieved all the intended reduction targets even as Japan’s annual real GDP growth stood at around 5% (Ogawa et al., 2010).

The centrepiece of the Japan’s energy conservation programme has been the ‘Act on the Rational Use of Energy (エネルギーの使用の合理化に関する法律)’²³, enacted in 1979,

²² Japanese yen is the official currency of Japan.

²³ This law has since been revised several times, with the latest taking place in 2008, just before the Kyoto Protocol’s first commitment period (2008-12). It has remained at the centre of energy efficiency policy in Japan (Ogawa et al., 2010; Geller et al., 2006). The English translation of this law is available from <http://www.japaneselawtranslation.go.jp/law/detail?id=1855&vm=04&re=02>.

which specified energy conservation measures and guidelines for factories, buildings, and machinery and equipment, while giving considerable power to the relevant authority to implement them (Tanabe, 2010). Moreover, in the running up to the enactment of this law, a series of policy measurements have already been in place, aiming at inducing private investments in energy conservation measures and equipment, and stimulating innovations in energy efficient technologies; this included fiscal measures e.g. low interest loans for the installation of energy conservation in factories, and special tax reductions and depreciation schemes; meanwhile, the Moonlight Project was launched in 1978, to undertake joint government-industry R&D on major energy conservation technologies which were too expensive and risky alone for the private sector to do (Fukasaku, 1995; Ogawa et al., 2010).

As a result, for instance, Japan's iron and steel industry achieved the lowest consumption of energy per unit of steel produced in the world by 1987 through the introduction of a wide range of innovations (Fukasaku, 1995). Meanwhile, by 1978 Japanese carmakers had already achieved the strictest carbon dioxide and nitrogen standards²⁴ worldwide (Kagami, 1995), resulting from the intensive R&D investment by the private companies, which subsequently led to technologies in e.g. improving the combustion efficiency of engine (Fukasaku, 1995).

It may be argued here that energy efficiency has served as 'future' directions in technological innovation (in functional terms, as '*F3: Guidance of the search*'), while relevant stringent regulations triggered innovations, as well as '*legitimation (F6)*'. To a large extent, this resonates with the so-called 'regulation-induced innovation hypothesis' (RiiH), postulated by Ashford and Hall (2011), which sees that health, safety and environmental goals can be co-optimised with economic growth through technological innovation (Ashford et al., 1985); in this sense, the introduction of stringent regulations, aiming at achieving higher standards of health, safety and environmental requirements, can simulate fundamental changes in technology, often by new firms or entrants, through the introduction of entirely new products and processes into the market, thereby displacing dominant technologies; for incumbent firms, only those who have the willingness,

²⁴ This was also a result of complying with 'The Basic Law for Environmental Pollution Control' enacted in 1967, which established environmental standards for air, water and soil quality and for noise level, as well as responding to the American Muskie law of 1970 (Wallace, 1995; Kagami, 1995; Fukasaku, 1995).

opportunity/motivation, and capability to innovate can survive, while the remaining are likely displaced from the market (Ashford and Hall, 2011). The development of RiiH shows the clear influence of evolutionary theories (ibid), while Porter and van den Linde have also contributed to this line of thinking, and, in a way, populated it, through their works on the 'Porter Hypothesis²⁵' (Porter and van den Linde, 1995a, b), which is seen as a weak form of RiiH (Ashford and Hall, 2011).

More so, as the Japanese experience has shown, RiiH requires an integrated approach and policy congruence, because *“what seems to matter is not only the stringency, mode (specification vs. performance), timing, uncertainty, focus (inputs vs. product vs. process) of the regulation, and the existence of complementary economic incentives, but also the inherent innovativeness (usually in new entrants) or lack of it (usually in the regulated firms) that the regulation engenders”* (ibid: 279). In this regard, it may be argued that, for Wales to catch up in the era of low carbon transition, all the four aspects discussed here need to be taken into consideration, in a holistic and coherent manner. They represent the different facets of innovation governance, i.e. while technological forecasting provides a long-term vision and direction for the future, the policies designed to support small business innovation (i.e. technology push), and stimulate demand (i.e. market-demand pull) for low carbon technologies, can help to promote innovation processes at industry-firm levels; these can then be further consolidated by relevant stringent regulations aiming for carbon reduction (RiiH), as a way to corroborate the direction of technology development while enabling institutional alignment. I shall further discuss these four aspects later in the context of how they may help to address 'system weaknesses', and alter functional patterns arisen from the functional analyses of the two selected emerging technological systems in Wales.

2.5 Concluding remarks

In this chapter, I have critically reviewed the literature on innovation systems at national, regional, sectoral and technological levels, and the functions approach, while tracing their roots to the evolutionary theory. A particular attention was also paid to how our understanding on innovation processes has evolved from early linear models to a more

²⁵ The 'Porter Hypothesis' postulates that *“properly designed environment standards can trigger innovation that may partially or more than fully offset the costs of complying with them”* (Porter and van der Linde, 1995a: 98). But it was seen as a weak form of 'regulation-induced innovation hypothesis', as it mainly focuses on the incumbent firms without recognising that new entrants can also be generated by such regulations (Ashford and Hall, 2011).

complex, integrated system perspective. In addition, due to the nature of technological and economic development in Wales, I explored the literature on technological catch-up, with the intention to draw insights from countries or regions that have successfully caught up. As follows, I would like to reflect on a few aspects that are important for this study.

Nelson and Sampat (2001) postulate that all economic activities involve the use of both physical and social technologies, which combine to determine the productivity and effectiveness of economic activities. In this sense, the study of the development of a given technology needs to explore not only the process of technology development and diffusion, but also the 'way-of-doing' things, e.g. how R&D activities are organised, manufacturing processes planned and carried out, and new products or services marketed, as well as factors that influence these processes. In this study, while the functions approach may help to uncover system weaknesses, and identify where the policy intervention is required most, the policy recommendation would also need to take into consideration how the relevant social technologies and institutional infrastructure may be developed to facilitate the changes required.

On the other hand, it is sensible to assume that a given TIS likely operates differently in a peripheral regions such as Wales from that in a more advanced regions, due to their differences in e.g. institutional settings, the level of local knowledge bases, and the embedded social technologies that likely affect how the functions may perform. However, the existing RIS literature does not seem to separate the study of peripheral (or less favoured) regions from that of advanced ones, while the latter has been often the exclusive subject of the RIS literature. To this end, the existing RIS literature has been unable to sufficiently elucidate why peripheral regions fail to innovate and develop their economies, and how they may improve. Meanwhile, whereas good practices in advanced regions may offer inspirations to emulate, peripheral regions such as Wales may not have the right social technologies and institutional infrastructure to deliver these good practices. This thus makes it relevant for this study to look into the literature on technological catch-up. Accordingly, four facets of successful catching-up experiences were explored, including 'technological forecasting', 'catching-up at the industrial-firm level', 'the role of domestic demand in the catching up process', and 'innovation induced by stringent government standards'; it is expected that they likely offer ideas on possible policy measure at the regional level that may help to build up the required institutional infrastructures and social

technologies, while addressing system weaknesses and improving the relevant innovation capability within the region.

The role of market demand has emerged as an important aspect where innovation processes are concerned, as posited in Dosi's Technological Paradigm and Trajectory. Therefore, it is reasonable to assume that demand (including domestic demand) likely plays an important role in helping emerging technologies to pass the formative phase and reach market maturity, entering a virtuous cycle. However, the role of demand has been comparatively overlooked in the existing IS and technological catch-up literature. As this study will further explore how domestic demand in e.g. construction may affect the innovation capability of the indigenous firms in Wales, it is nevertheless an area that needs further studies, in both theoretical and empirical terms.

Chapter 3. Research Methods, Analytical Framework and Case Study Selection

This chapter provides an overview of the research methods employed, the analytical framework developed, and case study selection, for this PhD study, to ensure the delivery of the research aims outlined in the introductory chapter. It also discusses the reasoning behind some of the methodological choices, with methodological limitations, strengths and novelty of the research also being discussed.

This chapter contains six sections. In Section 1, I elucidate the circumstances surrounding the choice of this specific research topic. Section 2 briefly examines the methods used in the study of the functions of innovation systems, and explains the broad approach taken within this research. In Section 3, the proposed bespoke analytical framework for the assessment of the IS Functions in this study is developed, subsequently addressing Research Question 1. Section 4 offers an elucidation of the research design, in terms of how the case studies were chosen, the interviewees selected, and the data collection and analysis carried out. Section 5 the methodological limitations, strengths and novelty of the research are discussed, while a summary is provided in Section 6.

3.1 Introduction: the choice of research topic

Over the past decade, my research at the Welsh School of Architecture (WSA) has involved the promotion of sustainability to building practitioners in both Wales and China. What I have drawn from this experience is that we already have the knowledge and many of the technologies and technical solutions necessary to enable us to build low and zero carbon buildings. However, due to various reasons, e.g. cost, skill shortage, or a lack of individual or collective motivation, a lot of these technologies or solutions are still not widely used in building practices. This raises the questions – why is it so difficult for industry and individual practitioners to change? Whether is it sufficient to address the low and zero carbon transition from purely an environmental, or technological, or even an educational perspective? My personal resolution to find some answers to these questions is what triggered this PhD study.

In early 2010, the *Low Carbon Built Environment (LCBE)* project, led by the Welsh School of Architecture, was funded through the European Regional Development Fund (ERDF) Convergence Energy programme. I was employed part-time on Work Package (WP) 7 '*Innovation, Technology Development and Market Development*' of the LCBE project. It thus seemed to be an ideal opportunity, as well as a logical move, for me to make connection between the research I was to carry out for WP 7 and the PhD study on low carbon innovations that I had already begun²⁶. The LCBE project therefore provided an overarching context and framing for much of the research undertaken for this thesis. In other words, this study is very much about a prospective low carbon transition in the built environment in Wales.

In addition, while studying Wales' industrial past, I found that the patterns of early industrialisation in Wales, and its post-war effort in building up a modern manufacturing sector, have constantly reminded me of what has happened in China since the introduction of the 'Open Door' policy at the end of the 1970s. Whilst the difference in the sheer scale of development between China and Wales may make such a comparison questionable, once the focus is placed on the way of doing things, or 'social technologies' and institutions, or policy adopted, the comparison suddenly becomes plausible. This adds a different dimension and a new layer of relevance to this study, even though such a comparison is not a subject of this study. As William Blake wrote, "*To see a world in a grain of sand...*" (Blake, c.1807). Through studying a low carbon transition in Wales, I personally felt that it might offer some clues for steering the same transition in China and other latecomer economies.

My study of the Wales' industrial past was integrated into a conference paper²⁷ that I co-wrote, titled '*Regional Governance, Innovation and Low Carbon Transition: exploring the case of Wales*' (Wang and Eames, 2010); materials from this paper will be then incorporated into Chapter 4. Meanwhile, when Chapters 5 and 6 of this thesis focus on the selected case

²⁶ This PhD study is part-time based, as I was working full-time at the WSA, managing and involved in a number of projects including the LCBE project. So, it was also practical to combine my PhD study with the LCBE project, if I wished to finish the PhD within the timeframe allowed. The LCBE project ran from 1 April 2010 to 30 September 2013.

²⁷ The conferences at which I have presented the above paper include "*Knowledge Collaboration & Learning for Sustainable Innovation ERSCP-EMSU conference*", held in Delft, the Netherlands, on October 25-29, 2010; "*RGS-IBG Annual Conference*", held in London, UK, on 3 September 2010; and "*Sussex Energy Group Conference, Energy transitions in an interdependent world: what and where are the future social science research agendas*", held in Brighton, UK, on 25th - 26th February 2010.

studies, they will draw findings and materials from an internal LCBE case study report – *Low Carbon Innovation in the Built Environment, Towards an Innovation Systems Perspective for Wales*, for which I was the sole author.

3.2 The Functions approach

As indicated, this study adopts the innovation system as an overall framework of inquiry while using the functions approach to explore the development of low carbon building technologies in Wales, whereas the resultant functional analysis is expected to inform regional governance for innovation in Wales. In Chapter 2, I have reviewed the evolution of the functions approach. As discussed, even though there is still the debate on whether a sufficient set of functions have been identified (Truffer et al., 2012), the seven functions respectively proposed by Bergek et al. (2008a) and Hekkert et al. (2007) have been widely accepted as key processes (or activities) that contribute to the generation, diffusion and utilisation of innovations and technologies. As shown in Table 2.2 (in Section 2.3, Chapter 2), the main deviation between the two sets of the functions is that Bergek et al. recognise ‘*development of positive externalities*’ as the seventh function of an IS, whereas Hekkert et al. exclude it.

While I draw insights from both Bergek et al. and Hekkert et al., the functions employed for this study are mostly based on Bergek et al., with ‘*development of Positive Externalities*’ included as one of the IS functions that will be examined. It can be argued that a TIS at regional or local level shares some features in common with the phenomenon of industry clusters²⁸, for which external economies of scale are seen as the result of spatial clustering of related firms, as well as the source of competitive advantages from which firms can derive (Schmitz, 1995). Thus, the emergence of positive externalities can be seen to show the system strength of a TIS, while also leading to the positive development of other functions (Bergek et al., 2008b), as already explained in Chapter 2 (Section 2.3). The functions employed in this study will be further described in the next section when I introduce the proposed analytical framework.

As to how the functions of an innovation system might best be studied, there is no single

²⁸ According to Porter (1998b: 197), a cluster is a geographically concentration of interconnected firms, specialised suppliers, service providers, firms in related industries, and associated institutions (e.g. universities, trade associations) in a particular field that compete but also co-operate.

widely agreed method, although two main approaches have emerged in the literature in recent years.

One is 'Historical Event Analysis' (Hekkert et al., 2007; Negro, 2007; Hekkert and Negro, 2009; Suurs et al., 2010), which perceives development and changes as sequences of events. However, a number of problems have arisen in the empirical studies adopting this method. First, it is suggested that this method may be unsuitable for studying some functions, e.g. 'knowledge diffusion', as it is sometimes difficult to define or identify many historical events to mark such functions. Meanwhile, not all events identified can be allocated to one of the functions, while, on the other hand, some functions can involve more events than others, even though the quantity of events is not necessarily a reliable indicator of the level of importance. Moreover, the use of this method can be highly subjective and open to personal bias, as researchers with different academic backgrounds can come up with different categorisations of events and allocate them to different functions (Hekkert and Negro, 2009).

The second method is the use of performance indicators to examine how the functions are being fulfilled. Since the 1950s, using indicators to assess the innovation performance of nations, regions or sectors has become an established practice (Milbergs and Vonortas, 2004). The development of innovation indicators has become ever more sophisticated, and has evolved from early linear conceptions of innovation focusing on input (e.g. R&D investment) and intermediate output (e.g. patent counts) to more process-focused measurements, which partly reflects the progress made by socio-economic analyses of technological advance and innovation over the last two or three decades (ibid). On the other hand, certain connections can be made between the two methods, as some events can be used as part of the performance indicators. For instance, with regard to '*Function 3: Guidance of the search*', positive expectation of a given technology or the introduction of relevant regulations by governments (Hekkert and Negro, 2009) can be seen as both an event and an indicator for evaluating the extent to which the function is fulfilled.

This PhD study examines the functions of a IS using performance indicators. In what follows, I elucidate how and which performance indicators have been selected for the chosen IS functions, and subsequently address Research Question 1: 'can a bespoke analytical framework be developed and used to analyse the emergent WTC and BISE

innovation systems in Wales?’

3.3 A bespoke analytical framework for the assessment of the IS Functions

While it can be quite straightforward to identify performance indicators for some functions, it becomes less obvious for the more complex functions like ‘F6: *Legitimacy*’ and ‘F7: *Development of positive externalities*’. There have been a number of attempts; some focused on using only quantitative indicators (e.g. Hekkert et al., 2007), others adopted both quantitative and qualitative indicators (e.g. Bergerk et al. 2008a; Kamp et al., 2009). In this study, I use both quantitative and qualitative indicators, due to a number of reasons. First, the TIS and the functions approach have often been used to study emerging technologies, as this study does, and, in this sense, it can be reasonably argued that the relevant quantitative data may not yet exist. Then, even if such data do exist, it may still be too early to solely rely on these data to presume future developments, as uncertainties are often associated with new technologies and innovation processes. In addition, the functions approach was developed to study the dynamic interactions between actors, and between actors and their institutional surroundings, and thus it may not lead to a full understanding of the present status of the system, if only quantitative data is used.

That being said, the selection of performance indicators was not plain sailing and a number of factors were taken into consideration: (a) indicators that were already proposed or used by other IS scholars, including those postulated by Bergek et al. (2008a), Hekkert et al. (2007), Kamp et al. (2009), a summary of which is presented in Table 3.1; (b) established innovation assessment practices that assess the innovation performance of countries or regions at global, regional and national levels; they include the *EU Regional Innovation Scoreboard* (European Commission, 2012b), *The Global Innovation Index: the Local Dynamics of Innovation* (Dutta and Lanvin, 2013), and *The UK Innovation Survey* (BIS, 2013); studying these practices has enabled a better understanding on how indicators are chosen and related to different aspects of innovative performance; (c) the research aim, which includes to establish whether the two systems have reached the formative phase; as discussed in Section 2.3, Chapter 2, different sets of indicators are often required when one tries to establish whether a TIS reaches a formative phase or a growth phase; (d) the fact that the proposed indicators need to be suitable for assessing the ISs of two different technological fields, so a more generic perspective is likely required.

Table 3.1: A summary of performance indicators for assessing the IS Functions proposed by different scholars

Functions	Bergek et al., 2008	Hekkert et al., 2007	Kamp et al., 2009
Knowledge development and diffusion *	Bibliometrics; No., size and orientation of R&D projects; No. of Professors and Patents; Learning curves.	R&D projects and investment; Patents; Network size and intensity; No. of workshops and conferences.	Type of organisations performing research; Type of research activities; Start of national research project; International recognition; Start of production; Production cost changes; Market size indication; Feedback from market; Collaboration between organisations on R&D; Formalised exchange methods.
Entrepreneurial experimentation	No. of new entrants, incl. diversifying established firms; No. of different types of applications; Breadth of technologies used and the character of complementary technologies employed.	No. of new entrants; No. of diversification activities of incumbents; No. of experiments;	Type of entrepreneur; Change in the number of entrepreneurs; Recent activities; Future (announced) activities.
Guidance of the search	Beliefs in growth potential; Incentives from factor /product prices; The extent of regulatory pressures; The articulation of interest by leading customer.	Targets set by government; No. of press articles that raise expectation.	Targets set by government or industry; Type of targets (research/ market/ installation); Support for goals; Technological expectations; Expected continuation of development and diffusion.

Functions	Bergek et al., 2008	Hekkert et al., 2007	Kamp et al., 2009
Market formation	Market size; Users /customers group, and articulated demand; Actor strategies; Role of standards; Purchasing process.	No. of niche market; Specific tax regime; Environmental standards.	Market size; Consumer motivation; Financial market incentives.
Resource mobilisation	Rising volume of capital; Increasing volume of seed and venture capital; Changing volume and quality of human resources; Changes in complementary assets.	Whether or not inner core actors perceive resources access as problematic.	Availability of -- Venture capital; (Research) employees; Specialised education programme; Raw materials.
Legitimation	Alignment with current legislation and the value base in industry and society; Volume of activities within the system; The attitude of various relevant actors and stakeholders; Change in demand.	Rise and growth of interest groups and their lobby actions.	Existence of advocacy coalitions; Activities of coalitions; Recent results of activities.
Development of positive externalities	Entry of new firms into the emerging TIS, providing complementary products/ service /technologies; Emergence of pooled labour market; Emergence of specialised intermediate goods and service providers; Information flows and knowledge spill-overs.		

* Both Hekkert et al. and Kamp et al. split “Knowledge Development and Diffusion” into two Functions i.e. “Knowledge Development” and “Knowledge Diffusion (through networks)”, while excluding the function of “Development of positive externalities”.

The proposed analytical framework consists of seven functions, with each function assigned a set of composite indicators, both quantitative and qualitative. Subsequently the functional analysis carried out in this study will be more descriptive in nature. Next, I first describe the theoretical context of each function, and then outline the performance indicators identified for the relevant function respectively.

Function 1: Knowledge development and diffusion

This function concerns not only the knowledge base of a TIS at the global level, but also the extent to which the knowledge base of a local TIS performs and evolves over time. The process to build up such knowledge base requires considerable interactions among different actors, internally and externally. Meanwhile, knowledge diffusion involves the transferring of knowledge and exchange of information, but becomes effective only when the transferred knowledge is internalised and translated into the capability of the receivers, in the form of new skills, products, or patents, etc. The existence of networks is considered to be essential for information exchange and a precondition for diffusion. In this regard, the performance indicators for ‘*knowledge development and diffusion*’ are proposed as follows, in Table 3.2.

Table 3.2: Performance indicators for Knowledge Development and Diffusion

- Type of actors performing research
- Type and source of knowledge development
- R&D financing
- Number of patents filed;
- Type of research collaboration (university/industry, incl. non-local organisations)
- Knowledge exchange mechanisms

Function 2: Entrepreneurial experimentation

The presence of active entrepreneurs is a first and prime indication of the performance of an IS. The entrepreneurs include both newcomers or start-ups, and incumbent companies who diversify their businesses into new technological segments. Nevertheless, the ability of entrepreneurs to experiment with new knowledge and technologies depends on their ‘economic competence’ *i.e.* firms’ inclination and ability to identify, expand and exploit

business opportunities (Carlsson and Stankiewicz, 1991), resulting in the introduction of new products or services etc. Table 3.3 below outlines the performance indicators proposed for ‘*entrepreneurial experimentation*’.

Table 3.3: Performance indicators for Entrepreneurial Experimentation

-
- Type of entrepreneurs / firms
 - Change in the number of entrepreneurs, including the new entrants
 - Number of new (related) products (services) introduced by firms
-

Function 3: Guidance of the Search

This function reflects how events or factors emerging in political, regulatory and social arenas, and markets, can influence the direction of technology development. They act as either incentives or pressures, and affect the direction of search, between different competing technologies, applications, markets, or business models, etc. To this end, performance indicators for ‘*guidance of the search*’ are defined as follows in Table 3.4. These indicators may act in combination or individually (Bergek et al., 2008a).

Table 3.4: Performance indicators for Guidance of the Search

-
- Vision or collective targets set by government or industry, *and/or*
 - Regulations and policy, *and/or*
 - Interests expressed by customers / users, *and/or*
 - Demand-orientated policy measures, e.g. procurement policy, *and/or*
 - Factor conditions, *and/or*
 - Industrial or social crisis.
-

Function 4: Market formation

This function contains activities that contribute to the creation of market demand for a new technology, which is either new to the world in general or may only be new for a given country or region. It often involves a searching process of what to sell, who to sell to and how to sell, sometimes within a protected market *i.e.* ‘*niche market*’. The performance indicators for ‘*market formation*’ are proposed as follows in Table 3.5.

Table 3.5: Performance indicators for Market Formation

-
- Market size and composition
 - Actor's marketing strategy
 - Financial incentives for emerging technologies
-

Function 5: Resource mobilisation

This function involves the allocation of basic economic factors, e.g. human, financial and materials resources. The scope of this function includes to deploy *competence/ human capital* through education in specific scientific and technological fields as well as in entrepreneurship, management and finance, *financial capital* (in the form of seed and venture capital etc.), and *complementary assets* such as complementary products, services, network infrastructure, etc. In this sense, the performance indicators for this function are defined as follows, in Table 3.6.

Table 3.6: Performance indicators for Resource Mobilisation

-
- Ability to retain and attract desirable talents
 - Availability of specialized education programme
 - Availability of raw materials
 - Access to finance, e.g. venture capitals, foreign investment and governmental grants
-

Function 6: Legitimation

Legitimacy is a matter of social acceptance and compliance with relevant institutions. It is crucial to attain legitimacy in order for resources to be mobilised, markets to form, and actors in the new TIS to acquire political strength. In the formative phase of an emerging TIS, the legitimation may mainly involve getting the technology accepted as a desirable and realistic alternative to incumbent technologies, through articulation of expectations and visions, and regulatory alignment. Table 3.7 below outlines the performance indicators proposed for 'legitimation'.

Table 3.7: Performance indicators for Legitimation

-
- Compliance with existing regulations /legislation
 - Meeting the expectations and value base of the society
 - Activity of advisory coalitions
-

Function 7: Development of positive externalities

This function is largely influenced by Marshall’s (1890) concept of external economies of scale, which suggests firms can benefit from the collective efficiency advantages, in terms of ‘pooled labour markets’, ‘specialised intermediate goods and service suppliers’, and ‘knowledge spill-overs’, as a result of clustering. There has been the argument that such collective efficiency was not a deliberate creation, rather an unintended or incidental by-product of some otherwise legitimate activity (Mishan, 1971). However, empirical studies on industrial districts (clusters) in both developed and developing countries have led to suggestions that consciously pursued joint actions by firms can also contribute to collective efficiency, as “*the competitive advantages derived from local external economies and joint action*” (Schmitz 1995: 530). Two types of such joint-action are identified: ‘cooperation between individual firms’, and ‘joint forces by a group of firms in the form of business associations, producer consortia and the like’ (Schmitz, 1997: 8). Thus, the performance indicators for the ‘*development of positive externality*’ are proposed as follows, in Table 3.8.

Table 3.8: Performance indicators for Development of Positive Externalities

-
- Emergence of a pooled labour market
 - Emergence of specialized intermediate goods and service providers
 - Increase in explicit inter-firm cooperation for specific purposes
-

The above performance indicators chosen for each function will appear together as Table 6.1 in Chapter 6, forming ‘a bespoke analytical framework for the assessment of the IS Functions’, which will then be used to examine the two selected emerging technological systems in Wales.

3.4 Research Design

3.4.1 Case study selection

In methodological terms, a case study can refer to a heterogeneous set of research designs (Gerring, 2004). For this study, I found that the definition offered by Seawright and Gerring (2008: 296) is of relevance, *i.e.* the method of case study contains “*the intensive (qualitative or quantitative) analysis of a single unit or a small number of units (the cases), where the researcher’s goal is to understand a larger class of similar units (population of cases). There is thus an inherent problem of inference from the sample (of one or several) to a larger population.*” To address this problem, it is required that the case(s) selected should be able to fulfil “*external validity*” or “*generalisability*” (Bryman, 2001: 50), so the finding of the case study becomes representative while providing useful variation on the dimensions of theoretical interest (Seawright and Gerring, 2008).

As described, the aims of this PhD study are twofold. Firstly, it aims to foster understanding of the development of low carbon building technologies in Wales using the IS and functions approach, and secondly it aims to investigate the extent to which the findings of the function analysis may offer a bottom-up perspective on how regional governance in Wales might help to alter the functional patterns, and improve the innovation capability of relevant Welsh organisations. This means that the findings from the selected case studies are first able to help to paint a general picture of the development of low carbon building technologies in Wales, and secondly they allow some analytical generalisation about the relevant innovation capability in Wales. In this regard, one of the main criteria that this study adopted, as to the selection of cases for study, was therefore whether there appeared to be a reasonable level of industrial activities and prospects with regard to the development of a given low carbon building technology across Wales, other than more practical reasons, *e.g.* time, and access, or personal interest.

On the other hand, as mentioned, this PhD has consciously made connection with the LCBE project, and used it to form an overarching context and framing for the research undertaken for this thesis. While there were practical reasons involved, as explained, this connection nevertheless provided insights into how Welsh experts perceived that a transition to a low carbon built environment in Wales might take place, technically, seeing that a lot researchers and industrial partners involved in the project have many years of

experiences of working and doing research in the built environment in Wales. Therefore, rather than to choose from a broad spectrum of available low carbon building technologies and solutions, by linking with the LCBE project, the field from which the case study might be chosen was narrowed down, *i.e.* within the scope of the LCBE project. In addition, since the LCBE project was funded under the *Framework for Innovation R&D and Technology - ERDF Convergence: PITI*²⁹, it was a compulsory requirement that an aspect of commercial exploitation would be addressed in the project. This somehow helped the selection of the case study, in terms of identifying the industrial bases of low carbon building technologies or solutions in Wales.

The LCBE project comprised one project management, and seven technical work packages which were:

WP1: Sustainable Building Envelopes, led by Tata Steel;

WP2: Lighting: Design and Implementation of Solid-State Energy Efficient Lighting, led by Swansea University;

WP3: Use of Timber in Building Construction, led by BRE Wales;

WP4: Low Carbon Design Solutions, led by WSA;

WP5: Urban Scale Demand and Supply, led by WSA;

WP6: Monitoring the Performance of Low Carbon Technologies, led by WSA;

WP7: Innovation, Technology Deployment and Market Development, led by WSA.

Whereas WPs 4, 5 and 6 involved low carbon solutions for the built environment in Wales, the possibility for the market deployment of these solutions seemed to be limited, for the time being; for instance, one of the WP5 deliverables was 'Prototype energy master planning model' for the urban scale³⁰, where this computation model contained certain potentials for commercialisation, which were not further exploited during the project period. Thus, these three WPs were ruled out at once.

²⁹ The Framework for ERDF Convergence: PITI aimed at raising value added by building business capacity to develop and take-up improved and new products, processes and services, through developing domestic research, technology and innovation capacity and ability to commercialise and exploit research, whereas the participation of both SMEs and larger firms were welcomed; some key indicators for the implementation of the Framework included *e.g.* enterprises assisted or created, gross jobs created, and new or improved products, processes or services launched (Welsh Government, 2008c).

³⁰ WP5 linked to two consultation projects that I have managed, which involved the development of a low carbon master-planning tool for Chinese partners. The low carbon model developed for the Chinese partners was then incorporated into the research carried out in WP5. When it may be argued that a certain level of commercial exploitation has been involved in the Chinese projects, since the Chinese partners funded the projects, the research carried out in WP5 was mainly R&D based, and at the stage of prototype.

Between WPs 1, 2 and 3, the low cost, energy efficient LED lighting technology involved in WP2 was also eliminated, due to the fact that at the time few industrial actors in Wales were involved in developing this technology. Thus, it likely raised the concern of how representative it would be if the technological ‘system’ of LED lighting was selected for study, whereas both WPs 1 and 3 presented better cases for study.

WPI ‘*Sustainable Building Envelopes*’ was led by Tata Steel, whose Welsh operation is the biggest industrial employer in Wales. The key objectives of this WP were to develop, test and prototype energy generating building components which integrate varied solar technologies (e.g. PV, solar air heating and ventilation system, and solar thermal) with pre-finished steel products. In the meantime, solar energy is one of the main low carbon themes within the Low Carbon Research Institute (LCRI)³¹ in Wales, and the selection of this case study thus allow a connection to be made with other LCRI Convergence projects, mainly the *Solar Photovoltaic Academic Research Consortium Cymru (SPARC CYMRU)*³², led by Glyndŵr University. As a result, I attended a seminar event organised under the SPARC CYMRU project, and was able to interview a number of experts and firm representatives who were linked to the project. In addition, there is already a well-represented solar industry across Wales, with a range of companies who specialise in different solar technology segments (Stafford, 2008), as I will further discuss it in Chapters 5 and 6. In this respect, it was believed that the study of ‘building integrated solar energy systems (BISE)’ in Wales would be able to help to deliver the aim of this PhD study.

The same can also be said of the selection of ‘Welsh grown timber for construction (WTC)’ for case study, linked to WP3 ‘Use of Timber in Building Construction’. This WP was led by the BRE (Building Research Establishment) Wales, and aimed at undertaking R&D into the use of Welsh grown timber for construction components or products that can help to deliver low carbon buildings in Wales. As will be further explored in Chapters 5 and 6, outside the LCBE project, Welsh organisations such as the Wales Forest Business

³¹ The Low Carbon Research Institute (LCRI) is a virtual organisation set up in 2008 with initial funding support from the Higher Education Funding Council of Wales (HEFCW). The purpose of the Institute is to help Wales to deliver a low carbon future, through uniting and promoting energy research in Wales, developing low carbon generation, storage, distribution and end use technologies, while offering policy advice. More information is available from the LCRI website <http://www.lcri.org.uk>.

³² The LCBE project was part of the LCRI Convergence Energy Programme, launched in September 2009, which received more than £15 million from the ERDF Convergence programme. More information is available from <http://www.lcriconvergence.ac.uk>.

Partnership (WFBP) and Coed Cymru have been carrying out R&D on the use of Welsh grown timber for construction since the mid-1990s, resulting in the introduction of e.g. the Ty Unnos – a hybrid modular volumetric off-site building system using Welsh grown Sitka spruce. Similarly, there is already a well-represented timber-based industry across Wales, which produces a range of wood products (Welsh Government, 2009). This showed that a reasonable level of industrial activities as well as prospects had emerged in Wales with regard to the development of WTC, and thus the study of WTC appears to be representative and helps to deliver the relevant analytical generalisation.

In addition, at the outset, the developments of BISE and WTC in Wales have shown some interesting contrasts. For instance, most obviously the industrial players involved in the BISE are large international firms such as Tata Steel (as noted, the biggest industrial employer in Wales), whereas most of the firms involved in the WTC are small businesses. Meanwhile, although both technologies are seen as emerging technologies in Wales, in terms of the product cycle of a given technology (Perez and Soete, 1988), at a global level, timber construction represents a mature technological field, whereas building integrated solar technologies are still at an early stage of commercialisation, as will be discussed in Chapter 5. To this end, it was expected that such contrasts would likely lead to interesting findings when the IS functions e.g. *Knowledge development and diffusion* and *Entrepreneurial experimentation* were examined.

3.4.2 Comparative study

Comparative study is employed in this study, partly following a tradition of empirical study of ISs, as discussed in Chapter 2, and the aforementioned contrast thus can be seen to embody the logic of comparison. That being said, the comparison in this study is essentially functions-based, i.e. for each of the seven functions, similar and different functional patterns will be assessed and compared, on the basis of the way in which and the extent to which each function has been carried out in the WTC and BISE TIS respectively. Since this study uses the performance indicators to assess the seven IS functions (as elucidated in the previous section), to a certain extent, the similar and different patterns drawn largely reflect how these performance indicators were fulfilled respectively in the two systems.

It is expected, from a bottom-up perspective, that the similarities and differences arising in the comparison will help to generalise the innovation capability of the relevant Welsh

organisations in the field of low carbon building technologies, while exposing both the 'system strength' and 'system weakness' in the relevant institutional, technological and economic structures in Wales. In turn, specific policy measures will be recommended accordingly, aiming at addressing the system weakness, and altering the functional pattern through adding (or reinforcing) inducement mechanisms, or offsetting (or removing) blocking mechanisms, so the relevant innovation capability in Wales will be improved and enhanced. As already discussed in Section 2.4, Chapter 2, the inspiration for policy recommendation is largely drawn from those countries or regions that have successfully caught up technologically and economically.

There has been the concern about whether more case studies were needed, since, according to Eisenhardt (1989), a cross-case analysis involving four to 10 case studies may provide a good basis for analytical generalisation. After much deliberation, it was decided that two case studies would be sufficient for the purpose of this PhD study, for a number of reasons. First, this study focuses the level of analysis on the regional level, specifically Wales, which is a relatively small nation; although it seems that only two case studies were chosen, the development of two chosen technological systems nevertheless encompasses a number of industrial sectors in Wales, e.g. solar, steel, construction, and forestry, as well as research activities in several Welsh universities. On the other hand, case studies only constitute a starting point for the analytical generalisation in this study; as explained above, the findings from the functional analyses of the chosen TISs will be further compared, while a historic perspective is also brought into the analysis, as will be explored in Chapter 4; this thus allows the functional patterns identified through the cases studies and comparative analysis to be further cross-examined in the context of 'path-dependence', linking the occurrence of current and future events to the past decisions, events, and circumstances, as a result of cumulative causation (Neffke et al., 2011). On the whole, it is believed that two case studies are sufficient for the analytical generalisation that will help to deliver the purpose of this PhD study.

3.4.3 Data collection and analysis: semi-structured interviews

Secondary data and existing literature were initially studied in order to obtain an understanding of: the chosen technologies; the socio-economic development in Wales; and, the theoretical constructs of the IS and functions approach; in turn, they helped to prepare for the field study (interviews), and data analysis. This involved extensive literature

reviews on a number of subjects: the evolutionary theory, innovation systems, technological catch-up, Wales since the industrial revolution (with focuses on socio-economical development and changes in policy and governance), and the development of timber construction and solar technologies; the latter was helpful for establishing the structural components of two selected TISs (in Chapter 5), and mapping their respective functional patterns (in Chapter 6). The sources of the secondary data include relevant books, journal and research papers, policy documents and technical reports from the Welsh Government, the National Assembly of Wales, the UK government, the European Commission, OECD, and other international organisations, as well as trade associations (e.g. the UK Timber Research And Development Association (TRADA) and the European Photovoltaic Industry Association (EPIA), etc.), and news articles, etc.

Primary data was collected by means of semi-structured interviews. Once the two technologies were chosen, their links to the LCBE project simplified access to the researchers and project partners who were involved in the relevant WPs; they thus were amongst the first to be interviewed. Interviewees were also identified by recommendation (i.e. the so-called 'snowball' principle), and through the membership directories of relevant trade associations, including TRADA and EPIA. Accordingly, two different focuses were taken when identifying interviewees for the primary data collection.

In the case of WTC, a supply-chain perspective was adopted. This is because this case focuses on increasing the use of Welsh grown timber in construction, which implies the need to improve the performance of the relevant supply chain, linking Welsh woodland owners, wood processors, architects and building practitioners. A number of innovative timber engineering systems that explicitly use Welsh grown timber have been developed by Welsh organisations in recent years. One of them is the "Tŷ Unnos" (meaning "House in a night" in Welsh) system, which constitutes the core of this inquiry. By following a supply-chain perspective, twenty interviews were carried out with interviewees including the relevant actors, amongst woodland owners, sawmill, secondary wood processors, architects, academic researchers, and related stakeholders e.g. landowner association and relevant government bodies.

With regard to 'building integrated solar energy systems', as the whole technological field and knowledge base are still evolving, and the development of relevant technological

systems is still at an early stage of commercialisation, a supply-chain perspective appeared to be less relevant. Instead, based on the secondary data, I identified as many relevant actors as possible that had head offices, or main research or production facilities in Wales. In this respect, fourteen relevant interviews were conducted, which included most of Wales-based solar technology firms, relevant academic researchers, government officials, and architects, etc. A list of the organisational affiliation of the interviewees for both case studies is available in Appendix A.

In both case studies, as mentioned above, the 'snowball' principle was applied, as the interviewees recommended or provided information that led to other relevant interviewees. Some interviewees also recommended seminars or events that they thought might be useful. Given the time allowed, I attended two industrial seminars and a conference in order to gathering information and further contacts for the interviews. These were: '*Growing Our Woodlands in Wales: the 100,000 hectare challenge*' organised by the Institute of Welsh Affairs and the then Forestry Commission Wales in July 2012; '*Promoting Timber in Construction*' organised by the Welsh Government in November 2012; and '*PV in Wales Post Feed in Tariff Reduction*' organised by the SPARC CYMRU project in March 2013.

All interviews proceeded in a similar manner, and took place between May 2012 and July 2013. Potential interviewees were initially contacted through emails that introduced the project, and explained the purpose of the interview, the interview topics or questions. Before the interviews, a set of open questions was prepared in order to provide some direction and structure (an example copy of the interview questions is available in Appendix B). However, interviewees were generally encouraged to speak freely. Most of the interviews were carried out face-to-face, although two were conducted by telephone. While most of the interviews lasted between 30 to 100 minutes, all interviews were recorded, and then transcribed by a professional transcription service. The materials obtained from the interviews have been used to examine the case studies in this study, although the identities of these individual interviewees were anonymised in the preparation of the thesis, in conformity with good ethical practice.

As the functions of innovation systems approach was chosen as the main analytical framework for this study, the interview questions were devised with the aim of

discovering the extent to which the functions were fulfilled in practice. Subsequently, the analyses (coding) of the interview transcriptions were theme-based, with each function representing a theme (or sub-heading). The contents of the interview transcripts were categorised into seven sub-headings. Due to the size of the data set (34 interviews), the coding was done manually and organised using a spread-sheet.

3.5 Methodological strength, novelty, and limitation

The analytical strength of this PhD thesis lies with the adoption of the IS functions approach as an analytical framework, with the principal task to unveil what actually happened or is happening in the selected innovation systems. This, to a large extent, resonates with some of the original intentions when the functions approach was first proposed (Bergek, 1998; Jacobsson and Bergek, 2004). By doing so, it is expected to reduce the risk that the validity of the conclusions of this study could be undermined by the inherent methodological, analytical and conceptual problems which have prevented the functions approach from being a fully established theoretical framework (Hekkert and Negro, 2009), as discussed.

Accordingly, the seven functions together with the performance indicators respectively selected construct a 'theme- and sub-theme- based' structure, which allows the empirical findings to be organised in a systematic manner. Meanwhile, as this study chose to use indicators of a more generic nature to assess the extent to which the IS functions have been fulfilled in the two selected TISs, it opens space for a more rigorous examination of the empirical data gathered; this thus helps to piece together the overall pictures of the developments of the two systems in Wales, which is seen to be essential for the analytical generalisation that this study sets to carry out; in the meantime, this level of details also allows the functional patterns to emerge, which can be argued to be important (if not critical) for studying any new technologies at their early development stage.

The use of the functions approach as the analytical framework also makes the comparison of different TISs possible, in that it becomes feasible to compare functional patterns through the exploration of the similarities and differences arisen between the two systems. This subsequently sheds light on the 'system strength' and 'system weakness' with regard to the development of low carbon building technologies in Wales, and provides the basis

for possible policy recommendation at the regional level that may help to alter the functional patterns, and address the 'system weakness'.

In addition, a historic perspective is also brought into the analysis (in Chapter 4), which allows the functional patterns and the 'system strength/ weakness' arising from the function analyses and comparative study to be further cross-examined in the context of 'path-dependence', linking the occurrence of current circumstances to the past decisions and events. While centring around the functions approach, this study takes a sequence of analytical steps to deliver the research aims, which in turn helps to build the intended argument in a progressive, coherent manner, and contribute to the validity of the conclusion of this PhD study.

One novelty of this study is the creation of 'network maps of interactions between actors' for each individual TIS to visually map the interactions between different actors as a given TIS evolves, as elaborated in Sections 5.1.2 and 5.2.2 (Chapter 5), and Section 6.3 (Chapter 6). It is developed as part of the attempt to establish the relevant IS structural components, *i.e.* actors and their networks, and contains a two-phase process: 1) it begins with the theoretical exploration of which actors (or actor groups) one would reasonably expect to be included in a well-functioning TIS, and how they would interact, and that results in the formation of a '*perceived*' network map of interactions between actors in a well-functioning TIS, as illustrated in Figures 5.2 and 5.5; 2) the '*perceived*' network map is then used as the basis to examine which actors have actually emerged in the given TIS, in association with the generation, diffusion and utilisation of the relevant innovation and technology, following the IS function analysis; that leads to the formation of a '*present*' network map of interactions between actors in the given TIS, as shown in Figures 6.4 and 6.5. In this regard, the network maps further provide a supplementary interpretation to identify the status or phase of a TIS, *i.e.* from an actors-network interaction perspective.

One primary weakness arising in the chosen methodology is that the selection of interviewees likely runs the risk of missing out people who represent firms or organisations that have exited the industry, the so-called 'survival bias' (Bergek, 2002). In some instances, even if such people are identified and contacted, as happened in this study, they may choose not to give their sides of story. Nevertheless, many of the interviewees

had been involved in their respective fields for a long time, and therefore arguably the study was still able to capture most of the big picture.

Meanwhile, there are two groups of actors who were not represented in the interviews. One was solar installers. None of the companies contacted was able to give an interview, with one of them cancelling the scheduled interview at the last minute. Knowledge of their views thus has had to come from secondary data. The other group was officials responsible for developing innovation policy in the Welsh Government, where my interview request was unfortunately declined. To compensate for this absence, I was able to interview one of the academics who sat on the 'Task and Finish Group' for the development of *Innovation Wales* – WG's latest innovation strategy. In addition, secondary data was again used for the study of innovation policy governance in Wales

3.6 Summary

This chapter has offered an overview of circumstance surrounding the choice of this specific research topic, and explained how the method of performance indicators was chosen for the study of the IS functions; subsequently, a bespoke analytical framework for the assessment of the IS Functions was developed, which comprises the seven functions of an innovation system, with each function assigned a set of performance indicators. This bespoke analytical framework will be used later in Chapter 6 to examine the two selected emerging technological systems in Wales: 'Welsh grown timber for construction' (WTC) and 'building integrated solar energy systems' (BISE) TIS.

Furthermore, the chapter elucidated the research design, in terms of the reasoning behind the case study selection, how the interviewees have been chosen, and the data collection and analysis were carried out, while some of the methodological strengths, novelty and limitations of this research were also explored.

In the next chapter, I will review the socio-economic development in Wales since the industrial revolution, and thus, from a historical perspective, explore the extent to which the past may have affected the economic, institutional and technological performance of Wales at present, *i.e.* in the context of 'path-dependence'.

Chapter 4. Wales: the Distance Travelled

“There are different ways of looking at the world. It would be easy to look back on the old century in Wales as one of exploitation, where mineral and human resources were systematically and ruthlessly expended in creating industrial dereliction and social exclusion (Williams, 1985; cited in Hill, 2000:1).

In evolutionary theories, history matters. It helps our understanding of current problems, of many social conventions, or more formally constructed social technologies and the institutional setup of the present-day, and mostly the phenomenon of ‘path-dependence’. This applies when we talk about the socio-economic predicament facing Wales. As the Institute of Welsh Affairs (n. d.: 1) summarised,

Productivity in Wales lags behind the rest of the UK as do exports, a sharp contrast with the picture 100 years ago when Wales ... (was) sending its coal to all corners of the globe. This one time predominance of coal...is still at root the heart of the problem. Wales failed in era of coal and steel – its other main industrial sector – to develop a diversified economy, and repeated attempts to correct this fault, through post-war direction of industry, inward investment incentives and the encouragement of indigenous entrepreneurialism have still not paid off.

According to the official figures published in December 2014 (Welsh Government, 2014a), Wales has the lowest level of GVA per head in the UK regions, at 72.2% of the UK average in 2013; while the unemployment rate in Wales is close to the UK figure, the average earnings on a residence basis in Wales are 12 % below the UK average in April 2014, with about 10% of the Welsh workforce employed in the public sector; Wales also has a lower rate of business start-ups, one third less than the UK average in 2013 (ibid). Thereby, as this research is looking ahead to a possible low carbon transition in Wales, it is necessary to go back and study its past, to help our understanding of the economic reality in Wales, and why a break from its past practices is needed if Wales is to catch-up in the course of a transition to a low carbon economy.

This chapter contains five sections. Section 1 provides a review of Wales’ transition to a high carbon economy, characterised by the rise and fall of its coal and metallurgical

industries, and discusses the emergence of a development pattern which left long-lasting effects on Wales' economic and institutional structures. Section 2 is dedicated to the examination of policy intervention by the British state in the wake of rising unemployment resulting from the rapid decline of the traditional coal and steel industries in Wales, and the development of modern manufacturing industries, and the reasons behind their decline. Section 3 elucidates the institutional context of Welsh devolution, the operation of a multi-level governance (MLG) in Wales, and the emergence of a new post-devolution Welsh identity and a distinctive Welsh low carbon 'transition' narrative. Section 4 explores the innovation policy governance in Wales. In Section 5, I then reflect on how the problems of Wales' past may provide clues in terms of overcoming the challenge of path-dependence.

4.1 Transition to a high carbon economy

Up until the 1830s, Wales remained predominately an agricultural society (Williams, 1995), geographically isolated from the rest of the UK, partly due to poor road links within and between Wales and England. Even though there was a scattering of small industrial activities, e.g. copper mines in Anglesey, copper-smelting works around the Swansea area, ironworks near Merthyr Tydfil, an emerging tinsplate industry in the Llanelli and Swansea area, and slate quarries in Gwynedd, Wales as a whole largely missed out on the technological and economical progress created by the first phase of industrialisation, and was left far behind its English neighbour (Rees, 1947, cited in Williams, 1995; Howells, 1977; Hobsbawm, 1968).

Industrialisation took shape in Wales in the age of steam in the second half of the 19th century – the spread of steam locomotives, steamships, the use of steam engines in heavy industries, which resulted in rising demand for the 'steam coal' of South Wales. Especially at sea, owing to its inherent qualities, e.g. high evaporative power and relative freedom from smoke, South Wales steam coal was given the 'seal of approval' by the British Admiralty as the premier marine fuel, and by the late 1850s the Admiralty bought almost all its coal supplies from South Wales. Thanks to the reputation of the British navy in the 19th century, most European continental navies as well as steamship companies throughout the world were eager to buy the production of Welsh pits (Morris and Williams, 1958; Asteris, 1986, Davies, 2007). Meanwhile, the demand for Welsh anthracite coals, mainly as domestic fuels, had also grown, due to the increasing use of coal-fired closed stoves in

continental Europe (Evans, 1939). Coal mining emerged as the largest industry in Wales by the 1870s and dominated the Welsh economy in the following decades (George et al., 1988). Coal production in South Wales peaked in 1913 at 57 millions tonnes, with 65% of this output being exported, through the docks constructed at Newport, Cardiff, Barry and Port Talbot, while around 30 per cent of the occupied males in Wales were working in collieries (Jenkins, 1975; Howells, 1977; Williams, 1995). At the beginning of the 20th century the price of world coal was set in Cardiff (Welsh Government, 2010b). In this regard, it can be argued that South Wales led the world in the transition to a high carbon based economy.

The decline of the Welsh coal industry started during the interwar period (1918 – 1939), resulting from a number of causes. First, alternative fuels such as oil began replacing coal for marine propulsion in the early 20th century, and by 1934 over half the world's shipping used oil as a power source (Marquand, 1936; Jones, 2000). Thus, in an ironical way, technical progress at sea, the single most important factor that was responsible for the rise of the Welsh coal trade, also became a leading factor in its decline (Asteris, 1986). Meanwhile, boiler appliances burning coal became more efficient partly as a result of adaptation to the coal shortages during WWI (ibid; Williams, 1995; Powell and Thomas, 1999). Politically, the British government's decision to resume the gold standard in 1925 led to an over-valued pound and subsequently devastated the overwhelmingly export-oriented industries in Wales (Williams, 1983; Lovering, 1984). These discouraging developments coincided with the more general influences on the supply side e.g. new competition in countries like USA and Poland (Powell and Thomas, 1999), as well as the exhaustion of more accessible coal reserves in Wales (Williams, 1995).

Welsh coal returned to growth temporarily during WWII and the boom decade of 1947 to 1957, due to rising demands for war and post-war constructions. The nationalisation of the coal industry in 1947 paved the way for government investment in modernising the industry. However, the downward trend resumed from the late 1950s onwards, due to poor economic performance in terms of profitability and productivity compared to overseas coal producers, and prolonged industrial actions in the 1970s and 1980s, as well as competition from alternative fuels. The least efficient pits were rapidly closed, which had a devastating impact on the South Welsh coalfield. The number of pits declined from 118 in 1960, to 51 by 1973, and subsequently to 2 deep mines and 50 small mines in 1994

when the industry was re-privatised. Its workforce shrank from around 87,000 in 1960 to 10,200 in 1987 (George et al. 1988). By 2012 just 12 coal pits were operating in Wales, employing slightly over 1100 people, with annual output under one million tonnes (Coal Authority, 2013). Figure 4.1 below offers a glimpse of dramatic changes in the coal production in Wales since 1854.

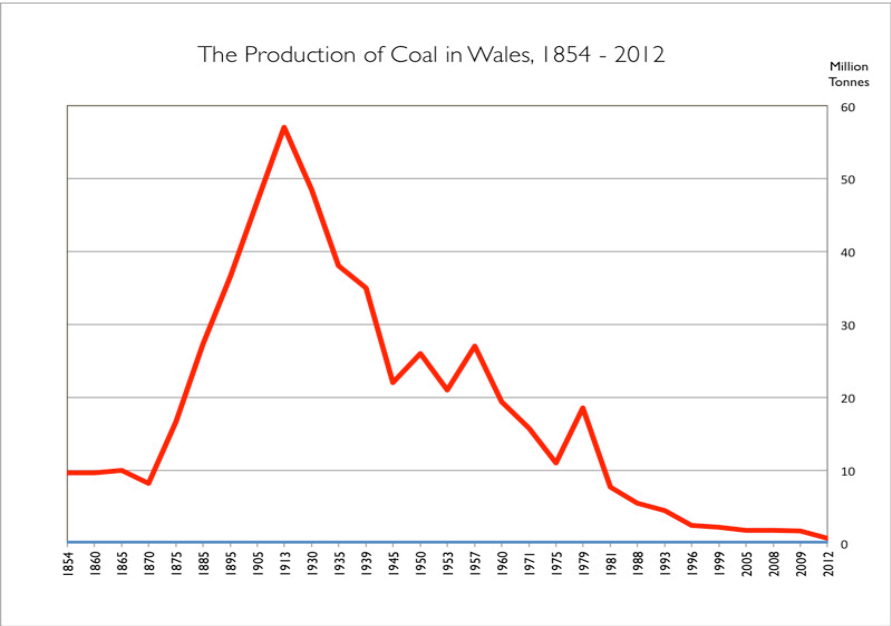


Figure 4.1: A historical trend of the coal production in Wales, 1854 – 2012 (compiled base on sources: Welsh Government, 1985; Jenkins, 1975; Thomas, 1977; George et al., 1988, and Coal Authority, 2010, 2013)

Metallurgical industries have always played a prominent part in industrial development in Wales, even before coal mining came into dominance. For instance, in the late 18th century copper mines in Anglesey were so productive that their owners were able to dictate the market price of the metal for a while (Howells, 1977). Meanwhile, for a considerable time the coastal region between what is now Carmarthenshire and Neath Port Talbot had been the main centre of British non-ferrous metal production (Roberts, 1979). Owing to cheap coal and labour available in the region, as well as the nearby docks where the ores could be disembarked, the Swansea-Neath area was endowed with a booming metal smelting industry, supplying 90% of British copper smelting capacity in the late 18th century (ibid), although the industry declined once the reserves of copper ores were exhausted in Anglesey in the second half of the 19th century (Jenkins, 1975).

Then, there was the south Wales iron industry, which was initially expanded to meet the need for military supplies for the Seven Years' War of 1756-63. By 1815 eight larger ironworks (e.g. the Dowlais Ironworks near Merthyr Tydfil) and a number of smaller ones were operating along the northern rim of the coalfield from Blaenavon to Hirwaun (Howells, 1977; Vaughan, 1975). The industry continued its expansion, as the long-term demand for iron was sustained by the constant need for military supplies, and railway building at home and abroad, as well as the use of iron for an ever-widening range of industrial and domestic products. By 1827, half of Britain's iron exports were produced by the south Wales iron industry (Howell, 1977). In the meantime, the iron industry also laid the foundations for the emergence of a major tinsplate industry, concentrated in the Llanelli and Swansea area from 1840 onwards (Humphrys, 1977).

The invention of modern steel technologies, e.g. the Bessemer process, revolutionised the Welsh iron industry. Some of the existing ironworks such as Dowlais and Ebbw Vale were able to adopt the new technologies and started manufacturing steel around the 1870s (Vaughan, 1975), but many others failed to do so. Meanwhile, new large-scale steelworks were built in East Moors Cardiff and Port Talbot in the late 19th century, with more constructed in south as well as north Wales into the 20th century (Jenkins, 1975). Much of the Welsh steel was used in the production of tinsplate (Howells, 1977). From 1870 to 1890, the south Wales tinsplate industry led the world in its production, and enjoyed a near monopoly of all foreign markets, with 75% of the production exported to the United States, for the use of hermetically sealed tin-can containers for the packing of fruits, meat, and fish (Evans, 1939). However, after the American imposed the prohibitive McKinley tariff on tinsplate imports, the industry suffered a significant blow and never fully recovered.

As with the coal industry, the decline of the Welsh iron, steel and tinsplate industries began during the interwar period, though with a slightly better result. This was largely attributed to the ability of the industry, however reluctantly, to diversify and find new markets, e.g. supplying the growing automobile industry in Britain (*ibid*). Meanwhile, from the 1930s onwards the British government has played a pivotal role in the modernisation of the Welsh steel industry, even though some of the decisions (e.g. to locate a strip mill at Ebbw Vale) were considered to be more political than economic (Wanhill, 1980; Baber and Mainwaring, 1988; Lovering, 1983). The Welsh iron-steel industry was nationalised in 1949 but de-nationalised in 1952, only to be re-nationalised again in 1967. During this period,

massive investment was put into the industry. However, after two worldwide oil crises in the 1970s and a three-month steel strike in 1980, the British steel industry as a whole lost its competitiveness to rivals in West Europe, Japan, South East Asia and Latin America. Some 50,000 jobs were lost in Wales between 1974 and 1984 (Baber and Mainwaring, 1988). British Steel was again privatised in 1988, followed by a merger with the Dutch steel producer Koninklijke Hoogovens to form the Corus Group in 1999. Later in 2007, the Indian owned multinational Tata Steel took over the Corus Group.

In Wales, only the plants in Port Talbot, Llanwern and Shotton survived, employing a total of around 7000 people at the beginning of 2014, although Tata has recently announced that around 400 jobs were to go at its Port Talbot plant (BBC News, 2014). On the other hand, Tata's Welsh operation has ventured into building integrated solar systems in recent years, and has been instrumentally involved in setting up both the *Sustainable Building Envelope Centre (SBEC)* in 2010, and the *Sustainable Product Engineering Centre for Innovative Functional Industrial Coatings (SPECIFIC)* in 2013, with the aim of transforming building façade into mini energy generators, as I will explore in the case studies later.

At the beginning of the 20th century, the Welsh industrial sector already exhibited some unusual characteristics: e.g. the persistent dominance of primary production (e.g. mining), and labour-intensive and manual occupations, lack of a sizeable, stable manufacturing and/or other secondary or intermediary sectors, the ascendancy of production methods and means that were inherently resistant to factory-type management and discipline (Williams, 1983, 1995), and, most evidently, an export-oriented economy that mainly fed raw materials to England and newly industrialised countries abroad. This made the Welsh economy immensely vulnerable to overseas competition and changes in the international trading context (Jenkins, 1975).

In comparison with what happened in England and other industrialising countries, it was suggested that the early industrialisation in Wales was driven largely by organisational innovations rather than technological ones (Lovering, 1983). As much of the capital invested came from outside Wales, primarily by Englishmen, they were rarely interested in modernising local production, or providing capital for industrial diversification in the region (Williams, 1983; 1995), or creating large local demand for new innovations (Lovering, 1983). The direct consequence was that the Welsh economy failed to diversify,

whereas those industries that generated wealth were stagnating technically (ibid). This led Hobsbawm (1968: 253) to suggest that “*the whole process of early industrialisation was something done to Welshmen rather than by Welshmen*”. Wales was characterised as an integral but peripheral part of the general UK economy (Williams, 1995), which was unable to generate innovations and was dependent for its transformation upon external decisions (Furtado, 1973).

4.2 The British state and the rise of the Welsh manufacturing sector

At the beginning of the 20th century, employment in Wales was dominated by mining, quarrying and metal manufacturing, as shown in figure 4.2, with few alternative employment opportunities. The decline in the coal and metallurgical industries resulted in heavy job loss in Wales, especially in South Wales, and the overall unemployment rate in Wales reached around 22% in 1937, as compared with 10.6% for the UK as a whole (Wanhill, 1980). The situation was so severe that the British government had to step in and began what was to become a long process of regional policy intervention. It began with the introduction of the *Special Acts of 1934 and 1937*, which sought to diversify the Welsh industrial base, mainly by introducing new elements into the manufacturing sector, as a safeguard against over-specification (ibid). The 1944 *White Paper on Employment Policy* (HM Government, 1944) also set the tone for regional policies in Wales up to the present-day, *i.e.* to maintain a stable and high level of employment.

From 1945 onward, a succession of regional policies, *e.g.* the *Distribution of Industry Act 1945* and the *Town and County Planning Act 1947*, stressed the need to diversify the industrial base through influencing the locations of new enterprises. Development Areas (previously Special Areas) were established in South Wales to attract inward investment. New factories and branch plants were set up in the old coal mining areas, which included government sponsored projects (*e.g.* munitions factories), private investments from South East England, the West Midlands and North West England. Several major international manufacturers, including the Ford Motor Company and Johnson & Johnson pharmaceuticals, were also persuaded to open plants in Wales (Wanhill, 1980). As a result, by the end of the 1960s one in three jobs in Wales was in manufacturing (including the steel industry) (McNabb & Rhys 1988).

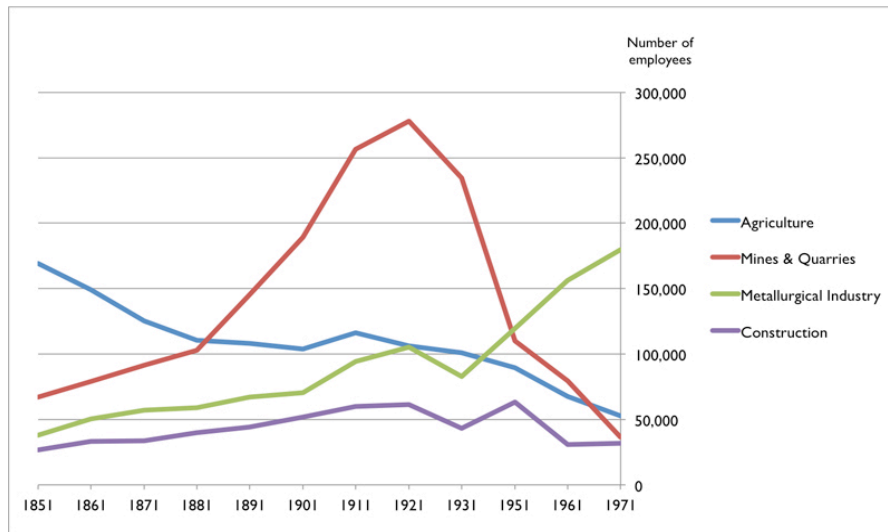


Figure 4.2: A historical employment pattern among the four major sectors in Wales: 1851-1971 (Sources: Welsh Government, 1985)

Throughout the 1970s more investment followed, including a growing influx of foreign direct investments (FDI) from USA, Canada and other European countries, succeeded by Japanese companies in the 1980s and Korean firms in the 1990s. However, the Welsh operations set up by these transnational corporations (TNCs), while mostly employing over 500 people, were either branch plants or subsidiaries of the existing firms, where higher-rank management and R&D personnel were rarely based, with over half of the jobs created being unskilled labour (Lovering, 1978, 1983). On the other hand, virtually all these firms produced for markets outside Wales, either for the UK as a whole or the EU market, with only four per cent of output going to other Welsh firms (ibid). That being said, the presence of a high proportion of the FDI branch plants in the Welsh manufacturing sector, e.g. accounting for around 70% of all manufacturing employment in Wales (McNabb & Rhys 1988), has nevertheless helped to structurally transform the Welsh economy, and led it to diversify into sectors such as engineering, metal manufacture, electrical and instrument engineering, automobile and related industries, petroleum and electronics (Lovering, 1978; Cooke, 2004).

However, the mid-1970s also saw the first signs of the decline in Welsh manufacturing, a trend that has continued to this day, as the Welsh economy has been struggling with the changing pattern of threats and opportunities thrown up by European integration, and the broader overarching processes of globalisation and liberalisation in the international trade context. Even though the steel and the linked industries contributed the single most

significant manufacturing job losses in the region, many new enterprises which were expected to be part of the Welsh manufacturing sector well into the 21st century have been lost (McNabb & Rhys, 1988). By 1997 manufacturing industry accounted for 27.9% of Welsh GDP, but fell to 17.9% in 2007, while the employment in manufacturing dropped from 208,200 in 1998, to 153,000 in 2008, and 143,000 in March 2014 (Welsh Government, 2008, 2014a).

Many saw that as proof of a long-term failure of regional policy in Wales since the 1930s. As Wanhill (1980: 39) stated, the regional policy of diversification, in practice, has turned out to be “*one of trying to capture as much new development as possible*”, without giving consideration of the theory of trade expressed in terms of comparative advantage; in the meantime, “*there has been little attempt on the part of policy-makers to evaluate the motives and appropriateness of enterprises wanting to locate in Wales*”, and that saw some investors having been more concerned with their aid payments than with production, whilst others disappeared quickly once had collected their subsidies.

Lovering (1983), on the other hand, argued that the policy intervention carried out by the British state since the interwar has largely acted in the ‘national’ interest, rather than the ‘regional’ (Welsh) interest. The typical example was its commitment to nationalised industries – Welsh coal and steel, which grew out of the alliance between organised labour (i.e. the demands of both trade unions and labour party) and industrial capital (i.e. the demand for cheaper organised outputs). No “*attempt was made to modernise the industries coherently, to develop associated industries as part of a powerful integrated bloc, or to link sectoral expansion to*” a regionally integrated economy (ibid: 66).

Yet, the British state was still seen as the single most important factor in providing and maintaining a higher proportion of employment and GDP in Wales (Lovering, 1999). Apart from its involvement in developing the Welsh coal and steel industries, central and local governments have grown into one of the biggest employers in Wales since 1945. Throughout the 1960s the British government actively dispersed its offices to South Wales, e.g. the then new national Driver and Vehicle Licensing Centre in Swansea (Wanhill, 1980); between 1981 and 1995, public administration, defence, health, social service and education created around 50,000 new jobs in Wales, more than twice the gross employment contribution of FDI in the same period (Welsh Office, 1996).

Therefore, just as the mining and metallurgical industries in past, the development of modern manufacturing in Wales has appeared to be almost entirely done by non-Welsh actors – overseas companies, the British state (through public ownership), and firms based elsewhere in the UK, while being predominantly export orientated (Lovering, 1978, 1983; Welsh Affairs Committee, 2005). As Wales-based manufacturers mostly produced for external markets, this again gave rise to a disintegration between the Welsh production system and the local demand profile, which was seen to have done little to improve the technological capacity in Wales (Lovering, 1983). On the other hand, there was the suggestion that the inward investors have led to an improved labour productivity in Wales, thus having a detrimental effect on the development of human capital (Jones, 2000).

Entering the 21st century, the industrial structure of the Welsh economy remained problematic, and was seen to be responsible for the widening prosperity gap between Wales and England, and the rest of EU. Questions e.g. “whether was there a Welsh economy after all?” (Williams, 1983) re-surfaced, given historically that most of the country’s transport and economic links run from east to west, rather than north to south: linking South Wales with Bristol and Birmingham, and the north to Merseyside and Liverpool. Despite the claimed manufacturing ‘renaissance’ in the 1980s and early 1990s (Price et al., 1994; Alden, 1996), Wales remained a peripheral part of the UK economy in general. Politically, however, a strong belief emerged among the Welsh political elites that further economic development in Wales required local control so development strategies could be attuned to local needs whilst helping to foster investment (Bishop and Flynn, 1999; McAllister, 1999).

4.3 Welsh devolution

Devolution in Wales took place after the 1997 Welsh Devolution Referendum³³ which resulted in an extremely thin majority (50.3% to 49.7% at a turnout of 51.1%) in favour of creating an assembly for Wales with devolved power (Denver, 2002). The National Assembly for Wales (NAW) was formalised in 1999, following the election of 60 Assembly Members (AM), with Cardiff chosen as the Welsh capital. The new Assembly took over most administrative powers from the post-war establishment *i.e.* the Secretary of State for

³³ This was the second referendum held in Wales over the issue of devolution. The first one was in 1979 with four in five Welsh voters rejecting the idea (Denver, 2002).

Wales and the Welsh Office³⁴ (McAllister, 1999). On the other hand, Welsh devolution is perhaps best viewed as more of a process than an event (Davies, 1999), whereby the settlement introduced in 1997 was not considered to be final, and more powers have since been transferred to the NAW.

The post-devolution Wales became a 'constitutional' region (Dickson, 2013) or a 'national' region (Cole and Palmer, 2011). The division of competency between the UK and Welsh government is defined in the *Government of Wales Act 2006*, which, following a 'yes' vote in the 2011 Welsh referendum³⁵, has given the NAW the power to formulate primary legislation over 20 devolved areas. They include agriculture, education, economic development, the environment, health, housing, local government and planning, etc. (detailed in the Schedule 5 of the 2006 Act). In the meantime, subject areas such as defence, tax and energy have remained reserved matters of the British Government, although there have been discussions on the devolution of further powers in areas including fiscal and energy matters. In 2011, the Commission on Devolution in Wales (the Silk Commission³⁶) was set up by the Secretary of State for Wales, with tasks to review the NAW powers and look into the case for further devolution (Bowers and Webb, 2012).

Having replaced the 1998 Act, the *Government of Wales Act 2006* also abolished the previous constitutional settlement, and created three separate bodies: (a) the 'Welsh Government' (WG, previously the Welsh Assembly Government before May 2011) that, led by the First Minister of Wales, resumes executive power with the Cabinet as the main decision-making body; (b) the 'National Assembly for Wales' as the legislature who has the responsibility to hold Welsh Ministers to account and approve budgets for the WG

³⁴ The Welsh Office was established 1964 for implementing government policies in Wales, and headed by the Secretary of State for Wales, a cabinet position promoted from the post of the Minister for Welsh Affairs in the same year. The Welsh Office was disbanded in 1999 upon the establishment of the NAW. Currently the Secretary of State for Wales has responsibilities to ensure that the interests of Wales are fully taken into account by the UK Government in making decisions that will have effect in Wales, to represent the UK Government in Wales, and to ensure the passage of Wales-only legislation through Parliament (Department for Constitutional Affairs, 2005).

³⁵ The 2011 referendum was held in Wales on 3 March 2011, which asked the question: "Do you want the Assembly now to be able to make laws on *all* matters in the 20 subject areas it has powers for?" Overall, 63.69 per cent of voters voted 'yes', and 36.51 per cent voted 'no', with an overall turnout of 35.2 per cent, (National Assembly for Wales, 2011). Before this referendum, the Assembly only had power to formulate subordinate legislation.

³⁶ It is called the Silk Commission because the commission was headed by Paul Silk, a former Clerk of the NAW (Bowers and Webb, 2012). A final report was submitted in March 2014.

programme; and (c) the ‘National Assembly for Wales Commission’, a corporate body providing support functions to the Assembly.

Arguably, devolution provides a genuine opportunity that, for the first time in hundreds of years, Welsh interests and values are placed at the centre of policy-making processes concerning Wales. Devolution has also forced Welsh politicians and civil servants to undergo a ‘sea change’ and switch their roles from policy-takers to policy-makers. Such changes moved the Welsh polity into a new territory (e.g. in terms of multi-level governance, as will be discussed in the next section), and put considerable reliance on the capacity of the Welsh civil servants and politicians to match the rhetoric surrounding the establishment of the Assembly and the WG, which have in past been accustomed to relying on the strategic inputs from Whitehall and Westminster (Bishop and Flynn, 1999).

A series of research papers, under the title ‘*A Stable, Sustainable Settlement for Wales*’, was published recently on the powers, capacity and accountability of the NAW, the Welsh Civil Service and political parties (Osmond and Upton, 2013). While being used as evidence to the Silk Commission, these papers have identified varied weaknesses in the capacity of the current institutional establishment in Wales. For instance, it is suggested that the policy-making process is often dominated by the well-resourced Welsh ministers and their Special Advisors, with very limited formal inputs from other sources either inside or outside the ruling political party (Elias, 2013), *i.e.* the Welsh Labour Party; there is also comment with regard to the capability of Welsh civil servants, leading to questions e.g. whether “*the right people with right skills are in the right place at right time*” within the Welsh civil service (Nicholl, 2013: 32); in addition, concerns are generally raised in terms of the availability of human and financial resources that are necessary for policy development and operational delivery in governing Wales (Cole et al., 2013; Elias, 2013; Nicholl, 2013); in some instances, problems are considered to be of a procedural nature and related to historical ‘ways-of-doing’ things in Wales (Elias, 2013).

4.3.1 Multi-level governance (MLG)

The UK’s EU membership brought a European dimension into the regional governance in the post-devolution Wales, in that the 2006 Act states that any EU obligation of the UK Government is a Welsh obligation with respect to devolved matters. On the other hand, Wales has a significant interest in a number of European funding schemes, including

structural funds, agricultural subsidies under the Common Agricultural Policy (CAP), and research funding under the Framework Programmes (FP) for Research and Technological Development (also called Framework Programmes, currently 'Horizon 2020' i.e. FP8). To this end, the WG is seen to have every incentive to ensure continued support for securing European funding (Dickson, 2013), even though calling on structural funds draws attention to the challenges facing the Welsh economy. It was even suggested that the issue around European funding mechanisms has helped the inauguration of a First Minister³⁷ whom the Welsh electorate wanted but was opposed by the then UK Prime Minister, thus a serendipitous result of multi-level politics (Jones and Rumbul, 2012).

A 'multi-level governance' is operated in the post-devolution Wales, and consists of political and institutional structures involving four tiers: local, regional (Cardiff), national (Westminster) and European (Brussels), according to the territorial scale. However, the relationships and interactions between the four tiers are not necessarily hierarchical in nature, as suggested in a recent study of MLG in Wales. After surveying 144 local government officials in Wales, the study indicates that: (a) most of the local services³⁸ chosen for study are governed concurrently by the four levels of governments; (b) across different service areas, different governance levels show variations in terms of their influences, and (c) a tendency towards the 'regional centralism' emerges as the WG seems to have greater impacts on many service areas, including education, housing and planning etc., as illustrated in Figure 4.3 (Entwistle et al., 2012). In a sense, these findings reflect the nature of MLG, which is often seen to constitute a broad process of institutional creation and decisional reallocation among nested governments at the supranational, national, regional and local levels that neither assigns exclusive policy competency nor asserts a stable hierarchy of political authority to any of these levels (Marks, 1993; Schmitter, 2004).

Moreover, MLG is seen to place increasing importance on the capability of institutional actors at regional and local levels. As Rhodes (1996: 66) argues, the challenge becomes to manage self-organising networks in a polity of multilevel dimensions, where "*game-playing*,

³⁷ Disagreement with the UK government on the question of match funding for the ERDF grant eventually led to Rhodri Morgan being chosen as the inaugural First Minister of a devolved Wales, an original choice of the Welsh Labour Party but opposed by the then UK Prime Minister Tony Blair (Jones and Rumbul, 2012).

³⁸ 15 key service areas were chosen for the research, which include front line services of education, child and adult care, housing, planning, public protection, transport, library, sports, waste and regeneration, corporate, and back office function like finance, democratic service and human resources (Entwistle et al., 2012).

joint action, mutual adjustment and networking are the new skills of the public manager”. Notwithstanding, our understanding on MLG is still under-developed as to the extent to which different levels of governance influence and interact with each other, and the processes that lead to effective networks and interactions between and across governance levels (Amundsen et al., 2010); whilst these concerns go beyond the scope of this study, they could certainly benefit from further research.

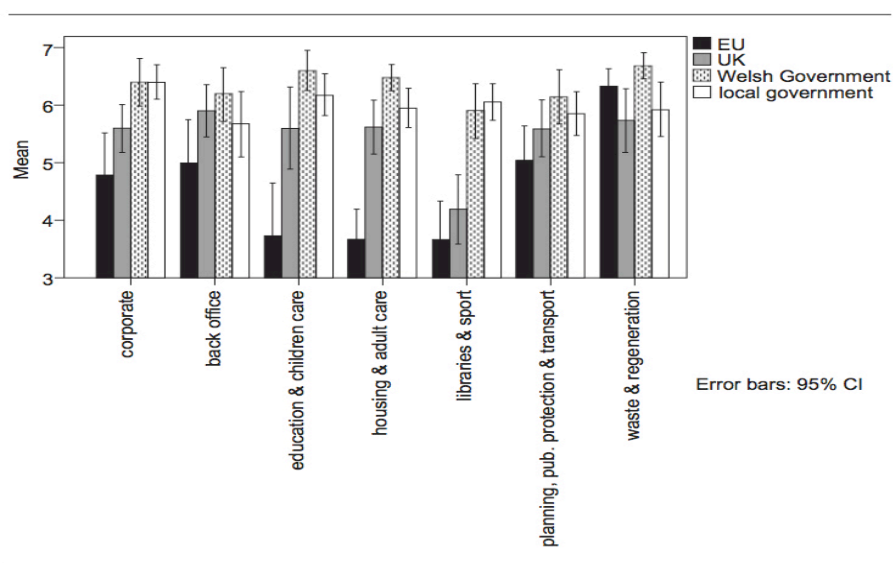


Figure 4.3: The impacts of varied governance levels on selected local service areas in Wales (Source: Entwistle et al., 2012)

4.3.2 Emergence of a Welsh low carbon transition narrative

Despite the significant constitutional changes brought about by devolution, energy remains largely a reserved matter in the UK, with authority and decisions resting with the central government in Westminster. However, the 2006 Act makes the promotion of sustainable development a statutory duty of Welsh Ministers (see Section 79). This makes Wales, one of the few nations around the world to have sustainability written into its constitution. In July 2014, the WG went a step further, and introduced the *Well-being of Future Generations (Wales) Bill* (previously the Sustainable Development Bill), aiming to provide a set of long-term well-being goals for a sustainable Wales.

On climate change, the WG published the *Climate Change Strategy for Wales* in 2010. The Strategy confirms that the WG’s principal target is “to reduce greenhouse gas emissions by

3% per year from 2011 in areas of devolved competence, against a baseline of average emissions between 2006 and 2010” (Welsh Government, 2010a: 34). To deliver this annual reduction target, the WG have devolved powers in a number of key areas. With respect to the decarbonisation of energy supplies, Wales holds the relevant planning and consenting powers for (renewable) energy generation projects of up to 50 MW onshore, or offshore projects of 1MW or below in Welsh territorial waters, and distribution networks up to 132 kilovolt (kV) (Upton, 2014). On the demand side, buildings, especially the residential sector, have been identified as one of the key sectors to help deliver the reduction target, especially seeing that the WG now has a wide-range of regulatory powers in both planning and building regulations to deliver low carbon built environment in Wales, as will be further discussed later in the thesis.

Furthermore, the WG published a series of reports and policy documents³⁹ between 2008 and 2012, in the context of tackling climate change and sustainability. While some of these documents may seem to be less relevant at present (for instance, the WG never formally introduced the *Renewable Energy Route for Wales*, while it is no longer possible to download the *One Wales: One Planet* document from the WG website.), they nevertheless collectively pointed to the emergence of a distinctive Welsh narrative for low carbon transition. As elucidated below, this Welsh transition narrative consists of four interwoven elements (Wang and Eames, 2010).

(i) Wales’ historic responsibility and exemplar role

Just as this chapter traced Wales’ industrial history, much of the Welsh policy discourse has been framed by an explicit acknowledgement of the role that Welsh coal and heavy industries played in the vanguard of the transition to the high carbon economy. Thus, what become important are the distance travelled and the opportunity to once again take an internationally leading role in the transition to a low carbon economy, especially in terms of playing an exemplar role for the newly industrialised and developing world.

³⁹ These include: Energy Wales: a low carbon transition (Welsh Government, 2012a), Low Carbon Revolution – The Welsh Assembly Government Energy Policy Statement (Welsh Government, 2010b); Climate Change Strategy for Wales (Welsh Government, 2010a); National Energy Efficiency and Savings Plan (Welsh Government, 2011); Bioenergy Action Plan for Wales (Welsh Government, 2009b); Capturing the Potential: A Green Jobs Strategy for Wales (Welsh Government, 2009c); One Wales: One Planet (Welsh Government, 2009d); Renewable Energy Route for Wales: Consultation on way forward to a leaner, greener and cleaner Wales (Welsh Government, 2008b).

(ii) Sustainable development and Welsh identity

Linked to this exemplar role is a desire to forge a new post-devolution national identity, which is embedded in the government of Wales' commitment to promote sustainable development. In this sense, the Welsh policy discourse places climate change in the context of sustainable development. Whilst Wales can no longer see itself as a nation of coal miners and steel workers, the post-devolution Wales increasingly views sustainability as part of its national identity (for its policy elites at least).

(iii) Wales' comparative advantage in renewable resources

Underpinning this commitment to sustainability is a belief that Wales is well endowed with renewable energy resources, which can contribute to rapidly decarbonising energy production. By virtue of its geographical location and climate, Wales is seen to possess a natural advantage in several areas e.g. wind and marine energy. It is suggested that 1200km of the Welsh coastline could potentially deliver up to 6.2 GW of marine energy, over 10 GW if the Severn Estuary⁴⁰ is included (Welsh Government, 2012b). Meanwhile, some 300 MW of wind turbines are already in operation onshore across Wales, with two large offshore wind farms (150 MW) off the coast of North Wales, while further schemes with a generating capacity up to 1.22 GW have been approved and are awaiting or currently under construction; this includes the 576 MW offshore wind farm near Gwynt y Môr, one of the largest off-shore wind farm being built in Europe (National Assembly for Wales, 2013). In relation to solar irradiance levels, Wales is seen as the region only second to South West England in the British Isles as to the capacity to generate solar energy (Bennett, 2012), evidently suggested by the steady increase in the amount of electricity generated from solar in recent years, resulting from Feed-in-Tariffs introduced by the UK government in April 2010, and later reduced (National Assembly for Wales, 2013).

(iv) Capturing the economic and social benefits of a low carbon transition

In addition to seeking to contribute solutions to the global challenges of climate change, the Welsh transitions narrative is also firmly built upon an expectation that action to meet carbon reduction objectives will help to solve Wales' entrenched social and economic

⁴⁰ The Severn estuary barrage tidal energy project was scrapped by the UK coalition government in 2010, due to the harsh economic situation facing the UK. In 2012, a new proposal was submitted to DECC by Corlan Hafren, a private sector consortium, to build a 25 billions barrage and generate five per cent of the UK's electricity for over a century. However, this proposal again collapsed (BBC News, 2013).

problems: creating employment and economic opportunities, reducing fuel poverty, and improving health and wellbeing for many of the nation's poorest communities. To this end, the renovation of the existing housing stock is seen as an ideal vehicle for this purpose. As stated in the *Low Carbon Revolution – The Welsh Assembly Government Energy Policy Statement* (Welsh Government, 2010b: 9), the “*Welsh housing stock currently has a relatively poor energy performance.... Tackling this backlog of hard-to-heat homes will create jobs, encourage skills, improve local areas,... directly reduce fuel poverty and carbon emissions*”.

That being said, in recent years concerns have been raised over the extent of political will and leadership on energy in Wales, especially in comparison with the more active and higher-profile leadership role played by for example the Scottish Government (Upton, 2013; Cowell et al., 2013; Thorpe, 2014). There are doubts as to whether Welsh Ministers have fully used their influences to drive through applications for renewable energy developments under 50 MW; or to amend elements of the regulatory regime that present a barrier to the relevant development; or to increase energy efficiency and reduce demand in a sufficiently concerted manner (Upton, 2013, 2014). The latter comment seems to be particularly relevant in the case of the amendments to the Part L (Conservation of Fuel and Power) of the Building Regulations for Wales; that, as mentioned, saw the originally proposed energy saving target of 40% for domestic buildings being watered down towards a mere 8%, when the new Part L for Wales was formally published in February 2014, following nearly two years of consultation between 2012 and 2014. I shall further discuss this later in the thesis.

4.4 Innovation policy governance in Wales

Wales was once at the forefront of regional innovation policy experimentation in Europe (Thomas and Rhisiart, 2000; Henderson, 2000), owing to its instrumental role⁴¹ in petitioning the European Commission to develop a regional innovation programme, and subsequently helping to shape the practical content of the Regional Technology Plan (RTP)

⁴¹ In the early 1990s, the European Commission's Directorate General for Regional Policies (DG XVI) set out a new concept entitled “Regional Technology Strategies” (RETAS), aiming to develop a pilot action in the field of innovation promotion at regional level and thus replace the old policy model for less favoured regions. In March 1992, the Head of the Welsh Development Agency met with the then EU Regional Policies Commissioner, and explained that they had been working on the idea of producing a framework for regional technology which seemed to fit in well with DG XVI's RETAS ideas. A month later the Commission received a proposal ‘*A Regional Innovation Strategy for Wales*’ from Philip Cooke and Kevin Morgan (1992) (Landabaso and Reid, 2003).

programme, whereas Welsh academics e.g. Cooke and Morgan have contributed the theoretical inputs to the process (Henderson and Thomas, 2003; Landabaso and Reid, 2003). Wales was one of the first four EU regions to pilot the RTP exercise, when EC formally launched the RTP pilot initiative under the European Regional Development Fund in late 1993 (Morgan, 1997; Henderson, 2000).

Spearheaded by the then Welsh Development Agency (WDA), the Welsh RTP exercise centred on a two-year process involving over 600 Welsh and non-Welsh organisations, which led to the publication of an Action Plan in 1996 (Henderson and Thomas, 2003). An important part of this process included thirty panel discussions over a nine-month period with inputs from representatives from industry, local government, higher and further education, schools, enterprise agencies, development bodies, and trade unions etc., which aimed at testing the findings of early desk-based research while exploring, interactively, appropriate solutions to the problems identified. In addition, a special one-off meeting of international experts was held to seek an outside perspective on the Wales RTP process and therefore avoid parochialism, whilst, across Wales, a consultation process had involved the production, distribution and presentation of a consultative report that detailed the main innovation issues, possible priorities and projects identified in the research and panel sections (Henderson, 2000; Henderson and Thomas, 2003).

This early RTP exercise in Wales was hailed as a model of best practices by the European Commission (ibid), and valued as a decisive break from the traditional infrastructure-led approach of the EU regional policy; it was seen to promote a process of building a collective learning capacity in a bottom-up and interactive fashion (Landabaso, 1997), while consciously working towards developing a stock of social capital and enhancing institutional capacity in these less favoured regions (Morgan, 1997). On the other hand, some limitations were also identified; mostly it was argued that this bottom-up approach adopted for the RTP exercise required the support of more top-down initiatives, because at the time the regional actors (e.g. WDA) did not have the legislative power to turn the RTP into policy and fully implement the priorities contained in the Action Plan (ibid; Henderson and Thomas, 2003).

Significant changes have taken place in Wales since the launch of the original RTP for Wales. Devolution has led to the creation of the National Assembly for Wales that has the

power to formulate primary legislations in a wide range of devolved areas, while the Welsh Government is able to develop policies e.g. with respect to innovation, science and technology, and implement them across Wales. On the other hand, the changes also occurred with the formal abolition of the Welsh Development Agency⁴² in 2006, part of the Welsh Labour Party's bonfire of the quangos (BBC News, 2012; Morgan, 2013); this saw WDA's economic development functions, including the responsibility for the design of innovation policies and strategies, as well as their implementation, being transferred to the then Department of Economy and Transportation (the current Department for Economy, Science and Transport) within the WG (Thomas and Henderson, 2011).

The abolition of the WDA has led some commentators to argue that the regional innovation system in Wales has been significantly hollowed out, with only the WG and Welsh universities constituting the key public sector actors in the Welsh RIS (Morgan, 2013). Meanwhile, previously active horizontal co-ordination mechanisms between regional actors, such as the industry-led Wales RTP Steering Group, have not been retained or replaced by some new participative multi-level co-ordination mechanism for innovation policy-making (Thomas and Henderson, 2011). This caused a significant decline in institutional diversity and intellectual pluralism in Wales, which in turn poses little or no constructive challenge to the dominant party (the Welsh Labour Party) and their policies (Morgan, 2013). Overall, the regional innovation governance in Wales is considered to be overly 'top-down' (Cooke, 2003; Thomas and Henderson, 2011; Academic Interviewee No.5, 2013), while Wales is seen to have gone from a leader to a laggard in terms of regional innovation policy experimentation (Morgan and Upton, 2005; Morgan, 2013; Academic Interviewee No.5, 2013).

⁴² The Welsh Development Agency (WDA) was the first regional development agency of its kind (Morgan, 2013) when it was established in 1976, under the *Welsh Development Agency Act 1975*. Its main tasks had been to promote Wales as a location for business, through encouraging business development and investment in Wales. After the devolution in 1999, WDA became accountable to the NAW, even though the power for allocating government loans to the Agency was shared between the Assembly and the UK government. WDA employed more than 1000 staff with a budget up to £3 billion when it was abolished in 2006 (Winter, 2005).

While the role of the WDA in relation to innovation policy was viewed to be implicit rather than explicit, the Agency was nevertheless credited with leading the development and implementation of the RTP in Wales, and making great strides in the implementation of technology and knowledge transfer policies and programme between 1990 and 2005 (Thomas and Henderson, 2011). There have been continuous calls to resurrect the Agency or a WDA-style successor body (David, 2012; BBC News, 2012; Henry, 2014; Jones-Evans, 2014). In 2014, the NAW launched an inquiry on the WG's approach to the promotion of trade and inward investment, in relation to the abolition of the WDA (National Assembly for Wales, 2014).

The original RTP was superseded by the strategy - *Wales for Innovation*, explicitly devised for the round of EU structural funds for the period of 2006-2013 (Davies, 2013), which was then supplanted by the latest innovation strategy *Innovation Wales*, launched by the WG in 2014 (Welsh Government, 2014c). While it was partly to fulfil the policy commitment made by the WG following the publishing of the *Science for Wales* (WG's science strategy) in 2012, this latest strategy shows a clear influence of the European agenda, namely the European Commission's research and innovation strategy for Smart Specialisation (RIS3, European Commission, 2012c). By embracing the Smart Specialisation approach, the *Innovation Wales* strategy posts a big departure from the conventional way of policy-thinking, and a significant contrast to the regional policy of diversification introduced since the 1930s as a safeguard to Wales' past problem with over-specialisation in the coal and steel.

This change of policy direction may be interpreted as an attempt to secure European funding⁴³ in that the adoption of RIS3 is the 'ex-ante conditionality' for any EU member states or regions that wishes to receive the EU financial support through the Structural Funds (European Commission, 2014). While it is beyond the scope of this PhD study to continue on this subject, the adoption of RIS3 nonetheless demands fundamental changes in terms of how innovation policy should be designed, delivered and evaluated, and how the regional innovation structure should be composed⁴⁴, a similar argument that this PhD study intends to make, and elaborate later in the thesis. As Morgan (2013: 120) puts it,

...the solution is not to be found in more devolution, more powers and more money - the current prescription for Welsh development problems - but in changing the political culture from a transactional culture, which is obsessed with process and compliance issues, to a transformational culture which is outcome-oriented and informed by the place-based policy paradigm.

⁴³ To date, the post-devolution Wales has received around £3.4 billions European structural funds, i.e. about £1.5 billion for the programming period 2000-2006, and £1.9 billion for the period of 2007-2013. It is estimated that some £2 billion will be available for the period of 2014-2020 (Welsh European Funding Office website: <http://wefo.wales.gov.uk/programmes/?lang=en>, [accessed on 26 February 2015]).

⁴⁴ The European Commission (2012c) proposes a sequenced six-step approach for developing the smart specialisation strategy: (1) analysis of the regional context and potential for innovation, (2) set up of a sound and inclusive governance structure, (3) production of a shared vision about the future of the region, (4) selection of a limited number of priorities for regional development, (5) establishment of suitable policy mixes, and (6) integration of monitoring and evaluation mechanisms. It basically requires a less top-down, more inclusive and participative policy-making and governance process.

4.5 Concluding remarks

This chapter was set to examine why Wales has remained a peripheral region while having failed in its catching-up effort from a historical perspective, by tracing Wales' transition to a high carbon economy from the second half of the 19th century onwards. Since history matters, the social, economic and institutional characteristics that have been responsible for Wales' past problems likely to stay and keep it from making full economic and technological progresses, if some fundamental changes do not take place, as a way out of 'path-dependence'. In this regard, a number of Welsh socio-economic and institutional characteristics that may have been attributed to Wales' continuous status of lagging-behind are summarised as follows,

First, the historical review has suggested that the economic development in Wales were often dominated by external interests, external capital and external demands, first in the era of coal and steel, then again during the post-war effort of industrial diversification. This inevitably causes a frequent disintegration between the Welsh production system and the local demand profiles. As explored in Chapter 2, innovation processes are driven by both 'technology push' and 'market-demand pull', whereas domestic demand can, for instance, benefit the user-producer interactions (Lundvall, 1988) that is seen to be important for successful product innovations, and contribute to the development of innovation capability of indigenous firms in a catching-up economy. In this regard, the absence of local market-demand may help to explain why Wales has rarely been able to create a basic industrialisation platform to encourage localised learning, and build up networks and institutions required for indigenous innovation (Cooke, 2004), and why so few high-value related or intermediary sectors were created even during the periods of economic growth. I will further discuss the role of domestic demand in the context of the innovation system later in the thesis.

Secondly, whereas devolution has created an elected government in Wales that can act on Welsh interests and values, in practice the Welsh Government has, to date, failed to improve Wales' socio-economic performance, and narrow the prosperity and productivity gaps between Wales and England (and the rest of EU as well). Exogenous factors, e.g. the global recession following the financial crisis of 2007-8, can be argued to have contributed to this situation, while the cause may also be ascribed to the nature of the Welsh devolution settlement since it does not allow the WG to borrow or raise taxes. However,

“*regional states are not powerless victims of circumstance*” (Morgan, 2013:122), and thus the doubt is inevitably cast as to the capability of regional institutional actors to adjust to external changes while making the best of the region’s assets. As Nelson (2008b) argues, whereas economic activities involve both physical and social technologies, compared to physical technologies, social technologies are more likely subject to the vagaries of human motivation and bounded rationality, and therefore are much more difficult to establish or change.

To this regard, a number of weaknesses in the existing institutional set-up in Wales have been suggested. For instance, the extent of WG’s political will and leadership in energy have been called into question, as Welsh ministers have seemed to be unable to fully use the regulatory powers provided; on the other hand, in the case of innovation governance, the problem was considered to be of a procedural nature, as the WG appears to almost monopolise the decision-making process, with no sustained, more participative multi-level co-ordination mechanism in Wales to provide the necessary constructive counterweight in innovation policy-making; or, as some commentators argue, “*devolution institutions continue to lack the clout, appetite for risk, or on-the-ground-assets that are required to make the difference*” (Bryan and Roche, 2014: 26). In this sense, I intend to address some of these weaknesses in the context of innovation and technological catch-up later in this thesis.

Chapter 5 Case Study: Introducing the Structural Components

In this chapter, I begin to investigate the extent to which the innovation systems of two emerging low carbon building technologies: ‘Welsh grown timber for construction’ (WTC) and ‘building integrated solar energy systems’ (BISE) have been taking shape in Wales. As explained in Chapter 3, the selection of two technologies was linked to two Work Packages of the *Low Carbon Built Environment* (LCBE) project, while the development of these technologies involves a number of business sectors that operate across Wales; this allows the findings and insights drawn from the two case studies to be representative, and provides a good basis for the analytical generalisation required as to deliver the aims of this PhD research.

This chapter contains three sections. Sections 1 and 2 offer an overview of the two selected systems respectively; they focus on the introduction of a number of structural components of the two TISs, mainly relevant ‘institutional structures’, ‘technology’, ‘actors’ and ‘networks’, and thereby establish the context in which the functions of the two systems will be explored in the following chapter. Section 3 contains a brief summary.

5.1 Case Study I: Welsh Grown Timber for Construction (WTC)

As noted, this case study links to WP3 of the LCBE project – ‘*Use of Timber in building construction*’. Led by the BRE Wales, WP3 was set to undertake research and development on the use of Welsh grown timber for building construction components or products that can help to deliver low carbon buildings in Wales. One particular issue that the LCBE project tried to address was that most of the construction products used in Wales to deliver low energy housing are imported (Jones, 2009). For instance, 75% of softwood consumed by the secondary wood processors⁴⁵ in Wales is imported (Griffiths et al, 2010), even though there are approximate 306,000 hectares⁴⁶ of woodland in Wales, one half of which is coniferous woodland (*i.e.* the sources of softwood) (Forestry Commission, 2014).

⁴⁵ Generally speaking, ‘primary wood processors’ are producers that process harvested wood to give basic wood products e.g. sawn woods, wood-based panels, paper and wood pulp (Forestry Commission, 2014), whereas ‘secondary wood processors’ are manufacturers producing wood products from the basic wood products.

⁴⁶ This makes circa 15% of the Welsh land area, which is considerably lower than the average forest coverage of 37% in Europe, but higher than the UK average of 13% (Forestry Commission, 2014).

On the other hand, there is already a well-represented timber-based industry across Wales that produces a wide range of timber products from panel boards, sawn wood, packaging, flooring and fencing, to niche products such as charcoal, and high-end value, low quantity furniture and craft products (Welsh Government, 2009). A 2010 *Survey of Woodland Enterprises in Wales*⁴⁷ estimates that around 1900 wood-based enterprises operate in Wales, supporting some 19,000 jobs (Griffiths et al., 2010). Among them is a strong, dynamic secondary processing sector of about 1500 businesses (Jaako Pöyry Consulting, 2004), which are seen to have the potentials to move up the value chain, and move into the production of more value added products, e.g. engineered wood products (EWP) for construction (ibid, Bryans, 2011), as this study sets out to explore.

After devolution, the Welsh Government (WG) took over the regulatory responsibility for forestry in Wales, as well as the ownership of state forests within the region, which account for about 38% of the 306,000 hectares of woodland, with a majority of that being conifers (Forestry Commission, 2014). The WG published its first forestry strategy in 2001, and the latest in 2009, i.e. *Woodland for Wales*. This strategy sets out the vision for the development of Welsh woodland and forestry industries in the following five decades (Welsh Government, 2009). It recognises the vital role of Welsh timber in financing woodland management, and supporting the growth of Welsh forestry sector, especially in rural areas; four key economic outputs are particularly identified: (a) “*more Welsh grown timber is used in Wales*”; (b) “*the forest sector is better integrated and more competitive, supporting the Welsh economy*”; (c) “*increased use of timber as a key renewable resource*”, and (d) “*a thriving, skilled workforce in the forestry sector*” (ibid: 36). To this end, the use of Welsh grown timber for construction (WTC) in Wales can certainly help to deliver these outputs, although it needs to overcome a number of institutional, technical, and economical challenges, as discussed further below.

Historically, Britain as a whole does not have a strong wood culture (Slee et al., 2005). The cause behind can be traced back to the Great Fire of London, which led to the whole country falling out of favour with timber construction, while the use of timber in

⁴⁷ ‘The 2010 Survey of Woodland Enterprises in Wales’ was commissioned by the Forestry Commission Wales, and carried out by Wavehill Consulting in 2010. But, this survey has been influenced by and drawn data from a previous study ‘Welsh Forestry Industry – Mapping and Benchmarking the Forest Industry’ that was undertaken by Jaakko Pöyry Consulting in 2004, and sponsored by the Welsh Development Agency in partnership with the Forestry Commission Wales. The findings of the Jaakko Pöyry report have contributed to the development of the latest Welsh forestry strategy (Welsh Government, 2009).

construction was further limited by building control regulations, starting with the *London Building Act of 1667*. It was not until the 1920s (just after the First World War) that timber frame housing was re-introduced in the UK, as one of the new methods of construction brought in to alleviate the housing crisis caused by the combination of the pressing demand for new homes, and a shortage of skilled labour (e.g. bricklayers) and essential materials (e.g. good quality bricks) (Ross, 2002). This trend was further accelerated after the Second World War, due to an even greater demand for rapid construction of new dwellings (ibid), and by the early 1980s timber-frame housing accounted for approximately 20% of new builds in the UK (Timber Frame Housing 2002 Consortium, 2003).

However, following some high profile negative media coverage with regard to the durability and fire risk of timber frame dwellings, especially the 1983 Granada Television documentary programme *World in Action*, namely the episode ‘the System Builder’⁴⁸, customers’ confidence in timber frame construction was severely undermined, and the timber frame housing market in the UK virtually crashed (ibid; Cavill, 1999; Ross, 2002). It took many years for the timber frame industry to re-build customers’ confidence, and its market place; in 2000 the share of timber frame systems accounted for only 12% of housing starts in the UK, reaching its peak at 25.8% in 2008 before the 2007-08 Financial Crisis triggered the downturn in the market for new homes (Structural Timber Association, 2010).

In terms of regulatory requirements, until the introduction of amended fire provisions in the 1991 Building Regulations for England and Wales, timber framed construction had been limited to a maximum of three storeys. The relaxation of this restriction accordingly allows timber frame buildings to be built up to eight storeys without any additional fire resistance measures other than those existing for three-storey constructions (Bullock, et al., 2000; Timber Frame Housing 2002 Consortium, 2003). Nevertheless, despite such changes, recent research indicates that regulatory requirements for fire safety, acoustics and vibrations, stabilisation, seismic design, and durability likely continuously pose challenges for timber construction in general (Östman and Källsner, 2011).

⁴⁸ The *World in Action* episode – ‘the System Builder’, broadcast on 20 June 1983, investigated building practices involving timber-framed construction (IMDb, n.d.). It revealed rot in the frames of nine-year-old homes on a Cornwall estate, and fire risk at a Barratt home in the Midlands, and subsequently alleged that timber-frame construction could not produce houses that would last (Cavill, 1999; Ross, 2002).

Technically, there is also concern over whether Welsh grown timber is structurally strong enough to be used for load bearing construction, which usually requires timber to be strength graded either visually or mechanically to the standard of C24⁴⁹, as a rule of thumb. The afforestation that took place in Wales after WWI has resulted in the planting of many fast growing, non-native coniferous species, in particular Sitka spruce, a species originating in North America. The mild and damp Welsh climate encourages these species to grow much faster than in their native lands, and this in turn produces low density and low strength-grade timber products. The majority of Welsh timber is strength graded to be of C16 quality, which is conventionally considered to be unsuitable for building structural purposes, even though there is a growing recognition that C16 is actually sufficient for construction use (Jones, 2010a; Business Interviewee N.5, 2012). Furthermore, the situation is complicated by the fact that considerable volumes of timber processed by Welsh sawmills have never been strength graded, and this means that they can only be used for lower graded purposes (Jones, 2010b).

There is also the matter with regard to the size of maximum available sawn timber in Wales, with the upper limit for Welsh sawn timber at around 215 mm in diameter (Bryans, 2011). This is considerably smaller than what is considered to be suitable for the timber frame systems designed to construct energy efficient buildings, since the higher insulation demand requires a greater wall thickness, for instance, 300 mm as typically required by the Passivhaus standard⁵⁰.

The aforementioned technical matters have thus contributed to the public perception of Welsh timber as being unsuitable for construction, in particular among key actor groups e.g. architects and secondary wood processors (Jones, 2010a). Consequently, many Welsh secondary processors do not source locally grown timber; for instance, only one of the secondary processors that I interviewed stated to use locally grown timber sometime (Business Interviewee N.2, 2012); in the meantime 75% of softwood consumed in Wales is

⁴⁹ C24 is one of the strength classes of the softwood grades that range between C14 and C50, although C16 and C24 are the two most commonly found in most merchants. More information is available at <http://www.trada.co.uk/faq/list/strength/Strength%20grading%20and%20structurally%20graded%20timber>.

⁵⁰ The Passivhaus standard is a voluntary building energy efficient standard, developed by Prof. Bo Adamson and Wolfgang Feist in the early 1990s. A Passivhaus building uses far less energy than standard UK Buildings, by achieving high levels of insulation and airtightness while recovering heat through a Mechanical Ventilation and Heat Recovery unit. Information is available from <http://www.passivhaus.org.uk/standard.jsp?id=122>.

imported (Griffiths et al, 2010). In this respect, a disconnection exists within the Welsh supply chain.

Meanwhile, the woodland management practices in Wales are widely seen as unsustainable. At present, less than half (i.e. 46%) of Welsh forest is certified under either the FSC (Forest Stewardship Council) or PEFC (Programme for Endorsement of Forest Certification), a majority of which (i.e. 83%) are at the previous FC estates (Forestry Commission, 2013). Although the absence of certification does not necessarily mean that the woodland is not managed properly, there has been the suggestion that a significant proportion of Welsh woodland, mostly privately owned, were undermanaged (McNulty, 2012). To this end, the way that Welsh woodland is managed imposes considerable uncertainty on the sustainable supply of locally grown timber. As Osmond and Upton (2012: 8) state in the report '*Growing Our Woodlands in Wales: the 100,000 hectare challenge*',

There is a deep-seated separation of 'forestry' and 'farming' in Wales, which has been reinforced by institutional separation over a long period. While most farms in Wales include woodland, many farmers do not see themselves as woodland managers or foresters. The reasons include lack of knowledge and skills, plus economic considerations. There are lower returns on woodlands than grazing or arable land, a potential loss of the capital value of land under woodland compared to farmland, and loss of flexibility. Once land is converted to woodland the expectation (backed up by the Forestry Act) is that woodland will remain as woodland.'

Furthermore, the recent creation of a single body – Natural Resources Wales (NRW), resulted from a merger of Environment Agency Wales (EAW), Countryside Council for Wales (CCW) and Forestry Commission Wales in April 2013, has added further uncertainty to the future of woodland management in Wales. Among the three bodies, FCW was generally considered to be less influential politically, especially compared to CCW (NGO Interviewee N.4, 2012; Civil Servant Interviewee N.1, 2012). This may be partly ascribable to the nature of FCW, i.e. when the Welsh team was managing the Welsh forest estate on behalf of the WG and advising on relevant policy, FCW was still affiliated to the Forestry Commission UK and not part of the Welsh Government statutorily; then, FCW largely considered itself as more of a business entity, as half of its operational budget came from trading timbers, whereas both EAW and CCW were regulators, which meant

that FCW was run very differently from the other two organisations (Civil Servant Interviewee N.1, 2012). When the merger was first proposed, the Welsh forestry sector was most vocal about their opposition, and feared that within the new single body the balance of power would be tilted towards environmental conservation and protection, at the cost of the commercial interests of the forestry sectors (National Assembly for Wales, 2012b). As one interviewee put it, *“this new environment body with regulators, people who are you know really good scientists, or really good biologists or whatever, but they’ve never sold anything in their lives. So we were concerned that they would lose that kind of commercial business thinking”* (Business Interviewee N.5, 2012). This concern is somehow reinforced by the fact that none of the NRW board members has a background in forestry or timber, although the real impact will likely surface in the next two or three years.

In addition, the existing institutional setup in the Welsh Government could cause some complications for the promotion of Welsh grown timber in construction, and requires considerable policy coordination potentially between three government ministers⁵¹:

- (a) **Minister for Natural Resources:** the relevant responsibilities include all activities of NRW; cross-cutting responsibility for sustainable development; cross-cutting measures of mitigation and adaptation in relation to climate change; policy relating to small-medium scale energy production, domestic energy, energy efficiency and the reduction of fuel poverty; all aspects of planning policy; Building Regulations.
- (b) **Minister for Economy, Science and Transport:** the relevant responsibilities include the provision of support to businesses in Wales; the promotion of Wales as a location for businesses and investment; entrepreneurship, enterprise and business information; economic sector panels (construction being one of the sector panels); energy policy, major energy facilities and infrastructure, devolution in energy matters, steel, coal, oil and gas; science; research and innovation.
- (c) **Minister for Communities and Tackling Poverty:** the relevant responsibilities include overall responsibility for delivering the Tackling Poverty Action Plan; regeneration; the housing and housing-related activities of Local Authorities and housing associations; supply and quality of market, social and affordable housing.

⁵¹ The information is obtained from the WG website <http://wales.gov.uk/about/cabinet/cabinetm/?lang=en>, [accessed on 8 February 2015].

There have been a number of reshuffles and re-structuring in the WG during the project period. For instance, there is no longer a Minister for Housing and Regeneration, with the responsibilities being absorbed by the Minister for Natural Resources and the Minister for Communities and Tackling Poverty respectively. While such changes may be necessary politically, it can cause confusion for businesses and the public in general. As the use of Welsh grown timber for construction becomes an inter-departmental matter, a number of problems may arise e.g. delay in decision-making, and lack of policy coordination across sectors, which could impede any progress already made.

Despite the aforementioned challenges, the potential for the use of Welsh grown timber in construction is otherwise boosted by the required transition to the low (or zero) carbon built environment in Wales, the UK and EU. This has led to a revived interest in timber as a construction material in the UK and elsewhere in recent years. Arguably the oldest building material, timber has many positive attributes, including high strength, good thermal insulation properties, and ease of erection and reassembly on-site. It is also aesthetically appealing with many ranges of colours and textures for design options. However, as a natural material, timber can burn, shrink, crack, warp, twist, bend, discolour, or be eroded by insects, if it is used inappropriately (TRADA 1995). To improve its performance, modern timber products and techniques have evolved with significant inputs from engineering science, materials science, and information technology, etc., which have redefined timber construction with innovations such as glued laminated timber (glulam), and modern methods of construction (MMC) (Steurer, 2006; *ibid*).

5.1.1 Technology and Timber construction

Timber is often viewed as a carbon neutral material, although this is not strictly accurate since embodied energy can incur during the processes of sawmilling, transportation, manufacturing, maintenance, removal and disposal. Nevertheless, it is argued that carbon sequestered in the growth of trees can offset much of the embodied energy (Jones, 2011; TRADA, 1995). While timber construction in the UK was disrupted by the Great Fire of London, and the subsequent regulatory controls, in other countries e.g. in Switzerland, and in Scandinavia and North America, timber has been continuously used for construction into the present day. New technologies and expertise have been brought in, to make wood more competitive with other materials, e.g. stone, brick, then steel and concrete (Steurer, 2006; Freedman, 2008; Kolb, 2008; TRADA, 1995).

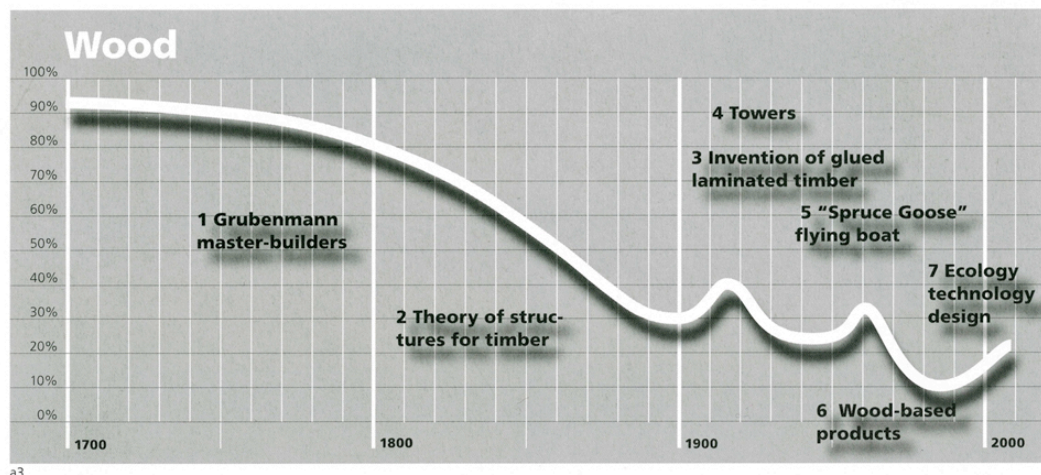


Figure 5.1: The development of timber engineering since 1700 (Source: Kolb, 2008)

Figure 5.1 above illustrates the evolution of timber engineering since the 18th century. One key breakthrough was the invention of glued laminated timber (glulam) in Germany in the late 19th century; it became the first generation of engineered wood products (EWPs), and is still used in modern construction for creating structures of large span (Thelandersson et al., 2004; Mettem, 2003). Since then, more EWPs have been invented, e.g. Softwood Plywood, Oriented Strandboard, Laminated Veneer Lumber, and Prefabricated Wood I-Joists etc. (MaKeever, 1997); these innovations enable more efficient use of the available timber sources that in the past were deemed undesirable due to smaller size or lower quality.

The development of timber engineering has also been closely linked with modern connection technologies, since they essentially affect the choice of load-bearing structure and the form of the structure (Reece, 1985; Steurer, 2006). The past century has seen a shift from traditional connectors such as shear plates, split rings, bolts and washers, to more innovative solutions, e.g. fully concealed connections which allow all of the principal members of a large structure to be placed in a single plane (Mettem, 2003). New materials, e.g. iron and steel, and the development of modern waterproof glues, have enabled a wide range of structures to contain both tensile and compression forces within themselves.

In addition, various tools and machinery have been invented, along with the emergence of iron and later steel industries, which enabled carpenters and builders to cut and shape wood with greater precision and ease, and made standardisation possible, while also

lowering the production cost (Steurer, 2006). Meanwhile, the introduction of MMC moves work from the construction site to the factory, with potentials for reductions in cost, time, defects, health and safety risks, and environmental impact, and a subsequent improvement in predictability, performance and profits (Pan et al., 2007). MMC include a range of processes and technologies e.g. prefabrication, off-site assembly and various forms of supply chain specifications, which can be applied to all build materials, with timber frame and timber structural insulated panels (SIPs) constituting the key MMC market segments (BRE, 2009).

While the wood-based industry is a mature industry globally, its revival has always relied and will continue to rely on the adoption of innovative science and technology. That saw wood technology leaving traditional carpentry work behind and becoming part of the natural and engineering sciences (Kollmann, 1967). At the EU level, the R&D agenda on wood technology has been largely driven by the '*COST (European Cooperation in Science and Technology) action on Forests, their Services and Products (FPS)*'. Table 5.1 gives a glimpse of the breadth of wood research in the EU, and demonstrates how chemical, physical and engineering principles have been adopted in the analysis of the properties and behaviour of wood, in wood processing, and wood product development and manufacturing, etc.; in the meantime further improvements or breakthroughs are expected in a number of areas, including wood supply, timber construction, material engineering, wood modification, wood aesthetics, machining and processing for primary and secondary wood processing, and technology assessment (Teischinger, 2010).

To catch up with the leading countries, the Welsh timber industry would have to compete based on high levels of innovation and integration across the entire sector (Bryans, 2011). In the past few years, considerable efforts have been made by a number of Welsh organisations, particularly the Wales Forest Business Partnership (WFBP, an industry led voluntary group with aims to make Welsh wood-based industries more innovative), and Coed Cymru (a public body dedicated to bring Welsh woodlands into sustainable management). In partnership with the Welsh School of Architecture, Cardiff University, the latter developed a hybrid modular volumetric off-site building system – the Ty Unnos – using Welsh grown Sitka spruce, which will be used as a starting point for the function analysis of the WTC TIS.

Table 5.1: A list of EU COST FPS actions on wood technology

E2 Wood durability	E50 Cell wall macromolecules and reaction wood
E5 Timber frame building system	E53 Quality control for wood and wood products
E8 Mechanical performance of wood and wood products	E55 Modelling of the performance of timber structure
E10 Wood properties for industrial use	FP0702 Net-Acoustics for Timber based Lightweight Buildings and Elements
E13 Wood adhesion and glued products	FP0802 Experimental and Computational Micro-Characterisation Techniques in Wood Mechanics
E15 Advances in drying of wood	FP0904 Thermo-Hydro-Mechanical Wood Behaviour and Processing
E18 High performance in wood coating	FP1006 Bringing new functions to wood through surface modification
E20 Wood fibre cell wall structure	FP1101 Assessment, Reinforcement and Monitoring of Timber Structures
E24 Reliability of timber structures	FP1004 Enhance mechanical properties of timber, engineered wood products and timber structures
E28 Genosilvaf: European Forest Genomics Network	FP1105 Understanding wood cell wall structure, biopolymer interaction and composition: implications for current products and new material innovation
E29 Innovative Timber & Composite Elements/Components for Buildings	FP1303 Performance of bio-based building materials
E31 Management of recovered wood	FP1205 Innovative applications of regenerated wood cellulose fibres
E37 Sustainability Through New Technologies For Enhanced Wood Durability	
E40 Innovative utilisation and products of large dimensioned timber including the whole forest-wood-chain	
E41 Analytical tools with applications for wood and pulping chemistry	
E44 Wood processing strategy	
E49 Processes and performance of wood-based panels	

Source: http://www.cost.eu/domains_actions/fps [accessed in October 2013]

5.1.2 Actors and networks of the WTC TIS

As reviewed in the Chapter 2, actors of an innovation system are individuals or organisations that contribute to the generation, diffusion and utilisation of innovations and technologies. They can be firms along the value chain (both up- and down-stream), research bodies (universities, or public or private research institutes or laboratories), interest organisations (e.g. Chambers of Commerce, or trade associations), venture capitalists, regulatory bodies, standardisation agencies etc. (Bergerk et al., 2005, 2008a). Nonetheless, as Carlsson et al. (2002) point out, the identification of actors of a given innovation system is closely related to the methodological issue of how the system boundary of an innovation system is defined. In other words, actors of a given TIS may be identified only after its system boundary is defined, for it helps to address how we know

that a specific actor belongs to a system, as well as how we may find all actors in the system (ibid).

The delineation of the WTC or BISE TIS in this PhD study involves two aspects. First is defining the geographical and administrative boundary of the two systems. For the purposes of this study these have been taken to be the borders of Wales. However, this does not mean that both systems are perceived as only operating within Wales. Rather this regional perspective provides a starting point to facilitate the analysis. Secondly, the boundary of the two systems is also defined by the 'technological paradigm' in which the respective innovation processes and technological activities are taking place, (although, in the case of building integrated solar energy systems (BISE), the associated technological paradigm still seems to be taking shape). As reviewed in Section 2.1.2 Chapter 2, whereas a technological paradigm comprises both the knowledge base of a specific technological field and the common patterns of problem-solving activities based on highly selected principles derived from natural sciences, it likely generates a cluster of possible technological directions, which thus lead other specific variables (e.g. economic, social and institutional factors) to come into play; together with technological factors, they determine the pace and direction of technological development paths or trajectories.

In a broad sense⁵², it may be argued that all these variables (technological, economic, social or institutional factors) are the direct or indirect outcomes caused by the interactions between various actors of a given TIS. On that account, finding the actors of a given TIS requires the identification of those individuals or organisations who can influence the generation, diffusion and utilisation of these variables. Carlsson et al., (2002) and Bergerk et al., (2005, 2008a) have suggested a number of sources and methods through which the actors of a given TIS may be identified. They include the membership directories of industrial associations, or participant lists for exhibitions; patent and bibliometric analyses; and the 'snow-ball' principle.

Taking the above discussion into consideration, this study divides the identification of the actors and networks of the two systems into two phases: first, it involves theoretically exploring which actors one would reasonably expect to be included in a well-functioning

⁵² Here, the term 'a broad sense' is used in analogy to Edquist's definition of 'innovation systems', which takes a much broader view than Lundvall's definition (see the footnote no. 8 in the Chapter 2).

WTC (or BISE) TIS, and how they would interact; this helps to address the concern that, as this study focuses on the regional level, it is sensible to assume that not all the actors that should be involved have already emerged at the current state of the two systems, not to mention that both systems are themselves still emerging in Wales. Then, the set of actors identified at the first step will be used as an analytical basis for examining which actors have already emerged in the systems in Wales. Thus, helping to assess the extent to which the WTC (or BISE) TIS has been formed in Wales (relating to the first half of the research aim) from an actors-networks interaction perspective. Next, I will theoretically explore the actors and networks of a well-functioning WTC TIS.

Whilst it is beyond the scope of this study to define the technological paradigm of timber engineering, the aforementioned review of technology and timber construction has shed some light on how the knowledge base of timber engineering has evolved in the past several centuries, and become a well-established technological field globally. Meanwhile, as both construction and forestry are traditional industrial sectors, many actors are already linked by economic activities defined in standard industrial classification systems. For instance, the UK Standard Industrial Codes (Office of National Statistics, 2007) defines the wood related economic activities under the following industrial sectors, including:

Section A. Agriculture, Forestry and Fishing – Forestry and logging (SIC02)

Section C. Manufacturing – Manufacture of wood and of products of wood, except furniture (SIC16.10, 16.21, 16.22, 16.23)

Section F. Construction – Specialised construction activities (SIC43.31, 43.32, 43.33)

Section G. Wholesale and retail trade – Specialised wholesale activities (SIC46.71, 46.73)

Even though there is the claim that the standard industrial classification systems often “*fails to capture many important actors in competition as well as linkages across industries*” (Porter 2000: 255; Carlsson et al., 2002), such classification systems can certainly serve as a starting point for the identification of the actors of the WTC TIS in this study. In the meantime, a number of other sources and methods are also used to identify the actors, which include searching the membership directories of trade associations, e.g. TRADA and WFBP, and reviewing scientific papers and research reports on wood-based clusters, timber engineering, and wood-based sectors in Wales (e.g. Mrosek et al., 2010; Regional Technology Strategies Inc., 2003; Jaakko Pöyry Consulting, 2004; Steurer, 2006; Bryans,

2011; Teischinger, 2010). This was further complemented by the interviews that were conducted for the case study, which provide insights into not only who should be but also who have already been involved in the WTC TIS, as will be discussed later in the next chapter.

Figure 5.2 below illustrates a 'perceived' 'network map of interactions between actors' whom one would expect to be involved in a well-functioning WTC TIS. The construction of the network map is largely based on a supply-chain perspective in which the core actors of the WTC TIS are seen to be linked by the basic material they process, *i.e.* Welsh grown timber. This by no means suggests that all actors have been identified, due to the somehow arbitrary nature of such process that is often partly based on informed guesses by the researcher (Carlsson et al., 2002; Walsham, 2006). On the other hand, as a technological innovation system "*is not static but evolves with alterations in the content of technologies and products as well as in the relationships among various technologies*" (Carlsson et al., 2002: 240), it is expected that new actors (or actor groups) will likely continue to emerge. After all, the history of timber engineering and timber construction has epitomised an evolving process of this kind.

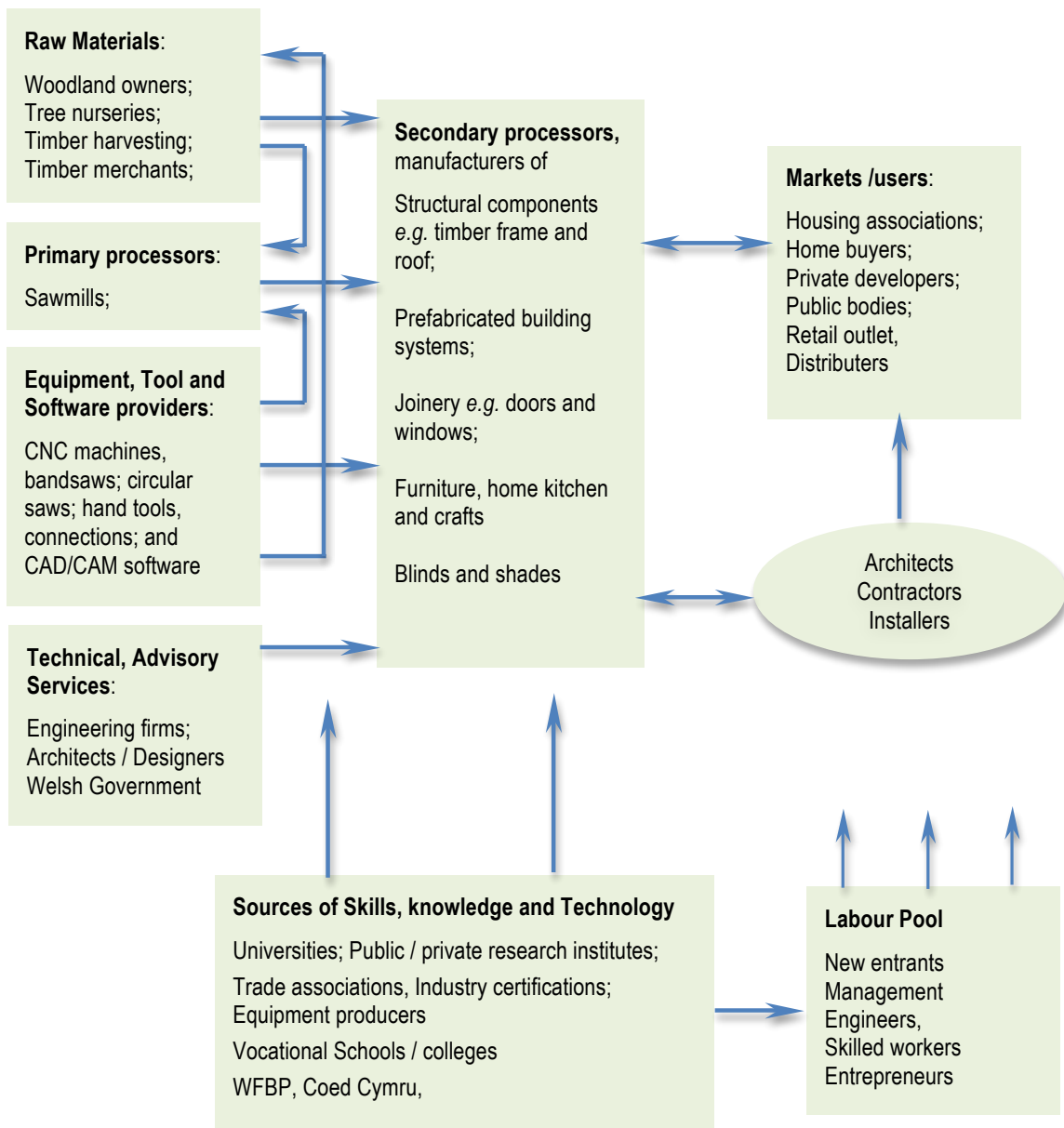


Figure 5.2: The perceived network map of interactions between actors in a well-functioning WTC TIS

5.2 Case Study 2: Building Integrated Solar Energy Systems (BISE) in Wales

As indicated, this case study is linked to WP 1 of the LCBE project – ‘Sustainable Building Envelopes’, which was led by Tata Steel. The key objectives of this WP were to develop, test and prototype energy generating building components which integrate varied solar technologies (e.g. PV, solar air heating and ventilation system, and solar thermal) with pre-finished steel products. On the other hand, as reviewed in the Chapter 4, the Welsh steel company (Corus) that Tata took over in 2007 is part of the Welsh industrial history, and Tata Steel’s Welsh operation has since remained as the biggest industrial employer in Wales; so, its involvement in solar technologies undoubtedly impacts Wales’ position in solar technology and innovations, as well as the Welsh economy in the long-run, as will be further discussed in the next chapter.

Meanwhile, the solar industry is similarly well represented across Wales, with a range of companies who specialise in different solar technology segments (Stafford, 2008). For instance, in the North, apart from *Tata Steel*, there is the Australia-based dye sensitized photovoltaic developer *Dyesol* that is working with Tata in incorporating dye sensitized solar cells (DSSC) technology onto steel materials to create integrated solar air systems for all types of building (Gifford, 2011); the Japanese company *Sharp Solar* based its solar PV plant near Wrexham with a production capacity of PV modules totalling 400 MW⁵³. As part of the Low Carbon Research Institute (LCRI), the Centre for Solar Energy Research (CSER) has proven expertise and reputation in researching novel PV materials and devices with a focus on commercial applications, while the CSER is also leading the Welsh Opto-electronics Forum (WOF) PV Group that has worked towards establishing a strong PV base in Wales (Stafford, 2008).

In the South, around Cardiff, *GB-Sol*⁵⁴ has a 4MW production facility supplying BIPV (Building Integrated PV) kits, custom architectural panels and specialist modules to the leisure and OEM (Original Equipment Manufacturer) markets; *IQE*⁵⁵ manufactures world-leading epitaxial wafer products for a wide range of technology applications including solar devices, and is well placed to move into concentrating photovoltaic (CPV) technologies;

⁵³ In December 2013, Sharp announced that it would end production of the solar panels at the North Wales factory in February 2014, due to changing market conditions (Hall, 2013; BBC News, 2013b).

⁵⁴ GB Sol company website <http://www.gb-sol.co.uk>, [accessed on 2 October 2013].

⁵⁵ IQE company website <http://www.iqep.com>, [accessed on 2 October 2013].

G24i has developed a dye sensitised thin film technology which can be integrated into a wide range of projects (Williams, 2013). Near Swansea, *Pure Wafer*⁵⁶ is a leading provider of silicon wafer reclaiming services and is capable of manufacturing monocrystalline photovoltaic cell products from recycled materials; meanwhile, the Sustainable Product Engineering Centre for Innovative Functional Industrial Coatings (SPECIFIC)⁵⁷, a newly established academic and industrial consortium, has set out to develop functional coated steel and glass products that can then be fitted into new or existing buildings as part of external walls and roofs which generate, store and release renewable energy, and thereby essentially turn a building into a power generator.

In mid-Wales, *Emerson*⁵⁸ produces a range of utility scale inverters for PV installation from 145kVA to 1590kVA; *Dulas*⁵⁹ specialises in providing technical advices across a range of renewable technologies including solar PV, while helping developers to plan processes at one end of the spectrum, and design, install and commission small scale projects at the other; *BayWa r.e. Solar Systems*⁶⁰ (previously DulasMHH) is one of the UK's leading suppliers of solar PV equipment, and provides technical support for system specification and regular solar PV training sessions throughout the UK.

In terms of the solar resource, as indicated, the relatively high solar irradiance level in Wales has made the region, especially South Wales, a favoured area for generating solar energy in the UK only after Cornwall and the Isle of Wight (Bennett, 2012; Academic Interviewee N.6; 2013), as illustrated in the Figure 5.3. The amount of electricity generated from renewable sources in Wales has been steadily increasing since 2004, and reached a peak of 7.9% of total generation in 2011, of which 9 GWh was generated from solar sources (Welsh Government, 2013e). Meanwhile, since the UK government introduced the Feed-in Tariff (FIT) Scheme in 2010, Wales has seen a significant growth in the number of solar installations, especially at the domestic level (National Assembly for Wales, 2013). The figures from the Department of Energy and Climate Change (DECC, see Figure 5.4) show that as of September 2013 over 29,000 Welsh homes have solar panels installed

⁵⁶ Pure Wafer company website <http://www.purewafer.com>, [accessed on 2 October 2013].

⁵⁷ SPECIFIC website <http://www.specific.eu.com>, [accessed on 2 October 2013].

⁵⁸ Emerson website <http://www.emersonindustrial.com/en-en/controltechniques/Pages/home.aspx>, [accessed on 2 October 2013].

⁵⁹ Dulas website <http://www.dulas.org.uk>, [accessed on 2 October 2013].

⁶⁰ BayWa r.e. Solar Systems website <http://www.baywa-re-solarsystems.co.uk>, [accessed on 2 October 2013].

which generate electricity for their own use and feed surplus power back to the grid (DECC, 2013b); this makes the relevant installation ratio at 177 per 10,000 Welsh homes that have PV panels installed, well above the British average of 118 (Shipton, 2013).

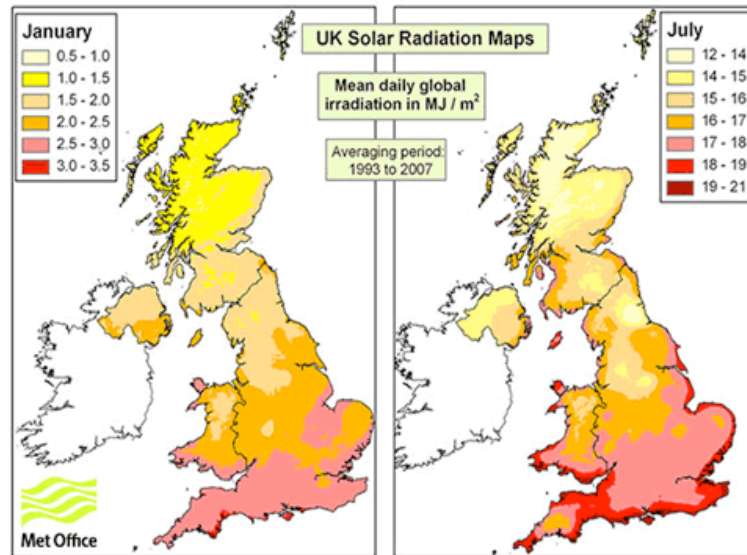


Figure 5.3: UK Solar Radiation Maps (Source: Met Office)

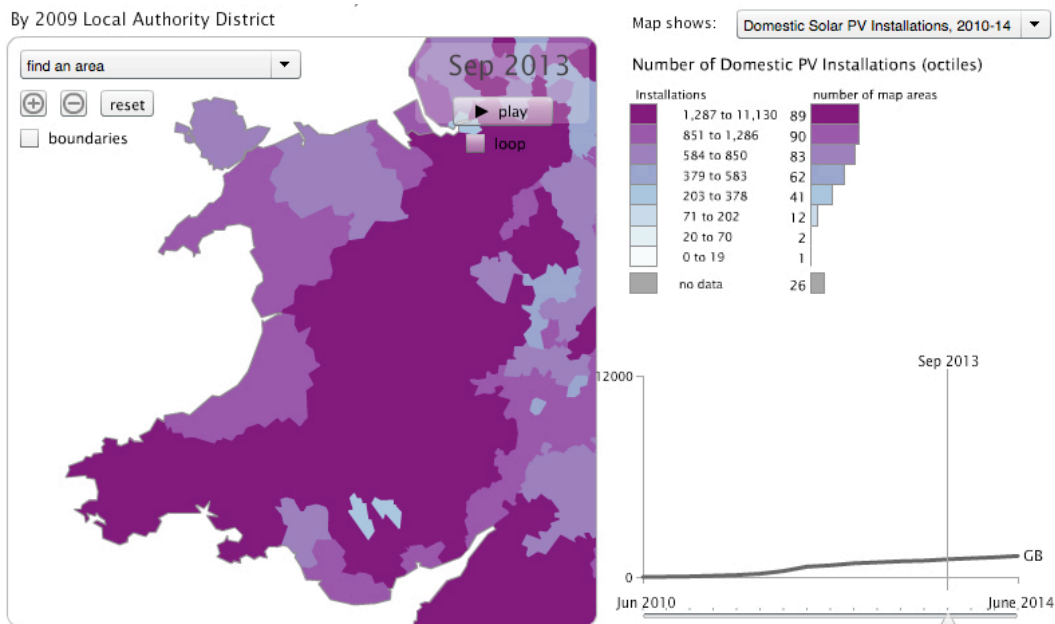


Figure 5.4: Domestic PV Installation in Wales, as of September 2013 (Sources: DECC⁶¹)

⁶¹ http://tools.decc.gov.uk/en/content/cms/statistics/local_auth/interactive/domestic_solar/index.html. [Accessed on 1 December 2014]

As explained, energy is largely a matter reserved for the UK Parliament. In the past, solar was often seen as a second tier renewable technology, and dismissed by many politicians as being too costly (Colville, 2014), but this stance has changed since the introduction of the FIT Scheme in 2010. The rapid growth in the UK solar PV deployment, especially at a smaller-scale ($\leq 50\text{kW}$), brought overall PV capacity to approximately 2.4GW⁶² at the end of June 2013, generating 1.4 TWh during July 2012 to June 2013 (DECC, 2013a, 2013c). Fully aware of the potential of solar PV, in 2012 the UK government included solar PV as one of the eight key renewable energy technologies that would help to create a clean, balanced UK energy mix, and subsequently launched the Solar PV roadmap in 2013 (DECC, 2013a), followed by the UK Solar PV Strategy in early 2014 (DECC, 2014a).

The Solar PV Strategy particularly prioritises the existing built environment rather than previously undeveloped land for PV deployment, with a strong focus placed on on-site generation. Two key markets are singled out: *a*) PV at smaller scale – typically smaller than 4kWp (kilowatt-peak), but up to 50kWp, normally deployed on and in housing, small commercial premises and community buildings; and *b*) mid-size deployment – larger than 50kWp and up to 1MWp, particularly on commercial and industrial buildings but also on larger public and community buildings (ibid: 17). As a matter of fact, this focus on mid-scale building-mounted PV systems was reflected in the Renewable Obligation (RO)⁶³ banding review for the period 1 April 2013 to 31 March 2017, in which building-mounted systems are given higher rates than ground-mounted solar PV arrays (DECC, 2012). Moreover, the Strategy explicitly recognises a growing global market for Building Integrated PV (BIPV), as well as an opportunity to develop a strong UK industrial base in the area, given that the UK already has a vibrant BIPV sector and well-established R&D capability on a range of PV technologies and applications, whereas the SPECIFIC is specifically introduced (ibid: 39).

This changing policy stance at the UK government level has direct impact on the deployment of solar energy in Wales. On the other hand, despite such changes at the UK

⁶² It is suggested that the UK in 2013 emerged as Europe's strongest market for large-scale projects, with subsidies (through the RO) attracting institutional investors and developers from across the EU (REN21, 2014).

⁶³ The deployment of large-scale renewable electricity generation (incl. solar PV) in the UK is incentivised under the RO, which was first introduced in 2002 on the basis of a single level system, but switched to a banded system varying by technology in 2009. The government reviews the banding levels for appropriate incentives every four years. From 1 April 2015 the RO will be no longer available for the solar PV installations of greater than 5MW (Ofgem, 2015a).

level, the Welsh Government's policy position on solar energy has remained largely untouched since the introduction of the *Microgeneration Action Plan for Wales* in 2007, in which solar technologies (both PV and solar thermal) are seen as part of the suite of technologies for microgeneration (Welsh Government, 2007b). In the 2010 *Low Carbon Revolution* energy policy statement (Welsh Government, 2010b), solar energy was mostly left out of the proposed actions on either small-scale renewables or low carbon electricity generation at a large scale; however, some renewable targets proposed in this Policy Statement have led some experts to question WG's engagement with the commercial reality of what can be delivered⁶⁴ (Upton, 2014). That being said, solar energy is again included in the latest '*Energy Wales: a Low Carbon Transition*' document, as one of the commercially proven renewable energy sources that can help deliver Wales' low carbon objectives (Welsh Government, 2012a). Still, overall there is a lack of delivery targets specifically proposed for the generation of solar energy in Wales.

As mentioned in Chapter 4, there are concerns over whether Welsh Ministers have fully used their influences to drive through applications for renewable energy developments up to 50 MW onshore which Wales holds relevant consenting powers. That may help to explain the relatively slow deployment of large-scale ground-mounted solar farms in Wales, particularly in comparison with those of South West England. According to figures released by the National Assembly for Wales (2013), there were only two ground-mounted solar farms with an installed capacity between 5 and 25 MW in operation in Wales by the end of June 2013, with a further nine projects approved and three projects going through the planning stage; this was significantly lower than those of South West England, in terms of both scale and number of projects, for the same period (Colville, 2014). In the meanwhile, the WG seems to be slow to amend elements of the regulatory regime that present a barrier to development; for instance, the Welsh planning system still places restrictions on the installation of solar panels on non-domestic buildings, which do not apply in England (Planning Portal, n.d. a, b; Business Interviewee N.11, 2013).

While there is no clear sign that the Welsh Government will change its policy stance on solar energy soon, the WG has invested considerably in the innovation and R&D of solar

⁶⁴ The question is raised when a stated potential 4 GW capacity for tidal stream/wave generation is included in the *Low Carbon Revolution* energy policy Statement, when at the time a widely quoted figure for what is realistic in the delivery of tidal/wave energy at the UK level was 1.4 GW (Upton, 2014).

technologies in Wales, mainly through the programme run by the Welsh Government Department for Economy, Science and Transport, with SPECIFIC being one of the major beneficiaries, as I will further explore in the next chapter.

5.2.1 Solar technologies and Buildings

Solar energy technologies can be characterised as either passive or active, depending on how the technology applied captures, converts and distributes solar energy. Passive solar energy technologies absorb solar energy, store and distribute it in a natural manner without using mechanical systems (Hernandez, 1996), and this can mostly be achieved through an architectural approach e.g. passive building design. By contrast, active solar energy technologies, e.g. PV and solar heating technologies, use mechanical systems to harness radiant light and heat to provide heating or cooling, and generate electricity, which are the subject of this study.

Active solar energy technologies are one of the most commercially deployed renewable technologies worldwide. They come in a variety of forms e.g. solar photovoltaic (PV), solar heat, and solar thermal electricity (from concentrating solar power plants) – in terms of technologies, and from small scale to large scales – and in terms of their uptake. Since 2011, the global solar sector has been going through a period of hyper-change (DECC, 2013a), and in some parts of the world solar electricity is now price competitive with grid electricity, especially in niche applications. Solar energy is growing into an important new global green technology industry. As one of the leading solar energy markets, the European solar thermal sector had a turnover of around €2.3 billions and employed 26,700 full-time workforce by generating 21 TWh of solar thermal energy in 2012 (ESTIF, 2013); meanwhile, the European PV sector had a cumulative turnover of approximately €30.8 billions and employed a workforce of 252,570 in 2012 (Observ'ER, 2013), with a total installed capacity of 81.5 GW by 2013 (EPIA, 2014).

On the other hand, in industrialised countries, around 35-40% of the total national primary energy use is consumed in buildings, while the figure can go up to 50% if the embodied energy of building materials and of the infrastructure serving buildings is counted (International Solar Energy Society, 2003). Thus, building integrated solar systems are increasingly seen as viable as well as attractive renewable energy solutions, especially for the urban environment. As the International Energy Agency (IEA, 2011: 69) describes,

“Buildings offer large surfaces to the sun’s rays. Capturing the sun’s energy will enable buildings to cover a share of their heat consumption, and a larger share of lighting needs and become significant sources of electricity. Furthermore, the increased use of thermal energy storage technologies in buildings will help improve demand flexibility and reduce the need for expensive electricity storage.”

Active building integrated solar solutions can be generally classified into two categories: Building Integrated Solar Energy (BISE), and Building Applied (or Adopted) Solar Energy (BASE). Together, they offer a number of advantages, e.g. alternative aesthetical solutions, on-site energy generation, higher conversion efficiencies, and better use of space (Chemisana and Mallick, 2013). BISE is the main research focus of this study, which, in principle, means solar systems that become part of the general building design, rather than being added after buildings (or at least the architectural design) are completed (Hestnes, 1999). The solar system becomes both a functional unit of a finished building, and a construction component of the building skin, replacing conventional building materials (Heinstein et al., 2013). A range of BISE technologies have emerged, mainly:

Building Integrated Photovoltaic (BIPV) incorporates PV modules into building envelope e.g. roof, skylight and wall, and they form part of the building structures, replacing conventional building materials. The PV system absorbs the solar radiation and transforms it into electricity, which can either be connected to the grid or designed as a stand-alone, off-grid system (Henemann, 2008).

Building Integrated Concentrating Photovoltaic (BICPV) Systems see solar concentrators incorporated in buildings and installed either on the building façade or on the roof; depending on the type of device, the system may be integrated in such a way that either is unseen, or plays some role in the architectural aesthetic, or constitutes part of an architectural concept. In comparison with PV panels, CPV provides a number of advantages, including higher electrical conversion efficiency etc. (Chemisana, 2011).

Building Integrated Solar Thermal (BIST) Systems contain two types of technology: ‘air systems’, e.g. a transpired solar collector in which solar thermal gain is captured by an absorbing medium and then directly used for space heating without storage; and ‘hydraulic systems’ that allow the storage of solar gain, suitable for both hot water production and space heating (or cooling) (Probst and Roecker, 2011).

Building Integrated Photovoltaic Thermal (BIPVT) Systems merge PV and

thermal systems into one, and can be integrated into the walls or roofing structure of buildings, simultaneously providing both electric and thermal energy (Anderson et al. 2009).

Amongst these, both BICPV and BIPVT remain experimental and still at an early stage of prototyping, with considerable technological obstacles inhibiting the commercialisation of both technologies (Sellami and Mallick, 2013; Ibrahim et al. 2014). BIST and BIPV, on the other hand, have gradually formed their own market segments globally. BIPV, in particular, is increasingly visible, as part of the roof systems, curtain walls, windows or tiles etc. BIST is less developed and applied, partly because of the generally low architectural quality that characterises existing BIST applications (Probst and Roecker, 2011). Nonetheless, some progress has been made by Welsh firms and organisations in developing BIST, mainly in the form of transpired solar collectors.

A **transpired solar collector (TSC)** is a solar thermal system used to preheat the ventilation air supply to buildings, using solar radiation as the energy source. The performance of a TSC depends on a complex balance of climatic conditions, size, absorptivity, building aspect, perforation pattern and air flow rates (Brown, et al., 2014). The system has been widely used in Canada and the USA since the early 1990s, achieving economic paybacks of between two and ten years. The introduction of the TSC into the UK market took place in 2006, while the technology has already shown a capability to provide 20% of a building's heating demand (Hall, et al., 2011). In Wales, Tata Steel took an interest in the TSC, and developed it into an additional micro perforated pre-finished steel skin which can be installed onto an existing (or new) structurally sound wall (metal and non-metal), creating a cavity between the wall and the metal skin; this new product is marketed under Tata's Colorcoat® ranges (Tata Steel, n.d.).

In terms of PV technologies, they have undergone considerable changes, leading to the cells being classified into four different generations (Jayawardena et al., 2013):

1st generation solar cells (1G) (high cost / high efficiency) comprise crystalline silicon solar cells (c-Si), the best-known solar cells (ibid; Boreland and Bagnall, 2006).

2nd generation solar cells (2G) (low cost / low efficiency) was developed with the aim of reducing the high costs prevalent in the 1st generation cells through the

utilisation of thin film technology, using materials including amorphous or polycrystalline Si, Copper indium gallium (di)selenide (CIGS), and Cadmium telluride (CdTe) (ibid; Boreland and Bagnall, 2006).

3rd generation solar cells (3G) (low cost / high efficiency) are still at the R&D phase and consist of a large range of technologies in varying stages of development, where the aim is to obtain higher performance than their 2G counterparts, whilst at lower cost. Two of the most dominant 3G technologies are organic (or polymer) solar cells, and dye (or semiconductor) sensitised (or mesoscopic) solar cells (ibid; Boreland and Bagnall, 2006).

4th generation solar cells (4G) (low cost / high efficiency / large areas) is at an early research stage, with the expectation to combine the low cost / flexibility of polymer thin films with the stability of novel inorganic nanostructures, while improving the optoelectronic properties of the low cost thin film PVs. (Jayawardena et al., 2013).

Both 1G and 2G PV technologies have been used in BIPV. Silicon wafer based crystalline cell (c-Si) products have been applied in BIPV since the start of the 1990s as in-roof solutions, opaque or semi-transparent façade elements, or as semi-transparent PV skylights. They currently still dominate the market (Heinstein et al., 2013), offering good cost-efficiency ratios, with multi-crystalline modules providing the module efficiency of around 15%, and mono-crystalline modules up to 20%, under ideal test conditions. Standard silicon wafer based (Si) modules are mostly rigid, opaque and flat, while semi-transparent solutions can be obtained by a specific encapsulation, typically in glass-glass laminates or by perforating the wafer. A range of coloured crystalline solar cells are available on the market, with back-contacted solar cells often used for BIPV because of their hidden contact busbars. However, the performance of c-Si can be affected due to high temperatures, or shading caused by the surrounding buildings or other obstacles; and, in some cases, all the connected modules within the same circuit suffer 'cutout' if one of them is shaded, although this shortcoming has been partly fixed after the recent development of micro-inverters that can be linked to each individual module and provide a new impetus for the integration of c-Si technology (ibid).

The other option to fix the above 'cutout' problem is through the second generation thin film technologies that are usually less affected by either partial shading, or high

temperatures. Thin-film (TF) technology is widely seen as better suited for BIPV than c-Si, for a number of reasons. First, the cost per square meter of TF technologies is a lot lower, which can replace conventional building elements that come in the same price range. Meanwhile, when the cell-efficiencies of TF modules are seen to be lower than c-Si, e.g. six per cent for brownish amorphous and ten per cent for black micromorph PV modules, under ideal laboratory conditions; however, these figures may become less significant for the annual energy production under real weather conditions in certain regions. In other words, the performance ratio of BIPV using TF can be better, especially in heavily built urban space, as the TF system is less likely to suffer significant losses of performance under conditions of indirect and hence lower sun irradiation caused by overcast weather conditions or shading. In addition, it is easy to manufacture translucent and semi-transparent modules with homogenous appeal through techniques such as laser scribing (Heinstein et al., 2013).

In the last several years, a number of 3G PV technologies, e.g. organic photovoltaic (OPV) and DSSC, have come out of the shadows of the first two generation PV technologies after many years of laboratory research, and shown promising potentials (Drachman, 2009; *ibid*). SPECIFIC is currently looking into the 3G PV technologies and their BIPV applications, with a definite aim of achieving manufacturing scale-up⁶⁵.

5.2.2 Actors and networks of the BISE TIS

As explained in the identification of actors and networks of the WTC TIS (see Section 5.1.2 above), a similarly two-phase approach was taken for identifying those of the BISE TIS. First, it involves theoretically exploring which actors one would reasonably expect to be included in a well-functioning BISE TIS, and how they would interact. This is then be used as an analytical basis for examining which actors have already emerged in the system in Wales, in order to help assess the extent to which the BISE TIS has been formed in Wales from an actors-networks interaction perspective.

For a nascent, emerging technology like BISE, it is expected that there is constant entry of firms into various points in the value chain, to fill the 'gaps' or meet novel demands in the evolution of the system. Each new entrant brings knowledge and other resources into the

⁶⁵ Information is available from the SPECIFIC website <http://www.specific.eu.com>, [accessed on 3 November 2014].

industry, and begins, through a learning process, to function within the TIS. On the other hand, the system also involves the formation of a division of labour, and is associated with further learning stimulated by specialisation and accumulated experience (Jacobsson and Bergek, 2004). In this sense, the identification of actors and networks was mainly carried out by using the 'snowball' method, where the actors already involved points to other participants. This was further complemented by other methods and sources including trade associations, scientific papers, research reports and policy reports on building integrated solar energy systems, solar technologies, and solar energy market, etc.

As this case study is linked with WPI of the LCBE project, the project team working on the work package formed the first point of contact, which subsequently led to further contacts, and so on. This was then complemented by searching the membership directories of relevant trade associations, e.g. the UK Solar Trade Association, and the European Photovoltaic Industry Association (EPIA), and by studying relevant documents, research papers and reports (e.g. El-Beyrouy et al., 2009; EPIA, 2012a, 2012b). As a result, the 'perceived' network map of interactions between actors in a well-functioning BISE TIS is proposed below in Figure 5.5.

As indicated, this, by no means suggests that all the actors have been identified, due to the emergent nature of the system. As the system further evolves, it is expected that new actors will enter the system and fill the gaps. When this happens, an external economy may be created in Wales, which would in turn enhance the competitiveness of the Welsh solar energy sector.

5.3 Summary

This chapter has introduced the key structural components of the innovation systems of two selected emerging low carbon building technologies: 'Welsh grown timber for construction' (WTC) and 'building integrated solar energy systems' (BISE) TISs. That includes the relevant 'institutional structures', 'technologies' and 'actors-networks' of the two TISs, and subsequently helps to establish the context in which the functions of the two systems can be properly examined in Chapter 6.

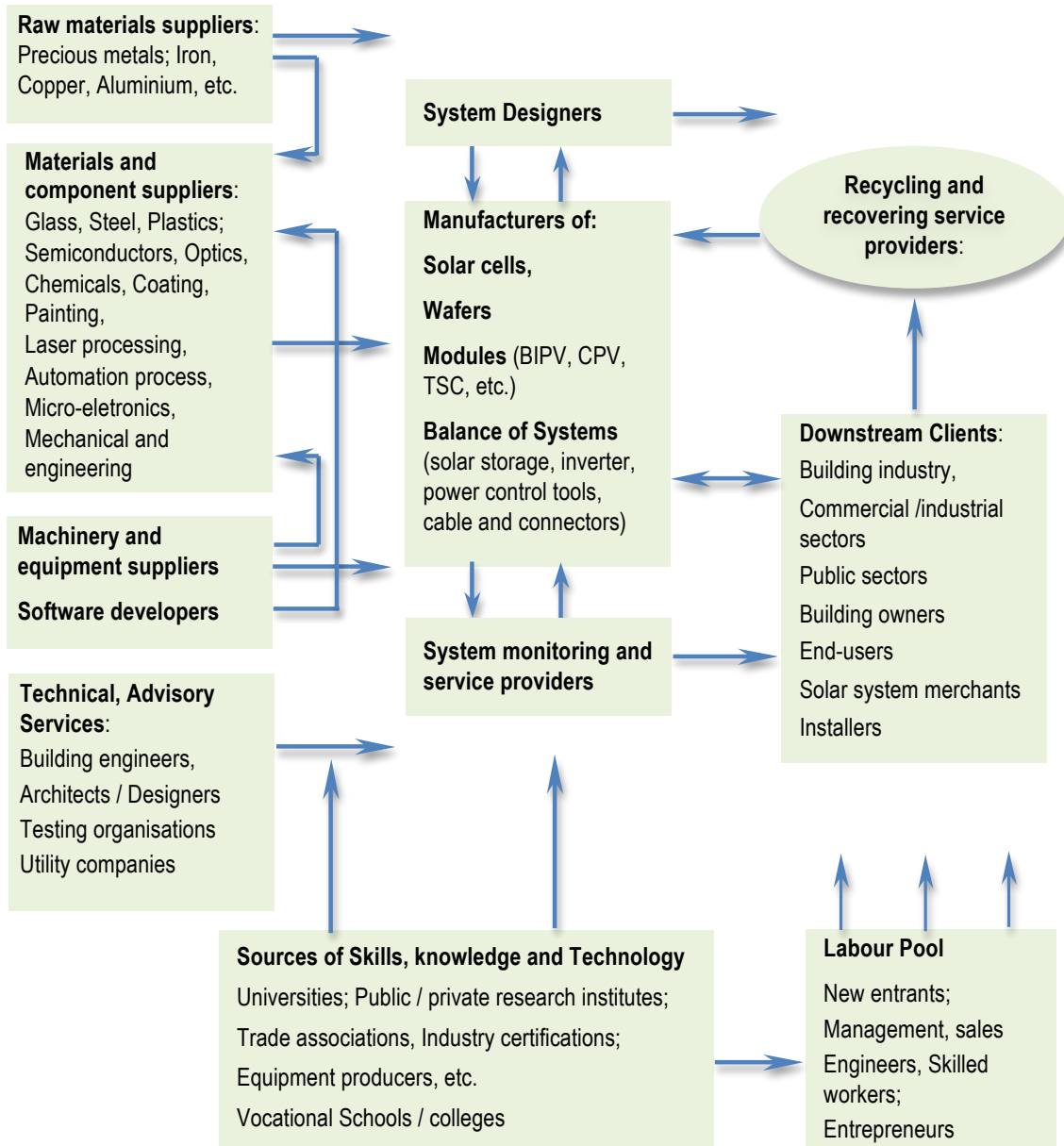


Figure 5.5: The perceived network map of interactions between actors in a well-functioning BISE TIS

Chapter 6 Case Study: Mapping the Functional Patterns

In previous chapters, I explored the key structural components of the two selected emerging technological innovation systems: 'Welsh grown timber for construction' (WTC) and 'building integrated solar energy systems' (BISE) in Wales, and set up the bespoke analytical framework for the assessment of the IS functions, as outlined in table 6.1 below. In this chapter, I move onto examining the functions of the two TISs, in terms of the extent to which they have been fulfilled in the WTC and BISE TIS respectively, and subsequently address Research Question 2.

This chapter contains three sections. Sections 1 and 2 are dedicated to examining the way in which, and the extent to which, the functions of the WTC and BISE TIS have been fulfilled respectively. In Section 3, I will discuss whether the two TISs have been formed in Wales, and how likely they may move onto a stage of market growth.

As reviewed (in Section 2.2.4, Chapter 2), the TIS approach, in relation to the aim of the study, can be applied to three levels of analysis: (a) a technology in the sense of a knowledge field, (b) a product or an artefact, or (c) a set of related products and artefacts aiming at satisfying a particular societal function e.g. health care or transport. In this regard, two different levels of analyses are adopted for the two emerging technological systems in this thesis. In terms of the WTC TIS, I take one product, *i.e.* the Ty Unnos system, as an initial point of the analysis, and explore the extent to which the functions of the WTC TIS have been fulfilled,

With respect to the BISE TIS, as introduced in Chapter 5 (Section 5.2.1), the term 'building integrated solar energy' (BISE) blankets a broad range of potential applications of PV and solar thermal technologies that can be integrated with building components (mostly building envelope) as multifunctional units, rather than any standardised, strictly-defined industrial products. In this sense, the functional analysis of the BISE TIS in Wales is carried out at the level of a set of related products and artefacts aiming at satisfying a particular societal function, *i.e.* secure energy supply from renewable sources while reducing GHG emissions from the built environment.

Table 6.1: A bespoke analytical framework for the assessment of the IS Functions

Functions	Performance indicators
Knowledge development and diffusion	<ul style="list-style-type: none"> ▪ Type of actors developing knowledge ▪ Type and source of knowledge development ▪ R&D financing ▪ Number of patents filed; ▪ Type of research collaboration (university / industry, incl. non-local organisations) ▪ Knowledge exchange mechanisms
Entrepreneurial Experimentation	<ul style="list-style-type: none"> ▪ Type of entrepreneurs / firms ▪ Change in the number of entrepreneurs, including the new entrants ▪ Number of new (related) products (services) introduced by firms
Guidance of the Search	<ul style="list-style-type: none"> ▪ Vision or collective targets set by government or industry, <i>and/or</i> ▪ Regulations and policy, <i>and/or</i> ▪ Interests expressed by customers / users, <i>and/or</i> ▪ Demand-orientated policy measures, e.g. procurement policy, <i>and/or</i> ▪ Factor conditions, <i>and/or</i> ▪ Industrial or social crisis.
Market Formation	<ul style="list-style-type: none"> ▪ Market size and composition ▪ Actor's marketing strategy ▪ Financial incentives for emerging technologies
Resource Mobilisation	<ul style="list-style-type: none"> ▪ Ability to retain and attract desirable talents ▪ Availability of specialized education programs ▪ Availability of raw materials ▪ Access to finance, e.g. venture capitals, foreign investment and governmental grants
Legitimation	<ul style="list-style-type: none"> ▪ Compliance with existing regulations /legislation ▪ Meeting the expectations and value base of the society ▪ Activity of advisory coalitions
Development of Externality	<ul style="list-style-type: none"> ▪ Emergence of a pooled labour market ▪ Emergence of specialized intermediate goods and service providers ▪ Increase in explicit inter-firm cooperation for specific purposes

6.1 Functions of the WTC TIS

6.1.1 Function 1: Knowledge development and diffusion

In Welsh, Ty Unnos means ‘house in a night’, originating from the Welsh tradition of putting up a house overnight on vacant land enabling to claim it as a home. The name was chosen to convey a hybrid modular volumetric off-site building system using Welsh grown Sitka spruce, while a two-storey house using Ty Unnos modules can be easily erected on-site in less than 12 hours (Coed Cymru, 2012). The R&D development of the Ty Unnos system commenced in 2006, and has been through several stages, as outlined in Table 6.2; the table also provides an overview on *the type of actors*⁶⁶ that have been involved in the varied stages of knowledge development, the *type of research collaboration*, as well as the sources of *R&D financing*.

Table 6.2: Varied R&D phases of the Ty Unnos system

<p>Feasibility study: 2006/7</p> <p>Funders: Countryside Council Wales, and the then Forestry Commission for Wales through the Welsh Forest Business Partnership;</p> <p>Funding size: £15,000</p>	<p>Project Partners: Coed Cymru; Design Research Unit Wales (DRU^W), Welsh School of Architecture, Cardiff University; School of the Environment and Natural Resources, Bangor University;</p> <p><i>Industrial partners</i> Cowley Timberwork (based in Lincoln, England); NEO Fabrication & Erection Ltd.; Plant Fibre Technology Ltd.; BSW Sawmills;</p>
<p>Research stage: Home grown Welsh eco house, 2007/11 (Incl. a 3-year PhD research)</p> <p>Funders: Technology Strategy Board Investment (EPSRC funded the PhD, but the amount is not available)</p> <p>Funding size:</p>	<p>Project Partners: Coed Cymru; DRU^W; Blaenau Gwent County Borough Council</p> <p><i>Industrial partners</i> Pontrilas Timber (based in Hereford, England); Kenton Jones</p>

⁶⁶ As I use the proposed performance indicators to assess the functions, I signpost the indicators (or the key words of the indicators) in *italic* to mark the relevant assessment that is carried out.

£205,680 (matched by £197,840 from partners)	
<p>Pilot & Demonstration projects: 2009-10</p> <p>Funders: Welsh Government; Blaenau Gwent County Borough Council</p> <p>Funding size: £75,000 (by the WG, for Project 1) £565,000 (by the Blaenau-Gwent council, for Projects 2&3)</p>	<p>Three projects involved:</p> <ol style="list-style-type: none"> 1. Ty Unnos proto-typical Pavilion , for the Smithsonian Festival, Washington DC, in 2009 2. Environmental Research Centre, at Ebbw Vale, in 2010 3. Ty Unnos ‘passiv’ longhouse, at Ebbw Vale, in 2010 <p>Project Clients: Coed Cymru (Project 1); Blaenau Gwent County Borough Council (Projects 2&3)</p> <p>Architect: DRU^w;</p> <p>Manufacturer: Kenton Jones (1&3) Cowley Timberwork (2)</p>
Source: Coed Cymru; WSA	

In terms of the *type and source of knowledge development*, the Ty Unnos project has been focusing on re-engineering standard sizes of Welsh grown Sitka spruce into strong, stable building components to form a prefabricated construction system, and thus demonstrating a range of higher value uses for Welsh Sitka spruce in e.g. structural beams and walls, without complicated manufacturing processes. The eventual Ty Unnos system comprises two simple engineered timber components: a hollow box section beam and a small section ladder beam (see Figure 6.1). When combined with frame connectors and Oriented Strand Board-based infill panels, the engineered components form an innovative whole building construction system which can be adapted to a variety of building types, from affordable housing in its modular form, to a one off studio or cabin suitable for smaller sized plots, as demonstrated in Figure 6.2 (Coed Cymru, 2012).

The Ty Unnos system as well as the building design using the system has won a number of innovation, design and timber construction awards. They include the 2009 Chartered Institute of Building International Award for Architecture and Surveying, the 2010 TRADA Wood Awards ERC entry short list, the 2011 InnovaWood European Forest and Timber Network ‘Laureate Prize’ for Ebbw Vale Visitor Centre, the 2012 ACE Engineering Excellence Award, etc. (Welsh School of Architecture, n.d.). However, the Ty Unnos

system has not been filed for a ‘*patent*’. The reason suggested is that, as the project has involved multiple partners at varied stages and drew funds from different public sources, the intellectual property rights of project partners have been largely diminished in that the knowledge of the Ty Unnos system is already in public domain (NGO Interviewee N.I., 2012). However, since Elements Europe Ltd. decided to bring the Ty Unnos onto market, the company registered the system under the trademark ‘Ty Unnos Modular™’ in 2009.

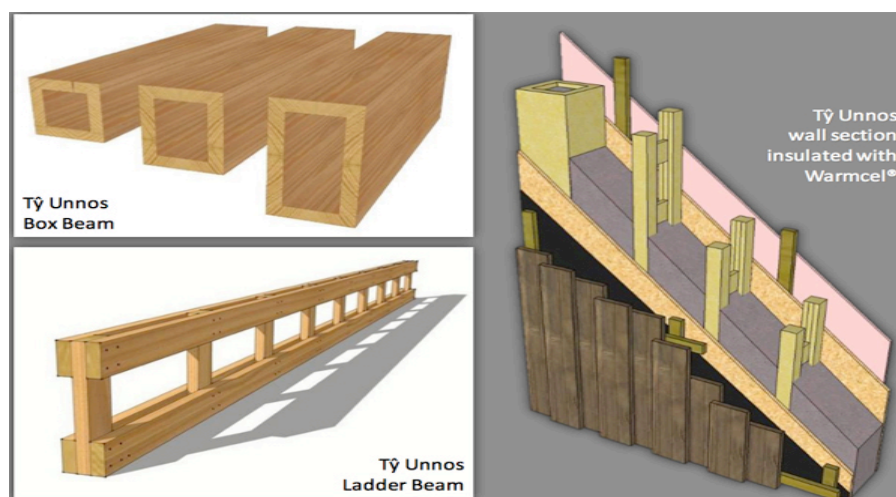


Figure 6.1: The Ty Unnos components (Source: Elements Europe)

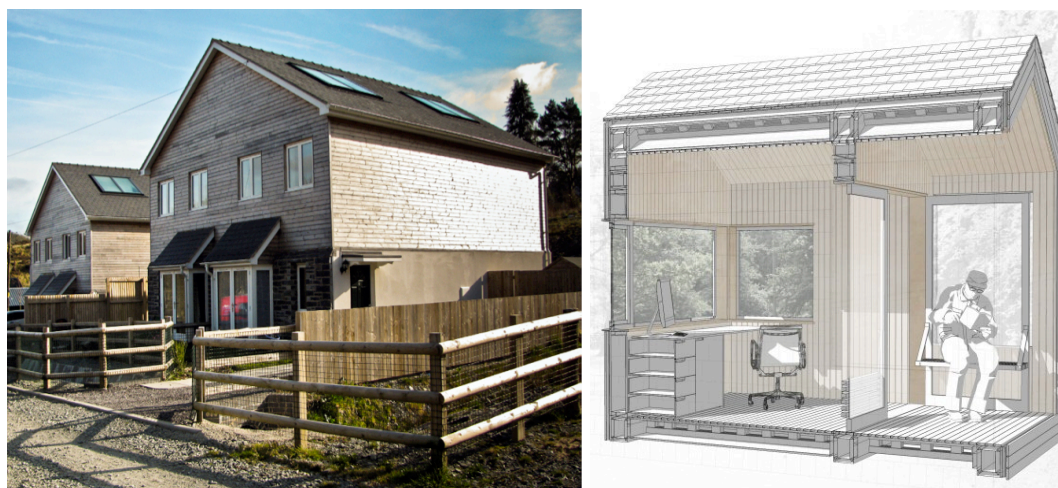


Figure 6.2: Buildings projects using the Ty Unnos system – the Glan Gors Affordable Housing in Dolwyddelan (left), and the Caban Unnos designed for the Pembrokeshire Show (right) (Source: Thomas, 2013)

As demonstrated in Table 6.2, an informal Ty Unnos *partnership* has been formed, with most partners working together for years. Outside this partnership, various *knowledge*

exchanging mechanisms have been used for the knowledge diffusion of the Ty Unnos system. In addition to the aforementioned design and innovation competitions, the system or the demonstration projects using the system have been put on display in a number of high profile public events or trade shows, including the *BRE Welsh Future Homes Exhibition* at Ebbw Vale, the *Smithsonian Folklife Festival* in Washington DC in 2009, the “*Grand Design*” *Live* at the Birmingham NEC in 2009, the *Timber Expo* in Coventry in 2010, the *Royal Welsh Show*, and the *National Eisteddfod for Wales* etc. Meanwhile, the system and related building projects have been introduced through publications in the form of conference papers, architectural journals and Best Practice Papers produced by national organisations etc.

Also, the knowledge of the Ty Unnos system and the related projects was disseminated via the member network of the Wales Forest Business Partnership (WFBP)⁶⁷, which consists of over 500 Welsh businesses and organisations (Business Interviewee N.7, 2012). As mentioned, WFBP is a voluntary organisation, and was set up and financed by the WG since c. 2005. It is run by businesses and organisations across the Welsh forestry sector, and has been active in supporting the implementation of the government’s forestry strategy, and promoting the production and marketing of higher value products and services using Welsh grown timber. Three initiatives were set up by the Partnership: Wood Knowledge Wales (WKW), Wood Source Wales (WSW), and Wood Fuel Wales (WFW). A number of people involved in the Ty Unnos project sit or used to sit on the board of WKW or WSW. Amongst, the WKW is responsible for leading industry innovation, and R&D, and facilitating knowledge transfer and information sharing through seminars and training workshops, and its website and newsletter etc.

The knowledge development and diffusion process of the Ty Unnos has demonstrated that Welsh organisations and firms are capable of collaborating with each other to turn an idea into an innovative solution and product. However, there is the concern over whether a more systematic approach is needed to guide the process of knowledge development and diffusion in the WTC TIS. Apart from the Ty Unnos, a number of new timber engineering systems have also been developed, which include:

- ‘*Welsh Brettstapel*’, a Brettstapel-based solid wood panelised system using Welsh grown softwoods including Douglas fir, Grand fir, Sitka spruce and larch; its R&D

⁶⁷ More information is available from WFBP’s website <http://www.wfbp.co.uk>.

was funded and managed by WKW, with research input from Edinburgh Napier University (Dauksta, n.d.);

- ‘New Welsh House’, a prefabricated super energy efficient panel system using Welsh grown Sitka spruce; its R&D was financed by Glasu⁶⁸ and WKW.

However, most of these R&D activities are disjointed, and generally fragmented in nature, where the individuals and organisations involved seemed to have very different agendas, driven by different interests; there is generally a lack of coordination so the opportunity for more collaboration has been lost (Academic Interviewee N.1 and N.2, 2012).

Whereas Coed Cymru⁶⁹ and WFBP have emerged as prime forces in promoting the use of Welsh grown timber for construction, there is otherwise no dedicated research organisation or group in Wales that are specialised in WTC. As a matter of fact, there are very few researchers who are working at a full-time basis in the field, which partly explains why Coed Cymru, WFBP and the then FCW have often sought assistance from non-Welsh research sources e.g. TRADA in England, Edinburgh Napier University and the Forestry Commission (FC) UK, both based in Scotland, in order to complement relatively weak R&D capacity in timber construction within Wales.

This fragmented nature also affects the overall level and dynamics of the knowledge exchange and diffusion within the system. As some interviewees described,

... you hold seminars to disseminate information to architects, builders, manufacturers, and clients, the same people who were interested in timber coming to those meetings. So it's the same people learning the same stuff over and over again, and it doesn't spread. (Academic Interviewee N.1 and N.2, 2012)

We've tried most things, shows, ..., very hard to get companies to play a part in it. We've tried networking events, everybody said it's a lovely idea and nobody turned up. (Business Interviewee N.7, 2012)

⁶⁸ Glasu is a rural development initiative providing assistance and support to businesses, individuals and community groups in Powys, and its website is <http://www.glasu.org.uk/en/index.php>.

⁶⁹ Coed Cymru was set up in 1985 by the UK government, with aims to return the Welsh forest to the indigenous species, and maintain the habitat, etc. But over the years their responsibilities have been adjusted to include the promotion of more recent woodland and the use of locally grown timber.

On the other hand, several interviewees have mentioned the existence of some formal or informal local networks that consist of mainly local firms or other stakeholders, which have allowed firms to tap into a wealth of local knowledge bases, and address enquiries locally (Business Interviewee N.2 and N.6, 2012). As indicated, it is estimated that, along the supply chain, about 1900 wood-based firms are operating in Wales; despite most of them being small or micro firms, a lot of them have been in business for long time, with an average age of businesses up to 21 years (Jaakko Pöyry Consulting, 2004); so, there are already considerable knowledge and skills among the Welsh wood-based sector. The challenge becomes how an effective mechanism can be set up, which enables the advantage to be taken of the existing knowledge base in Wales, while facilitating the development and diffusion of new knowledge.

6.1.2 Function 2: Entrepreneurial experimentation

Coed Cymru has tried to find a way to bring the Ty Unnos system into the construction market, which became possible when they met Element Europe (EE) in an event in 2008. After learning the system, EE decided to adopt the Ty Unnos system, and formally registered and launched it under the trademark 'ty unnos modular™' in 2009. As part of the Pickstock Group, EE is a market leader in providing off-site building solutions and high quality of accommodation to various sectors, e.g. hotels and student dormitories, mainly made of lightweight steel frame systems. In this respect, the Ty Unnos fits well with the company's profile, while allowing EE to diversify into timber frame systems.

Because EE does not have the expertise in timber engineering, the firm has simply assumed the collaboration with the existing Ty Unnos partnership, and, to some extent, formed an 'open' value chain along which various partners perform individual activities respectively. So, it includes Kenton Jones Joinery that is responsible for prototyping and manufacturing the Ty Unnos components, Hughes Architects for building designing, and Burroughs for structural engineering providing the cutting list, while EE is in charge of marketing, sales, fitting, and on-site assembly, as well as overall project coordination. In the meantime, Coed Cymru has been continuously involving, in terms of providing technical and research support, e.g. helping to obtain the TRADA Q Mark certification⁷⁰ for the Ty Unnos system.

⁷⁰ The TRADA Q Mark is a quality mark awarded to a manufacturer, installer or maintainer of a construction product or a range of construction products; the relevant information is available from <http://www.bmtrada.com/en-gb/certification/product-certification/q-mark-product-certification>.

Geographically, four of the Ty Unnos partners are located close to each other in mid-Wales, with Burroughs based in Cardiff to the South. Having said that, it is worth pointing out that, although the founders of the Pickstock group (the parent company of EE) are Welsh, EE bases both its head office and factory at Oswestry, a nearby English town in the Midlands. This closeness has allowed the partners to meet⁷¹ regularly and discuss technical and commercial matters. Meanwhile, it was suggested that EE was seeking collaboration with other secondary wood processors in South Wales to manufacture the Ty Unnos modules; this will be likely operated under a licence system, to help meet possible future demand for Ty Unnos module in the South (Business Interviewee N.1, 2012).

The first Ty Unnos housing development that EE completed was Glan Gors Affordable Housing in Dolwyddelan (see Figure 6.2), North Wales, which consisted of four three-bedroom semi-detached houses. Each house comprised two complete Ty Unnos modules, one for each floor; they were fully finished to a quality controlled factory condition, including the installation of internal finishes, windows and doors, bathrooms and all electrical services and appliances prior to transportation to the building site; the assembly was then completed in a matter of hours on preformed foundations (Coed Cymru, 2012). These houses were designed to meet Level 4 of the Code for Sustainable Homes.

Given the size of the Welsh firms in the sector, few firms have internal R&D capacity (Civil Servant Interviewee N.1, 2012), in both financial and personnel terms, to innovate and develop new products. 'Imitation' is often used as a way for product development via e.g. the acquisition of design software (Business Interviewee N.3, 2012), or following the design and specification of others' under a paid licence e.g. Passivhaus window (Business Interviewee N.4, 2012). In this regard, the R&D process of the Ty Unnos system may become an innovation model for the future development of WTC products or systems, where universities or public research institutes carry out research of relevance to firms through e.g. joint research projects, or consulting arrangements. I will discuss this in more details in Chapter 7.

Overall, the *type of the firms* involved in the development of the Ty Unnos systems are mostly existing businesses that seek to diversify into new market segments. In terms of

⁷¹ I was invited to an informal meeting held in Kenton Jones Joinery in 2012, and given the opportunity to first-handedly learn how the partnership was working.

change in the number of entrepreneurs, the involvement of EE has provided much desired business expertise in establishing the market position of the Ty Unnos systems; but at present the number of firms involved is still very limited, although the weak demand in the UK housing market may also attribute to this situation, as will be discussed later. With respect to *the number of new products introduced by firms*, as mentioned earlier, two other new timber engineering systems (i.e. 'Welsh Brettstapel' and 'New Welsh House') have also been developed by the actors of the WTC TIS, and both are market ready.

6.1.3 Function 3: Guidance of the search

The initial intention behind the development of the Ty Unnos system was to produce low cost, social housing using Welsh grown softwood. At the feasibility stage, the project team recognised that most of the modern timber frame manufacturers in Wales used imported softwoods due to their greater stability and superior strength properties, and thus the simple substitution with Welsh grown softwood was not an option. It required a system that could stabilize the main structural components while eliminating the need for conventional trussed rafters; this meant a radical departure from the existing practice (Welsh School of Architecture, 2007).

At the R&D stage, the research team took some *factor conditions* into consideration, and acted on the so-called 'selective factor disadvantages'. It began with the worst-case scenario (Academic Interviewee N.1 and N.2, 2012), i.e. the relatively low density quality of Welsh Sitka spruce that has a tendency to twist while drying, so it is often used for lower value products e.g. pallets and fencing, rather than for structural purposes. Instead of trying to modify the physical properties of Welsh Sitka spruce in order to improve its strength performance, the research team developed the Ty Unnos system to accommodate Welsh spruce's relatively low density quality. More so, the system is designed to be manufactured on the existing machines and tools, using existing skills and craftsmanship (NGO Interviewee N.1, 2012). This therefore allows the Ty Unnos system to easily fit into the existing production capacity of many Welsh wood processors without additional investment in new machines or tools.

On the other hand, overall *changes in the political and regulatory arenas* have generated the possibility for the increased use of timber in buildings. These include the promotion of sustainable construction, the mandate requirements for carbon reduction, the regulatory

pressures set by the Building Regulations to achieve higher building energy efficiency, and the introduction of the Code for Sustainable Home, etc. These movements have combined creating a level playing ground for timber to compete with other building materials in the UK. Meanwhile, timber construction has also demonstrated its potential to deliver low and zero carbon building (in terms of *technical expectation*), e.g. UK's first Code Level 6 (zero carbon) house (at the time of construction), the Larch House in Ebbw Vale, South Wales, is a timber frame structure using locally sources materials (Design Commission for Wales, n.d.).

As a representative of Elements Europe encapsulated why they adopted the Ty Unnos system:

Because it is sustainable, because it's Welsh, because hopefully (of) the quality that we do with the off site manufacturing. I mean there's other ways of building in timber, timber frame housing for example, but you've got issues with shrinkage, it's not as quick to build like that as well, Ty Unnos is a very quick system to build with. (Business Interviewee N.1, 2012)

However, the lack of *demand in the UK housing market* has become a main bottleneck for the market uptake of the Ty Unnos system. More than one interviewee have argued that the WG needed to fund demand e.g. through its social housing programme. Meanwhile, the policy incentives in terms of *Building Regulations* or *public procurement* that can help to stimulate the demand for using locally grown timber for construction are also not sufficiently installed in Wales at moment.

As indicated, the responsibility for Building Regulations was devolved to the WG on 31 December 2011. After a consultation process lasting almost two-year, the new Welsh Building Regulations Part L took effect recently, which sets requirement to reduce GHG emission in new home by a mere eight per cent (against 2010 standards). This is only equivalent to achieving Level 3 of the Code for Sustainable Home, plus one additional energy 'credit' (Samuel, 2014, DCLG, 2010). However, the situation will change soon, due to the agenda set by the European Energy Performance of Building Directive on Nearly Zero-energy Building (Directive 2010/31/EU), which requires all new buildings constructed in Europe after 2020 to be virtually carbon neutral and all new public building to comply as of 2018. The WG has promised to review the new Part L in 2016, in order to comply with the EU Directive (Sargeant, 2013b).

In terms of *public procurement policy*, the WG adopts a *Sustainable Building Standards*⁷² to guide its procurement process for public building projects, which requires a minimum Code for Sustainable Homes level 3 for residential development, and BREEAM excellent or equivalent for non-residential development. In theory, these requirements do not create sufficiently favourable conditions for timber construction in general. In practice, it is suggested that the public sectors' procurement process is extremely risk averse, and thus does not tend to support innovation, while always going for the cheapest bidder (Business Interviewee N.7, 2012). One architect commented that the concern over the maintenance and replacement of timber as building materials over a building's lifetime (in term of revenue cost) has made some public sector clients reluctant to use timber (Architect Interviewee N.2, 2013). In this sense, more specific requirements or higher standards are needed, if public procurement is to become an important policy driver for the use of locally grown timber in the construction of public buildings.

6.1.4 Function 4: Market formation

As mentioned, Coed Cymru helped Elements Europe obtained the TRADA Q Mark for the Ty Unnos Modular™, shortly after the latter took over the system. By obtaining the Q Mark, the Ty Unnos Modular™ becomes mortgageable, and complies with the LABC (Local Authority Building Control) Warranty, which thus increases the marketability of the Modular (Business Interviewee N.1, 2012).

EE markets the Ty Unnos Modular™ mainly for the UK low-rise affordable residential market, ranging from one-bedroom apartments throughout to four-bedroom houses with a selection of bungalows – in terms of housing types (Elements Europe, n.d.). The firm have been actively engaging with housing associations, builders and developers, to promote the Ty Unnos and raise general interest in the Modular (Business Interviewee N.1, 2012). One result of such campaigns was the construction of Glan Gors Affordable Housing development in Dolwyddelan, as introduced previously. In addition, EE has brought the Ty Unnos to the Grand Designs Live at the Birmingham NEC in October 2009, which garnered wider interests (Elements Europe, 2009). In the meantime, EE has set up an individual website (<http://tyunosmodular.com/index.html>) to specifically introduce and market the Ty Unnos Modular™, from which the product brochure can also be

⁷² Information is available from the WG website:
<http://wales.gov.uk/topics/sustainabledevelopment/design/standards/?lang=en>

downloaded. Providing that EE is already a market leader in off-site construction solutions, the company seemed to be confident in establishing the market of the Ty Unnos system, once the housing market is picked up.

The involvement of EE has seen a rather different *marketing strategy* from the one that is often used by Welsh firms. Traditionally, Welsh firms tend to invest little in marketing, with hardly any strategy; 'word of mouth' advertising seems to be widely applied among Welsh firms. As one interviewee stated, they do not do marketing, due to the quality of their works, and architects and clients who have worked with them often recommend or come back to them for the next projects (Business Interviewee N.3, 2012). It is also suggested that increasingly Welsh firms use the Internet and the firm's website as a main marketing tool for their products and services, sometime with the help from WoodSource Wales (WSW). On the other hand, even when firms have carried out advertising, the market they target is confined. One interviewee pointed out that they only targeted direct customers within a 50 mile radius, because 50 miles was about as far as people want to travel to see a product; also because their business required on-site installation and after-service, it is impractical if long-distance travel is required (Business Interviewee N.2, 2012). In all, it appears that the size and nature of Welsh businesses have confined their ability, resource, and sometimes ambition as well, to grow their market presence.

On the demand side, the UK *housing markets* as a whole have not yet recovered from the credit crunch at the time of this thesis, following the 2007-08 Financial Crisis, even though a number of studies have repeatedly stressed serious housing shortages in the UK. The latest estimation is that Britain needs to build at least 243,000 homes a year to keep up with the number of new households being formed (The Lyons Review Commission, 2014), while a separate study suggests that about 284,000 will be needed in Wales alone by 2026 (Holmans, 2010). In reality, only 137,000 homes were built annually over the last ten years (The Lyons Review Commission, 2014), although this does suggest that the demand for new houses in the UK will persist.

Whereas there is no *financial incentive* for encouraging the use of locally sourced timber for construction in the UK, the share of timber frame housing among UK housing starts has increased steadily since the financial crisis, with its share reaching at 23.6% in 2012. When this figure is still below the peak level of 25% in 2008, Wales has seen an increase of

up to 26.6% (Structural Timber Association, 2013a). In theory, even a small percentage of this market will be substantial, and help to establish the market presence of the Ty Unnos Modular™ or other WTC products. In practice, the Ty Unnos Modular™ is still a new product, and is facing an uphill to climb in term of competing with incumbent products and systems on the markets.

6.1.5 Function 5: Resource mobilisation

As explained, the development of the Ty Unnos system has intentionally set barriers for entry low, in terms of both the timber quality, manufacturing cost and production techniques. This allows most of the secondary wood processors with existing skill sets to easily produce the system using existing machines and tools, while the Welsh Sitka spruce of present quality is sufficient for the system. In the short term, resource mobilisation thus does not pose a problem for the market deployment of the Ty Unnos. Hence, I will examine this function from a long-term perspective.

In terms of the *ability to retain and attract desirable talents*, the 2009 Welsh forestry strategy states that the Welsh timber sector is facing the prospect of an aging workforce and a shortage of new entrants in the long run, due to low pay and poor career prospect (Welsh Government, 2009). Firms have expressed the difficulty to find the right people with the right skills and expertise (Business Interviewee N.3, 2012; Jaakko Pöyry Consulting, 2004). Some have suggested that, sometimes, once being trained, the good employees likely chose to leave and start their own businesses (Business Interviewee N.4, 2012). This may be seen as a sort of knowledge spill-overs, but nevertheless contributes to the perceptions of skill shortage (David Langdon Consultancy, 2004). The Strategy has called for actions to assess the skills gaps at all levels of the sector and the availability of appropriate education and training, but there is no such report available at the time of this thesis. Thereby, in order to establish a basic understanding on *the availability of specified education program*, I did an initial online scoping through websites including City & Guilds (C&G), and UCAS, etc., and drew the impression that the number and availability of relevant courses at all level were still very limited in Wales.

At the apprentice level, only a few colleges in Wales offers C&G level vocational courses on carpentry, carpentry and joinery, chainsaw training etc.; on the other hand, as commented by one interviewee (Business Interviewee N.6, 2010), even though the

students enrolled obtain relevant qualifications, they may still not have the right amount of experience to be qualified to work in a real working environment. Modern technologies and automation of manufacturing process have re-shaped the wood-processing sector. While the level of traditional skills involved is no longer as sophisticated as in carpentry or craft work of the old days, a new set of skills becomes compulsory for the sector, in terms of the operation and maintenance of electronic machines, finishing techniques, assembly, process control of gluing and bonding, etc. Because most of these skills are tacit in nature and can only be acquired through learning by doing, on-the-job training is widely practised in the sector, and firms regularly take in college graduates on the apprenticeship scheme, which is sometime organised through the local construction training group (Business Interviewee N.6, 2012). It was suggested that it normally took five to six years to get people trained up to the standard (Business Interviewee N.4, 2012; *ibid*).

At the university level, only Bangor University provides courses on forestry at both under- and post-graduate level in Wales. However, it was suggested that the focus of the courses is more towards land management than forestry (NGO Interviewee N.4, 2012); on the other hand, as the first UK university to award forestry degrees, Bangor has lost some key staff to Edinburgh Napier University in recent years (Business Interviewee N.8, 2013). At a professional level, a number of studies have suggested that key actor groups (e.g. architects and structural engineers, surveyors) are ill equipped with the necessary knowledge and skills to use timber in construction (Jones, 2011; Roos et al., 2010). One way to improve this situation is the provision of CPD (Continuing Professional Development) courses. WKW has previously organised CPD courses on e.g. timber cladding and '*designing with timber*', but has not done so recently, partly due to lack of resources. Currently, the LCRI offers an online CPD course '*Welsh Timber in Building Construction: myths & facts*', under the *Welsh Energy Sector Training* (WEST) project; however, because WEST is funded by the European Structure Fund, only people who live or work in the Convergence area (West Wales and the Valleys) can access the course, free of charge.

As to *raw materials*, as introduced, there are approximately 306,000 hectares of woodland in Wales, of which 38% is the previous FC woodland, and is now managed by the Natural Resource Wales (NRW)⁷³, while the remaining 62% belongs to individual landowners,

⁷³ This figure 38% does not include areas owned or managed previously by other parts of NRW, i.e. the former Environment Agency Wales and Countryside Council Wales (Forestry Commission, 2014).

NGOs, community groups, educational establishments and unitary authorities. In term of species, approximate 151,000 hectares are covered with coniferous species with 65% in the former FC estate, in which Sitka spruce accounts for almost 60% of the conifer stock (Forestry Commission, 2014; Welsh Government, 2009). Table 6.3 below forecasts the annual availability of the Welsh grown softwood for the period between 2013 and 2061, with a declining trend observed.

Table 6.3: Softwood availability forecast for the woodland in Wales, 2013-2061

Annual average in the period	Former FC estate	Non-FC sector	Total softwood
thousand cubic metres overbark standing			
2013 – 2016	1,082	901	1,983
2017 – 2021	991	949	1,940
2022 – 2026	895	1,087	1,982
2027 – 2031	778	775	1,553
2032 – 2036	934	736	1,670
2037 – 2041	794	679	1,473
2042 – 2046	531	490	1,021
2047 – 2051	585	521	1,106
2052 – 2056	495	734	1,229
2057 – 2061	679	694	1,373

Source: Forestry Commission, 2014

Given the weather conditions in the UK, it is suggested that the growth rotation length for coniferous species such as Sitka spruce is typically between 35 and 45 years (Moore, 2011). This therefore indicates that restocking and new planting need to take place now, in order to sustain the softwood production of Welsh grown timber in the longer run. The WG has proposed to grow an additional 100,000 hectares woodland in Wales, and thus increase the Welsh woodland coverage up to 20% by 2030. The main policy drive behind is to contribute to WG’s target of an annual three per cent GHG emissions reduction (Osmond and Upton, 2012). Since its introduction, this new policy has stirred up a number of concerns among the key actor groups e.g. landowners, foresters and sawmills. Many considered it as wishful thinking, due to its oversight of special interests of some key actor groups (NGO Interviewee N.5, 2012; Business Interviewee N.5, 2012; Osmond and Upton, 2012). For instance, whereas the forestry sector wants to ensure that the right species are planted in the right locations, and subsequently managed sustainably to allow commercial harvesting, farmers and landowners want to learn how their financial future

can be secured if they convert agricultural land to woodland. The latter is also compounded by a culture of 'dependency' and subsidy that is seen to widely exist among Welsh farmers, and has prevented them from managing lands or what grow on their land according to market or long-term commercial interests (NGO Interviewee N.5 and N.4, 2012; Deans, 2014).

The '100,000 hectares' target is delivered through the Glastir Woodland Creation scheme, as part of the Rural Development Plan (RDP) for Wales (Welsh Government, 2014d), while the Woodland Opportunities Map, or the 'traffic light' mapping system, guides where trees can be planted. Since its inception, the uptake of the Glastir grant has been sluggish among Welsh farmers (NGO Interviewee N.5, 2012; McNulty, 2012). The WG has recently finished a consultation on the Glastir scheme under the latest RDP period (2014-2020), and a number of new proposals have been put forward, including the introduction of a stand-alone Glastir Woodland Management scheme to offer grant support to both farmers and non-farmers for woodlands management, while the traffic light map will also be reviewed, revised and amended (Welsh Government, 2014d). However, these changes may not take effect until 2016 at the earliest.

With respect to *access to finance*, the economic downturn and slow housing market have added financial strain on the sector. Governments at all levels (the EU, UK, WG and local) remain the main financial providers to Welsh firms, organisations and individuals (e.g. farmers). A number of firms interviewed confirmed that they have previously used government grants to purchase equipment etc. (Business Interviewee N.3 and N.4, 2012). On the other hand, the lack of demand in the housing market has greatly affected the firms' willingness to borrow and expand their businesses.

6.1.6 Function 6: Legitimation

Generally speaking, a certain level of legitimation has been achieved in terms of timber construction in general, as well as in the case of the Ty Unnos. As indicated, 'building with wood' has become more acceptable now, due to a general trend towards sustainable construction, and *regulatory demand* for low carbon, low energy buildings. In the UK, *the public's acceptance* of timber construction has been gaining ground in recent years. For instance, timber frame accounts for 75% of the UK self-build market (Self Build Home Magazine, n.d.); as noted earlier, among the housing starts in 2012, the UK average share

of timber frame is 23.6%, with the figure in Wales rising to 26.6%. A recent survey commissioned by the Structural Timber Association (2013b) also suggested that over 70% of UK's leading contractors, developers, architects and RSLs (Responsible Social Landlords) have claimed that they would specify more timber in future.

With respect to the Ty Unnos, the system has raised widespread interests among key actor groups through a series of proactive marketing steps taken by the Ty Unnos partnership. This includes the presence at major trade shows, public or professional events organised by professional bodies, WG and local councils, e.g. Timber Expo, Grand Design Live, the BRE Welsh Future Homes Exhibition, the Royal Welsh Show and the National Eisteddfod etc. Meanwhile, the Ty Unnos and its demonstration projects have won a series of design, innovation and building engineering awards over the years, including the 2009 Chartered Institute of Building International Award for Architecture and Surveying, the 2010 TRADA Wood Awards ERC entry short list, the 2011 InnovaWood European Forest and Timber Network 'Laureate Prize' for Ebbw Vale Visitor Centre, the 2012 ACE Engineering Excellence Award, etc. All these added some sorts of validation of the public profile of the Ty Unnos system.

In addition, there is some indication that the relevant WG department has looked into the possibility of bringing timber housing into mainstream housing (Civil Servant Interviewee N.2, 2012). As mentioned, following the adoption of EU's Smart Specialisation strategy, nine key sectors have been identified by the WG, with construction among them. Encouragingly, the first public event organised by the then newly established Construction Sector was a public seminar on '*Promoting Timber in Construction*' in 2012, in which the Welsh Minister for Economy, Science and Transport (Edwina Hart) attended and gave a speech. In my subsequent interview with a senior civil servant from the Construction Sector, it appeared that some inter-departmental discussion has been carried out between Ms Hart and the then Minister for Housing and Regeneration, with regard to the possibility of using timber construction for regeneration projects; it was also suggested that some consideration has given to the possibility of using the Ty Unnos for the construction of temporary houses in the flood-affected area in North Wales, and the accommodation units for workers during the construction stage of a proposed new nuclear power station in Anglesey (Civil Servant Interviewee N.2, 2012).

One factor that was repeatedly singled out during the interviews was 'cost'. As introduced, the Ty Unnos system is designed and marketed as being affordable, but it may still not be cost competitive comparing to incumbent construction methods or systems in Wales. EE has been in search of a 'decent' sized order to make the production running with the aim of improving cost-effectiveness (Business Interviewee N.1, 2012); however, before they can produce cost-effectively they may have difficulty in landing such an order, especially as the public sector and housing associations continuously face budget cuts; so, there is a danger of a 'chicken and egg' or a 'Catch 22' situation.

In general, the commercial deployment of the timber engineering systems using Welsh grown timber faces some old prejudices in the marketplace, with respect to the quality of wood (Business Interviewee N.5, 2012), and production cost, etc. They are the ever-present challenges facing the legitimation process, since different actor groups e.g. policy-makers, architects, builders, and contractors need to be persuaded and lobbied on different matters, as to policy priority, demand, and bounded socio-technical rationality. The current *advisory efforts* within the WTC TIS are fragmented, as different actors e.g. WFBP, Coed Cymru and BSW (who has Wales' biggest sawmill) were often acting separately with little co-ordination between them; in this respect, more coordinated effort and increased alliance (e.g. involving architects or builders) may be needed.

6.1.7 Function 7: Development of positive externalities

As there is already a dynamic wood sector, particularly a strong secondary processing sector, operating in Wales, this raises the potential for the emergence of pooled labour market in which more firms or new start-ups may engage in the development of WTC. However, the UK construction sector has seen a severe decline in activities since the onset of the financial crisis, whereas the lack of demand has greatly affected the market uptake of the Ty Unnos Modular™ and other WTC products. To this end, at the moment it is difficult to assess whether it is mostly caused by inherent weaknesses or exogenous factors, in terms of a lack of the emergence of a *pooled labour market*, or *specialised intermediate goods and service providers* in the current WTC TIS.

On the other hand, there are clear signs of *inter-firms and organisations cooperation* in the Ty Unnos partnership, as well as in the R&D process of other WTC products, while the Ty Unnos system is a direct result of knowledge spill-overs between the partners.

6.2 Functions of the BISE TIS in Wales

6.2.1 Function 1: Knowledge development and diffusion

In Wales, solar research at the university level has been carried out since the 1980s, but only in recent years has the overall research capacity been strengthened, resulting from significant research investment by the Welsh and UK governments, and research councils. A new research focus has emerged *i.e.* BISE. An overview on the *type of actors* who have involved in the knowledge development in Wales, the *type of research collaboration*, as well as the sources of *R&D financing* is outlined in Table 6.4. It shows that over £35 millions have been committed to the research into PV and BISE technologies in Wales between 2008 and 2013, whereas most of these research projects involve various industrial and academic partners. Amongst them, SPECIFIC has been given IKC status, and is one of the seven Innovation and Knowledge Centres (IKCs)⁷⁴ across the UK.

Table 6.4: An outline of the major BISE related R&D projects in Wales between 2008-2013

Project Description	Partnership	Sponsor(s)	Grant value
PV Accelerator Centre in 2008, for 3 years	Tata Steel, and Dyesol Ltd.	WG's Smart Cymru programme	£5 m
Low Carbon Research Institute (LCRI) , established in 2008, with PV as one of the research themes	The PV group led by Glyndwr, Bangor and Swansea University	HEFCW (via the WG)	£0.83 m
Sustainable Building Envelope Centreⁱ , established in 2010	Tata Steel, and LCRI	ERDF Tata Steel	£0.5 m £1.5 m
LCBE project: WPI - Sustainable building envelopes	Led by Tata Steel	ERDF Tata Steel	£0.59 m £0.92 m
Solar Photovoltaic Academic Research Consortium Cymru (SPARC Cymru)	Glyndwr, Bangor and Swansea University	ERDF	£4 m
Sustainable Building Envelope Demonstration projectⁱⁱ (SBED)	WSA, and Tata Steel	ERDF	£3 m
SPECIFICⁱⁱⁱ – Sustainable Product Engineering Centre for Innovative Functional Industrial Coatings,	Swansea University, Tata Steel, and 10 other industrial and academic partners	EPSRC / TSB, WG,	£10 m £2 m

⁷⁴ The Innovation and Knowledge Centres (IKCs) are the UK's approach to the commercialisation of emerging technologies of the disruptive nature. Since 2007, seven IKCs have been awarded. More information is available from <http://www.epsrc.ac.uk/innovation/business/opportunities/ikcs/>.

Project Description	Partnership	Sponsor(s)	Grant value
Solar Futures Laboratory , linked to SPECIFIC	Led by Swansea University, involving Bangor University and WSA,	WG's Sêr Cymru programme.	£6 m
COATED² – EPSRC Centre for Doctoral Training in Industrial Functional Coatings, linked to SPECIFIC, funding period between Oct. 2015 and March 2023	Led by Swansea University, involving 11 industrial partners	EPSRC	£2.6 m

More information is available from the website of these research centres or programme:

- i. Sustainable Building Envelope Centre - <http://www.sbec.eu.com>
- ii. Sustainable Building Envelope Demonstration project - <http://sbed.cardiff.ac.uk>
- iii. SPECIFIC, Solar Futures Laboratory and COATED² - <http://www.specific.eu.com>

Industrial actors, Tata Steel in particular, have arisen to play a pivotal role in steering the research direction and agenda of BISE in Wales, which saw the focus of knowledge development (in terms of *type and source of knowledge development*) extending from science based to system integration, and manufacturing processes that enable production scaling-up. A range of BISE related technologies have been or are being exploited under the above projects or programme, which include Transpired Solar Collectors (TSC); diurnal heat storage technology; c-Si panel system; perovskites, CZTS (copper, zinc, tin, sulphur), organic PV and dye sensitized solar cells (DSSC) technologies.

At a smaller scale, Welsh firms such as GB Sol and Pure Wafer have looked into various BISE innovations. For instance, GB Sol has introduced a roof-integrated system using solar panel laminates as the structure of mounting system, which won a Solar Power Portal Award in 2013, while the firm is also capable of developing bespoke glass/glass laminates. Pure Wafer, on the other hand, as a worldwide leader in the provision of wafer reclaim service, is currently looking into solar tile and BIPVT systems, under the WG funded Open Innovation project (Business Interviewee N.10, 2013).

Overall, the researches and innovations carried out by the Welsh universities and firms have very much focused on application-specific knowledge, material processes and manufacturing processes etc. As one interviewee said,

What we don't do is the fundamental research, there are plenty of very good people in the UK

doing that work at the moment, and globally, so we don't compete with them. What we do is we develop the manufacturing processes that enable the scaling of those products...we have the university research portfolio, ... collaborations with Imperial College, Bath, Bristol, Sheffield, Oxford,...we have a model that exists to get that fundamental research right through to the global market..." (Academic Interviewee N.7, 2013)

That being said, c. 20 solar related *patents* have been filed by Welsh universities and firms between 2008 and 2013, based on a simple online search of the UK Intellectual Property Office database in late June 2013, by using key words e.g. solar and PV.

The *research collaboration* has not been confined just between Wales-based firms and universities, when increasingly the collaboration has included firms and universities located outside the Welsh border. Most evidently, the pan-UK consortium set up for SPECIFIC includes Imperial College London, University of Sheffield, Bath University, and University of Bristol (linking in particular with the study of 'PV Technology based on Earth Abundant Marterials (PVTEAM)'), as well as industrial partners such as BASF and NSG Group etc.

Multi-faceted *knowledge exchanging mechanisms*, formal or informal, have been employed for knowledge exchange and dissemination in Wales. For instance, both LCRI and Tata offer a range of CPD courses, while firms such as GB Sol and BayWa r.e. provide regular training sessions to PV installers. The LCRI annual conference has been highly commended by firms and other actors for bringing together a disparate group of people across Wales and the UK into one place once a year, while facilitating opportunities for networking and information exchange. Seminars and exhibition events have been organised under different research projects or programme, whereas more conventional methods, e.g. conferences and scientific journals, continuously play an important role for knowledge diffusion.

Moreover, demonstration projects are seen as an important measure for both knowledge exchanges and marketing. This includes the SBEC building at Tata's Shotton site in North Wales, with both solar thermal (e.g. TSC) and PV technologies designed into its building envelope, while their operations are integrated with a range of enabling building services and associated technologies. Since its inception, SBEC has been visited by a variety of stakeholders (or actors). In addition, eight more demonstration buildings of different types (residential, commercials, industrial, schools, hospitals and care homes etc.) will be

completed across Wales, under the Sustainable Building Envelope Demonstration (SBED) project; all are existing buildings with TSC and solar PV to be incorporated into the building's envelope. The technical performance of these systems will be monitored, while the economic viability and cost effectiveness of the related technologies will be assessed, and the results will be disseminated to a wider industry audience.

6.2.2 Function 2: Entrepreneurial experimentation

As indicated, Tata Steel has emerged as the major industrial player in the development of BISE in Wales. As noted earlier, the companies that preceded Tata Steel were part of the Welsh industrial past. Even though the Welsh steel industry has experienced a series of nationalisations, privatisations and takeovers, its significance to the Welsh economy has remained and it is the single biggest industrial employer in the region. The development involving BISE technologies is mostly managed and operated through its coating line division *i.e.* Tata Steel Colors, which bases at Shotton in North Wales; Tata Colors mainly manufactures pre-finished steel for building envelopes, amongst which is one of the most specified construction products of their types in the world, with the industry's leading product performance guarantees of 30 and 40 years, depending on whether it's a wall or a roof system; 50% of its output is exported to the European market (Business Interviewee N.9, 2013).

About eight years ago, Tata Colors set out searching for the next step change innovations within the context of sustainability and climate change. The process involved discussions, along the supply chain, with architects, designers, contractors, end users, and also professional bodies such as the Construction Products Association and Renewable Energy Associations. The company eventually narrowed down to five ideas, which include the TSC and PV. The latter also saw the beginning of Tata's collaboration with the Australian firm Dyesol, which specialises at dye-sensitised solar products, and subsequently set up its UK operation in North Wales (Business Interviewee N.9 and N.12, 2013).

Since then, Tata has developed TSC under its Colorcoat® ranges, and launched it onto market as 'Colorcoat Renew SC®: *integrated solar air heating solution*' in 2012. A number of the buildings have been installed with this system, including the SBED building, the Deeside Leisure Centre, both in North Wales, and Jaguar Land Rover Deck 92 in the West Midlands. The other new product that Tata has involved is the SOLON SOLbond Integra PV

steel rooftop solution, resulting from a partnership with the SOLON Group, which was launched onto market in 2011.

Nevertheless, Tata’s main innovation focus has been to develop functionally coated steel products and manufacture them on an industrial scale. It is a process that began with the partnership between Tata Steel and Dyesol in 2008, followed by a collaboration with the Welsh School of Architecture and LCRI in 2010 (with focus on how varied solar and related systems might be integrated with building design and construction, and how these systems perform in real situations); that eventually led to the setup of SPECIFIC in 2011, involving a Pan UK academic consortium and industrial partners. Figure 6.4 demonstrates how this process was put together by Tata with an ambition to become either a market leader in the field, or at least a significant follower in 10 years (Business Interviewee N.9, 2013).

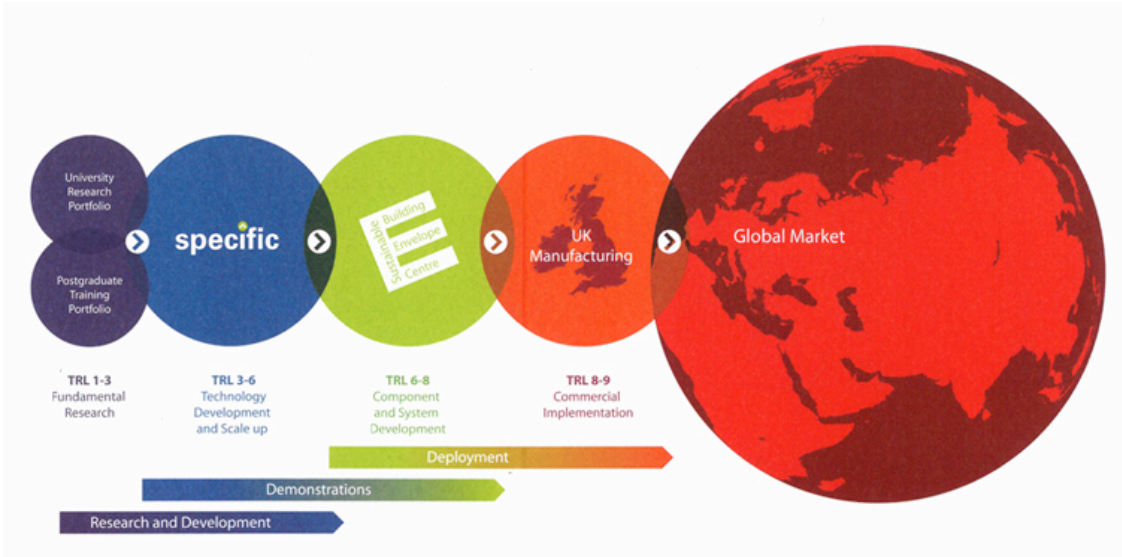


Figure 6.3: An innovation pipeline for functionally coated building components: from fundamental research to global market⁷⁵ (Source: SPECIFIC)

At a smaller scale, GB Sol and Pure Wafer have also been engaging in BISE innovations. Established in 1980, GB Sol is a spin-out from Cardiff University, currently based at Taff Well near Cardiff. It began to develop roof-integrated systems in 1993, and one of its products won a Solar Power Portal Award in 2013. The firm has also been competitive in various niche markets and is capable of developing bespoke glass/glass laminates, which

⁷⁵ The green circle in the middle represents the Sustainable Building Envelope Centre (SBEC).

include the UK's first range of terracotta / red PV modules, and laminates for solar tile products that are exported to Europe. GB Sol develops most of these products in-house, sometime with technical input from architects (Business Interviewee N.11, 2013).

Based in Swansea, Pure Wafer, on the other hand, is a worldwide leader in the provision of wafer reclaim services. It diversified into solar PV business c. 2009, and has previously manufactured solar panels using reclaimed monocrystalline silicone; however, due to cheap imports from the Far East, the production line was subsequently suspended. While Pure Wafer's current solar business focuses on providing consultancy for the development of large solar farms in the UK, the company has looked into the development of niche products with the intention to move back as a solar manufacturer. The technologies that the firm looks into are solar tile, and BIPVT systems, both of which are studied as part of the WG funded 'Open Innovation Initiative' project (Business Interviewee N.10, 2013).

In addition, companies such as Emerson and IQE have both shown some credentials in the field of BISE and related products or systems. With its head office based at Newtown in mid-Wales, Emerson is a leading manufacturer in control techniques, and began to exploit the inverter market for PV systems c. 2008 after spotting the opportunity in the German market. It has since developed and manufactured utility scale PV inverter systems for customers across the world. Although Emerson has set its current priority on the utility scale, it does not rule out the possibility to tap into the rooftop and BIPV markets in future. "*It is just a question of priority really*", as a member of the firm commented (Business Interviewee N.16, 2013).

The other interesting case is IQE. Based at St Mellon, Cardiff, IQE is a global leading epitaxial wafer supplier (Edison, 2014). These wafers can be designed into devices used in wireless, optical networking, Concentrating Photovoltaic (CPV) and lighting etc. The company became involved in the research of CPV technologies after its acquisition of a 9% stake in the American company Solar Junction in 2012 that currently holds the world record for solar cell efficiency (Business Interviewee N.15, 2013).

In all, similarly to the WTC TIS, most of the *new entrants* in the BISE TIS in Wales are existing firms who saw opportunities in solar energy and decided to diversify into the sector as part of a long-term growth strategy. Apart from GB Sol, most of these firms are

large multi-national companies, and are strategically important for the Welsh economy or the local economy, to say the least, which gives them considerable lobbying power over the Welsh Government. As a matter of fact, Tata, Pure Wafer and IQE have recently been chosen by the WG as anchor companies under its 'Open Innovation Development Award'⁷⁶, which aims at promoting collaborations between anchor companies with other Welsh firms (especially SMEs), exploring best practice approaches, and nurturing innovations.

To date, *the number of firms entering the BISE TIS in Wales is limited, while there seems to lack of e.g. recent academic spin-offs.* On the other hand, the involvement of these large firms may prove to be an advantage for the development of BISE in Wales, especially at the current trading environment, for they can better withstand market pressures caused by e.g. price dumping and overproduction that have taken place in the global PV market since 2011 (Heinstein et al., 2013), while exploiting the opportunity for manufacturing scaling-up.

6.2.3 Function 3: Guidance of the search

At present, three intertwined elements are seen to hold the key to the market deployment of solar technologies in general: (a) *government policies* e.g. Fit-in-Tariffs (FITs); (b) *advances in technologies*, in terms of solar cell efficiency and materials development, etc., and (c) *the level of cost-parity* to fossil fuel options. The interplaying of these elements can decide if more investment will be brought into the technology and sector. As some interviewees pointed out,

So I think legislation could act as an incentive to kick start markets but fundamentally the economics have got to work because those incentives are only short term.... So there are certain factors which encourage uptake, but economics has got to be a primary driver and ease of integration into the building, on a retrofit basis as well, that's what this centre (SBEC) was set up to do. (Business Interviewee N.9, 2013)

There's been some pretty significant investment so far, but I think we're still in this sort of hiatus waiting for policy moves to make it more attractive. But it's not just policy moves, it is technology as well. So I think if ... CPV has the best chance of being able to demonstrate

⁷⁶ The Open Innovation Development Award is a two-year initiative, and seven anchor businesses are selected, information available from <http://wales.gov.uk/newsroom/businessandconomy/2013/7614975/?lang=en>.

huge increases in efficiency and those efficiency increases lead to lower cost per watt, which have then a knock on effect on the adoption. ... from a cost point of view it's getting close to being competitive, but it does need some policy decisions in there to say that this is the route we're taking. (Business Interviewee N.15, 2013)

It is widely agreed that, to date, the rapid growth of the global PV market is policy-driven, mostly by feed-in policies *i.e.* Feed-in Tariffs or Feed-in Premiums (FIPs), which have been enacted in around 70 countries by 2013 (REN21, 2014). Meanwhile, the experience of BIPV in Germany, France and other countries also indicated the decisive influence of state promotional programme on the expansion and acceptance of BIPV. For instance, the 100,000-roof programme in 1999 set out the market deployment of BIPV in Germany, which was further secured by FITs, interest free loans, and the legal requirements set by the renewable energy source Act (*Erneuerbare Energien Gesetz, EEG*); all these have driven Germany into the largest BIPV market in the world (Schuetze, 2013), with a high level of expertise among BIPV installers, designers, architects and manufacturers, accompanied by a high-level of awareness among German end users.

In the UK, there are signs of catching up, in policy terms. The introduction of FITs in 2010 has boosted the UK PV sector and led to a relatively unexpected increase in terms of the Total Installed Capacity. For instance, 2013 saw the UK almost doubling its annual installed capacity while surpassing Italy as the second largest European market for PV installation (EPIA, 2014). This unexpectedly high level of uptake of solar technologies has seen the FIT rate (for electricity generation) for PV dropping from, *e.g.* £41.3p per kWh in 2010 to £14.38p at the end of 2014, for the solar PV project with Total Installed Capacity of 4kW or less (Mendonça, 2011; Ofgem, 2015b). Meanwhile, the UK government has also shown great interests in on-site renewable electricity generation from early on, and considered it to be most efficient technically (Mendonça, 2011). For instance, unlike the German-style FITs, the UK FITs scheme separates the payment to electricity generation from that to electricity export, with generation receiving a far higher return than export, *e.g.* at £41.3p per kWh versus £3p per kWh when the scheme was first introduced in 2010. This prioritisation of on-site generation is also reflected in the 2014 UK Solar PV Strategy, which promotes to use the existing built environment rather than previously undeveloped land for PV deployment, with key market segments identified as: small-scale rooftop installations on housing; mid-size commercial and industrial rooftops; public buildings, and

BIPV etc. (DECC, 2014a). Such policy stand provides certain level of the political assurance for the uptake of BIPV in the UK, and the development of BISE technologies in Wales.

In terms of renewable heating, the UK government introduced the Non-Domestic Renewable Heat Incentive (RHI) and Domestic Renewable Heat Incentive in 2011 and early 2014 respectively. Both operate in a similar manner to the FIT, with tariffs being paid to owners who install renewable heat generation systems. Among the renewable heat technologies that are eligible under RHI, TSC is excluded in that it is not counted as a renewable technology under the current EU *Renewable Energy Directive (2009/28/EC)*⁷⁷ (DECC, 2011); amongst solar technologies, only flat plate and evacuated tube solar thermal panels are currently qualified for both the Domestic and Non-Domestic RHI.

While FITs and RHIs provide immediate financial incentives, the changes in building codes and regulations have also increasingly promoted the inclusion of BIPV in building projects. As one architect indicated, extra BREEAM points are awarded for the installation of PV in buildings (Architect Interviewee N.3, 2013). As building codes and regulations are being further tightened in Europe, e.g. the recast of the Energy Performance of Building Directive in 2010. This suggests that in the long run the market deployment of BISE will highly likely converge with the development of the market in low energy, zero carbon buildings.

At the *industrial level*, since 2011 the PV sector has been experiencing a period of volatile change and a painful consolidation phase, with many companies being pushed out of business, leading to a substantial reshuffling of the major players (REN21, 2014). To counteract this, the sector continued to innovate, diversify products and service, and cut costs, whereas solar cell efficiencies continued to increase with more records announced in 2013 and radical improvements in materials, e.g. perovskite, offered the potential for high-performance yet inexpensive solar cells. Meanwhile, as the PV module prices dropped, partly due to oversupply on the market, in countries with high levels of installed capacity, PV began to affect the electricity markets, technically, quantitatively, and economically as well (IEA, 2013). Collectively, it is believed that, after this painful cleansing of the market, a massive counter trend will follow with the sector carried forward by more advanced technologies (Heinstein et al., 2013). This view was agreed by a number of the

⁷⁷ Tata has been lobbying both the European Commission and the UK government, to get TSC recognized as an active renewable technology, but with little success so far (Business Interviewee N.9, 2013).

interviewees, with one suggesting that this rapidly moving landscape reminds him of all the signs of the emerging of a new industry (Business Interviewee N.15, 2013), while others believe that the future for PV is “*not what has happened to date, producing panel to clamp on to buildings, but all about the real integration*” (Business Interviewee N.12, 2013).

‘Turning building into power station’ has become a *vision* of key industrial and academic actors of BISE TIS in Wales. For SPECIFIC, this vision is translated into finding solutions to functionalise building envelopes that generate, store and release energy, through the deployment of smart coating onto steel and glass substrates as well as advanced energy storage technologies. It is expected that once production lines are scaled up the cost of such products will be able to compete with conventional materials (Academic Interviewee N.7, 2013).

6.2.4 Function 4: Market formation

Despite the massive growth in the global solar PV market, the market deployment of BIPV is sluggish, with the segment remaining as a mere niche presence (Heinstein et al., 2013). However, a recent market research has projected a compound annual growth rate of 18.7% in the BIPV market from 2013 onwards; in terms of *market size*, the BIPV segment is projected to reach a global installed capacity of 1.15 GW by 2019 (Transparency Market Research, 2013, cited in Clover, 2014). The same report also suggests that the *key product segments* will include rooftop, BIPV window installations, and curtain walls (as the fastest-growing product segment), when, technologically, the current market domination of c-Si technology will be challenged by thin film, as well as organic photovoltaic (OPV) and DSSC technologies; in geographical terms, it is believed that Europe will remain the market leader, due to the ever-more stringent legislative requirements in its building sector (ibid).

With respect to building integrated solar thermal (BIST) systems, there is some indication that a *potential market* for Transpired Solar Collectors may emerge in the UK, especially in the non-domestic building sector. Since 2010, TSCs have been included in the Simplified Building Energy Model (SBEM), as one of the renewable energy technology options. The SBEM is the official tool for calculating the non-domestic Building CO₂ Emissions Rate (BER), and can determine if a building design is compliant with the Part L of Building Regulations (Hall, 2010). Moreover, TSCs have recently been added as one of the 45 measures that is eligible for the Green Deal Finance; this means that TSCs can now be

installed as one of the energy saving measure in domestic or non-domestic properties (e.g. business premises or community buildings) in Great Britain, while the upfront cost of installation is paid by a loan (Richards, 2013). The inclusion in both the SBEM and Green Deal scheme are seen as important steps for TSC manufacturers and related sectors to make leeway into the heating market in the UK for large commercial and industrial projects, in terms of both new builds and retrofits, as well as smaller-scale renewable energy installations. Nevertheless, the technology inevitably faces fierce competition from other renewable technologies e.g. solar PV and heat pumps.

As indicated, up until now the solar energy market has been very much policy driven, and seems to likely stay this way in foreseeable future. This adds some challenges for the BISE sector in terms of *marketing* their products or services. As one interviewee pointed out, “*it’s difficult to market in a market which is driven by government policies and their changes*” (Business Interviewee N.11, 2013). Moreover, the nature of BISE technologies means that firms no longer just sell physical building components or materials, but “*energy generation capacity*” (Business Interviewee N.9, 2013), and this leads to a whole different proposition and marketing profile. In a way, the marketing challenge facing the BISE producers or suppliers can be encapsulated as follows; “*The solar industry presents marketing professionals with unique challenges: poorly-educated consumers, misleading mainstream media, anti-renewable campaigners, policy shifts and anti-dumping troubles have all contributed to an ever-changing outlook.* (Bennett, 2013)”

With respect to *marketing strategy*, sustainable communication is generally seen to hold the key to the market acceptance of BISE technologies (Heinstein et al., 2013). To this end, different communication measures have been used by the actors of the Welsh BISE TIS (which often overlaps with the Function of *Knowledge Development and Diffusion*, and *Resource Mobilization*). First, free of charge training has been provided to installers and others by firms such as GB Sol, Sharp, BayWa r.e. and Emerson, as a combined educational and marketing tool. GB Sol’s training particularly addresses necessary knowledge and hand-on experiences on how to install BIPV systems. Meanwhile, at their premises, Tata and SPECIFIC have exhibition areas dedicated to showcasing latest technologies, products or systems that they are working on or produce, which again serve both marketing and education purposes. As one interviewee explained (Academic Interviewee N.7, 2013),

Small scale demonstrators are here, so we bring people in here to try and encourage them to

give us ideas about what they want....So although I'm effectively a laboratory scientist from day to day, more often than not I'm brought in here to discuss our developments with people who are a whole range of the supply chain and in the market as well, people who own buildings, who build them, who are architects, who are large corporations, who have multiple portfolio of buildings... they will interact with us and will talk about the developments which are on the medium to long term horizon and ... on the short term horizon, and they will give us feedback on where they think those products could be.... And that's an interaction which has proved to be very fruitful, we've learnt a lot from that.

Demonstration building projects again are seen as an important marketing tool for BISE technologies, as they allow firms to show how technologies can be deployed in different environmental settings, individually, or in combination, and how they perform in use, which provides concrete links between what has been tested in the laboratory environment and how it is performing in the real world (Business Interviewee N.9, 2013). More critically, these projects can show users how concrete paybacks, in term of power generation and saving, can be made. They can also be taken as case studies and used to encourage an accelerated uptake of the technologies into the market (Business Interviewee N.9 and N.12, 2013).

As mentioned, there are already a number of demonstration buildings in Wales and elsewhere in the UK, including those soon being completed under the SBED project. However, firms have expressed that more could have been built, and some have argued that Wales can become a 'test bed', or 'lead market' as called by Beise (2004), for the BISE technologies (Business Interviewee N.9, 2013; Academic Interviewee N.6, 2013). This proposition has certain inherent logics resonating with empirical experiences elsewhere, which suggested that BIPV developments in the building sector are often localised, and serve domestic markets in a lot of cases. This is because the full integration of a PV system often demands a complex and tight interlocking of all stakeholders along the supply chain (Heinstein et al., 2013). As noted, Wales is already a hotspot for solar energy, in terms of the domestic PV installation rate that is above the UK average, which shows great public support to the technology. So, together with the strengthening research capability, there is no reason why Wales cannot become one of the leading markets for BISE technologies in Europe, although this will require political commitments from the Welsh and local governments (linking to Function 6: legitimation).

While the UK does not have a *specific tariff* for the market uptake of BISE technologies, as countries e.g. France, South Korea and Malaysia do (IEA, 2013), the Solar PV Strategy has begun to create a favourable policy environment. It is suggested that some sort of financial measures are under consideration in order to help the market penetration of these technologies (DECC, 2014a), although it may not be introduced before the coming General Election in 2015. In the meantime, the deployment of BISE continuously relies on the existing incentives, e.g. FIT, RHIs and Green Deal Finance.

6.2.5 Function 5: Resource mobilisation

As to *ability to retain and attract desirable talents*, the creation of the SPECIFIC Innovation and Knowledge Centre in Swansea has critically raised Wales' research capability in the field of BISE, and enabled SPECIFIC to recruit and build up teams of engineers and scientists; after all, "*science is about people; it's about capacity; you need lots of people, not just a few; it's about not being hard academics and having very straight minds; it's about being quite lateral*" (Business Interviewee N.12, 2013). Whether or not the last trait can be met, only time can tell. In terms of the numbers, SPECIFIC has recently secured further funding from the UK government to set up a new Centre for Doctoral Training in the field of functional coating (COATED), with 40 research doctorate posts to be created between 2015 and 2018, which does not include about 30 doctoral students already working at SPECIFIC. Therefore, a talent pool (linking to Function 7: development of positive externality) is emerging in Wales.

Meanwhile, the WG has also been actively involved in attracting outstanding researchers to Wales, under its *Sêr Cymru* program, with the aim of enhancing and building upon the research capability in Wales. One of the results is the appointment of Professor James Durrant, from the Imperial College London, to lead the *Sêr Cymru* Solar Initiatives based at SPECIFIC, with the research focusing on the technological development of printed PV devices.

At the present industrial level, several companies nonetheless expressed concern over the difficulty of recruiting graduates with rounded skills for which the companies are looking, in terms of deeper understanding of the respective fields while mixing these with good business (e.g. sales and marketing) and communication skills (Business Interviewee N.15, N.16 and N.11, 2013). Such concerns can be partly seen as whether universities, Welsh

ones in particular, are able to provide courses or programme relevant to the current needs of Welsh industries. For instance, Emerson has student sponsorship programme and a continuing education programme on power electronics with three British universities, but none of them in Wales (Business Interviewee N.16, 2013).

On the other hand, in terms of workforce on factory floors, Wales' past as a primary location for Japanese semiconductor and electronics branch plants has given the region a skilled and flexible labour force and middle-rank production managers and technicians who can go straight into assembly lines manufacturing solar modules (Business Interviewee N.11 and N.13, 2013). This certainly enhances the Welsh potential as an important manufacturing destination for solar cells in Europe, despite the recent setback caused by Sharp's decision to close down the solar panel production line in its Wrexham plant.

With respect to the *availability of specialised educational programme*, many Welsh firms offer training programme to their downstream clients on fairly frequent basis, as mentioned. At a more professional level, a number of CPD courses with regard to PV have been set up by the LCRI through the Welsh Energy Sector Training (WEST) project. In 2013, Tata also began to provide a range of RIBA approved CPD courses at its Shotton site. In association with SPECIFIC, the College of Engineering in Swansea University is running several educational programme, targeting different levels of learning: one of them is the outreach and engagement project 'Materials: Live!'⁷⁸ which is devised to deliver CPD activities, while also engaging A/AS level students and encouraging young people to pursue STEM (Science, technology, engineering and mathematics) related careers; the other is the METaL project⁷⁹, which is a work based training programme about metallurgical and materials knowledge, and more than 10 individual courses have been developed to date. Both the WEST and METaL projects are financed by the European Structural Fund, with certain conditions applied to ensure people who are working and living at the so-called convergence area (West Wales and Valleys) can benefit the most; but, both projects are initially funded for a three-year period (e.g. the funding for WEST will end in 2015), so it is unclear if these courses will continue once the funding periods expire.

⁷⁸ The program information is available from the Materials Academy website <http://www.materials-academy.co.uk>.

⁷⁹ The website for METaL project: <http://www.project-metal.co.uk>.

At the higher educational level, both Swansea and Glyndŵr universities offer either under- or post-graduate level degree programmes. In partnership with the British Photovoltaic Association (BPVA), Glyndŵr recently started a master's degree on PV, which is designed to shed light on the behaviour of photovoltaic materials, the issues involved in system design and processes used in the manufacture of photovoltaic technologies. At Swansea, the Materials Academy was created to provide training from the factory floor throughout to postgraduate level training; other than the aforementioned 'Materials: Live' and METaL projects, the Academy offers a number of undergraduate degrees on materials science and engineering; at the postgraduate level, since 2009 a one-year research masters program MRes has been in running that combines taught courses with a 10-month research project defined by industry, that is supplemented by the doctoral program EngD (related to COATED) that involves a taught component and a four-year research project defined by industry.

In term of *raw materials*, while there are varied concerns over the possible 'shortage' of rare earth minerals for developing clean energy technologies including solar PV, the research on the next generation PV has moved away from the use of rare metals to produce PV panels. One of the criteria employed at SPECIFIC is the use of low cost, earth-abundant materials that allows manufacturing at scale, which is reflected by SPECIFIC's involvement in the *Photovoltaic Technology based on Earth Abundant Materials (PVTEAM)* project led by the University of Bristol (DECC, 2014a). On the other hand, the Welsh firm Pure Wafer is one of the market leaders in the wafer reclaim technology that allow the re-use of improved silicon test wafers. Therefore, it is sensible to assume that, in the long run, the development of the BISE TIS in Wales is unlikely impeded by the shortage of raw materials.

As shown in Table 6.3, the Welsh firms and research institutes have demonstrated *ability to attain government grant* for R&D. Varied firms also mentioned that they have been at the receiving end of different government loans or subsidies at various stages, for research (through e.g. A4B, open innovation, Smart Cymru), or business expansion. On the other hand, across the UK, a number of *financial programme or initiatives*, of both public and private natures, have been made available for the solar industry, including crowd funding, lease finance, and the Energy Entrepreneurs Fund (DECC, 2014a).

6.2.6 Function 6: Legitimation

In terms of *meeting the expectation and value base of society*, solar has increasingly become the most recognised form of renewable energy generation among the British public, which is backed by a number of public surveys. DECC's public attitudes tracking survey⁸⁰ has constantly placed solar as the individual renewable energy source that the British public supports most, with an 80% of supporting rate (DECC, 2014b). This sentiment also emerged in an earlier UKERC survey on public values / attitudes and acceptability of transforming the UK energy system, in which the UK public views on solar energy include that (Parkhill et al., 2013):

- Solar energy is highly favourable and positively associated with clean energy futures.
- There is a recognition of large scale deployment in the form of 'farms', yet the more pervasive conception is of solar PV at the household level
- 66% of respondents agree that promoting renewable energy sources, such as solar and wind power, is a better way of tackling climate change than nuclear power.
- In terms of different forms of microgeneration technologies, solar energy and wood burners etc. were generally viewed favourably, in part because they provide a way to supply and control energy in the home.

With respect to *compliance with existing regulations or legislation*, the inclusion of solar PV in the UK renewable energy mix and the publishing of the UK Solar PV strategy have been key steps for the legitimation of BISE in the UK, as for years solar has been seen as a second tier renewable technology, largely dismissed by most politicians in the past as being too costly (Colville, 2014). On the other hand, as indicated, the future market deployment of BISE technologies will be driven by the need to meet building codes and regulations, as much as by the overall energy policy. This may shift the focus of legitimation from the UK government level to the regional level, since both planning and Building Regulations are part of the WG's remit.

As discussed previously, despite the changing scenes in the global market as well as the changes in the UK policy, WG's position on solar energy has not changed, which remains

⁸⁰ The Department of Energy & Climate Change set up a tracking survey in March 2012, in order to understand and monitor public attitude to DECC's main business priorities, and the survey results are published on a quarterly basis, and available from <https://www.gov.uk/government/collections/public-attitudes-tracking-survey>.

as part of microgeneration solutions (Welsh Government, 2012). This thus raises the question whether it is time for WG to revisit its energy policy to give solar energy a more prioritised status, seeing that considerable amounts of government funding have been invested in developing BISE technologies. There is also a need to properly assess the role of BISE in helping to develop the Welsh economy (in association with Wales' innovation potentials in the field), as well as its role in helping Wales to deliver its carbon reduction target. More importantly, the WG can do so without more devolved power from the Westminster. As a start, for instance, the WG could remove the planning restriction for the installation of PV on non-domestic buildings, which is not required in England.

On a positive note, as noted, most industrial actors of BISE TIS in Wales are major players in the Welsh economy, or local economy. Meanwhile, there is also the Welsh Opto-electronics Forum (WOF) PV Group, based at St Asaph, which has previously published a PV Solar Energy Road Map for Wales, and was active in advising the WG on solar energy policy. Most of these firms and organisations including LCRI are linked to or know each other, one way or another. So it will be interesting to see if these firms and organisations will put their weight together, to form an efficient *advisory coalition*, to lobby WG's position on solar energy and BISE in Wales.

6.2.7 Function 7: Development of positive externalities

As indicated, Wales' past experience with the steel industry, and the semiconductor and electronics manufacturing, have left a pool of skilled and flexible workers who, including the middle-rank production managers and technicians, could be important for the future manufacturing scale up of BISE products. Moreover, the creation of the SPECIFIC and COATED programmes will foster a legion of highly qualified specialists in the field of functional coating. In this sense, it is reasonable to assume that a *pooled labour market* of varied levels has been or is emerging in the BISE TIS in Wales.

In the past few years, the fast development of solar energy market in Wales has seen *the emergence of some specialised intermediate service providers*. For instance, BayWa r.e Solar System Ltd., is specialised as a wholesale supplier to solar PV installers across the market for domestic, commercial and public sector premises, while providing comprehensive technical support to installers; the Solar Design Co. provides simulation software and survey tools for PV, solar thermal and heat pump design etc. While no such specialized

intermediate goods and service providers seem to have emerged yet in relation to the BISE in Wales, there is no reason to assume that they won't emerge once a domestic market for BISE is created. This is because, according to an EPIA study, BISE often creates jobs along the value chain, with the estimation that every MWp (megawatt peak) installed likely creates between 12 to 20 associated indirect jobs in e.g. raw materials suppliers, production equipment and electrical devices, depending on the technology (EPIA, 2012b).

In terms of *inter-firm (or organisation) cooperation*, it is evident that the BISE TIS operates increasingly in an 'open innovation' system, with collaborations emerging not only between Welsh firms and Welsh research institutions, but also between Welsh organisations and non-Welsh universities and firms, especially in the case of SPECIFIC. In addition, Tata, Pure Wafer and IQE are chosen as anchor firms by the WG to lead the 'Open Innovation Initiative', tasked with fostering cooperation with locally based SMEs and nurturing innovations. Thus, it can be expected that further information sharing and knowledge 'spillovers' will likely emerge in the BISE TIS in Wales.

6.3 Concluding remarks

In the previous sections, I have respectively examined the extent to which the functions of the WTC and BISE TIS in Wales have been fulfilled. Based on these functional analyses, I next discuss if the two TISs have reached the 'formative phase' respectively, while making certain assumption on whether they will move onto the phase of 'market growth'; or, in other words, whether they likely enter a 'virtuous' or 'vicious' cycle.

As reviewed in Section 2.3, Chapter 2, two different interpretations have emerged in the IS literature, with regard to what constitutes the formative phase of a TIS. Bergek et al. (2008a), on the one hand, propose the use of indicators; so a TIS reaching the formative phase usually demonstrates the formation of a rudimentary structure, characterised by the entry of some firms and other organisations, the beginning of an institutional alignment, and the formation of network. On the other hand, Hekkert et al. (2007) and Suurs et al. (2010) postulate the concept of 'motors of innovation', and suggest that not all functions would perform sufficiently during the build-up of a TIS, whereas some functions are more likely to induce others into motions and subsequently trigger a virtuous cycle. Accordingly three such functions or 'motors of innovation' are proposed, *i.e.* the function of *Entrepreneurial experiments*, or *Market formation*, or *Guidance of the search*. As follows, I

discuss whether the WTC and BISE TIS have reached the formative phase respectively from both perspectives. In the meantime, I will identify the relevant actors and map their interactions that have emerged in the two systems, and thus help to decide whether they have reached the formative phases also from an 'actors-networks interaction' perspective.

I generally consider that both WTC and BISE TISs have reached the formative phase, but to different extents. With respect to the WTC TIS, the function analysis shows that local networks and partnerships, formal or informal, have been formed in Wales, in the form of e.g. the Ty Unnos partnership, and WFBP's member network; when comparing the actual actors that have emerged in the WTC TIS with '*the perceived network map of interactions between actors in a well-functioning WTC TIS*' (Figure 5.2), it shows that, despite their limited number, a range of key actors, e.g. architects, researchers, firms, building engineers, local councils, have been observed to be actively involved in the development of the WTC TIS, which is highlighted in Figure 6.4; nonetheless, it needs to be pointed out that certain 'Open' element has emerged in the system, with both Wales and non-Wales based firms and organisations having involved in the system.

Meanwhile, the institutional alignment has taken place in terms of meeting the expectation of sustainability, and the regulatory requirements of low carbon and low energy buildings, whereas the public acceptance of timber construction has been growing steadily in Wales, the UK, and across the world. In addition, a number of innovative products have been developed, and are market-ready, e.g. the Ty Unnos Modular™, the Welsh Brettstapel, and the New Welsh House, which have been the result of knowledge spill-overs due to inter- firm and organisation collaborations.

On the other hand, at present none of the proposed motors of innovation seems to perform strongly enough to induce a virtuous cycle to propel the market diffusion of WTC products. The function analysis has suggested that the lack of demand in the UK housing market was the bottleneck for the slow market deployment of the Ty Unnos and other WTC products; in the meantime, without a 'decent' sized order has also prevented firms (e.g. Elements Europe) from optimising the production process, reducing cost, and making the new products (systems) more cost competitively. When this situation may be interpreted as being largely caused by exogenous factors (e.g. the economic downturn caused by the Financial Crisis), rather than inherent weakness, regional governments are

not powerless victims of circumstance, and the Welsh Government should show that they are capable of adjusting to the external changes while fully taking advantage of the policy power that they already have to create a favourable business environment for the local firms. For instance, an obvious policy option is for WG to use policy measures to create demand for the WTC products, which will likely help to induce both the function of *Market Formation*, and *Guidance of the Search*; such measures may include the introduction of more specific conditions into the procurement standard, or raise the regulatory requirements sooner rather than later, etc. I shall discuss it in the next Chapter.

With regard to the BISE TIS in Wales, similarly the function analysis reveals that networks have been formulated in Wales, once comparing with ‘*the perceived network map of interactions between actors in a well-functioning BISE TIS*’ (Figure 5.5); they include the pan-UK consortium set up for SPECIFIC, the (formal or informal) networks formed through the projects and events organised by the LCRI partners (e.g. SPARC Cymru, the LCRI annual conference), the training or CPD programs offered by e.g. GB SOL and Tata, and the Open Innovation projects funded by the WG. More obviously, the analysis shows that the network reach has gone beyond the Welsh border, linking with actors based in the rest of the UK, as well as of international nature. Different types of actors have been engaged in the system, as highlighted in Figure 6.5.

Institutional alignment has also been taking place, in terms of e.g. contributing to meeting the targets of renewable energy generation and GHG emissions reduction, and the regulatory requirements of low carbon and low energy buildings, the high level of public support for solar energy. Most importantly, what has set the BISE TIS in Wales apart from the WTC TIS is the role of *Entrepreneurial Experimentation*, in which the firms entering the TIS have been able to mobilise necessary resources, lobby for government grants, and practically drive the agenda and direction of the search.

It is evident that *Entrepreneurial Experimentation* has become the ‘motor of innovation’ for the BISE TIS in Wales, although there is a downside to the basis of this entrepreneurial motor. First, the current entrepreneurial experimentation is still limited to a very small group of actors, with Tata dominating the scene. Meanwhile, there is considerable technological uncertainty, as the success of the BISE TIS in Wales is particularly associated to whether SPECIFIC is able to deliver its objectives. Up until now, the technologies

SPECIFIC are focusing on are either at the early stage of R&D, or their performances e.g. OPV and DSSC are still unstable and do not yet meet with high standard building requirements (Heinstein, et al., 2013). This thus requires more investment in *Knowledge development and diffusion*, more *Guidance of search*, and more proactive *Market formation*. In Chapter 7, I will discuss in more details on how inducement mechanism may be added to alter or improve the relevant functional patterns.

To summarise, in Chapters 5 and 6, I have looked into the development of two selected emerging TISs in Wales, i.e. 'Welsh grown timber for construction' (WTC) and 'building integrated solar energy systems' (BISE) in Wales, and examined how the functions of the two emerging technological systems have been fulfilled, to date. While I have argued that both systems have reached the formative stage, their potentials to reach the phase of market growth are varying, as discussed above. This subsequently addressed Research Question 2, as follows:

Q2: To what extent have the functions of the WTC and BISE TIS been fulfilled? Based on the results of the function analyses, what conclusion can be drawn with regard to the status of the two TISs?

In the next and final chapter of this PhD thesis, I will further explore the relevant functional patterns by comparing the two systems. It is expected that the similarities and differences arisen would help to better generalise the relevant innovation capability in Wales, and subsequently offer a bottom-up perspective on possible policy recommendation for the regional governance in Wales.

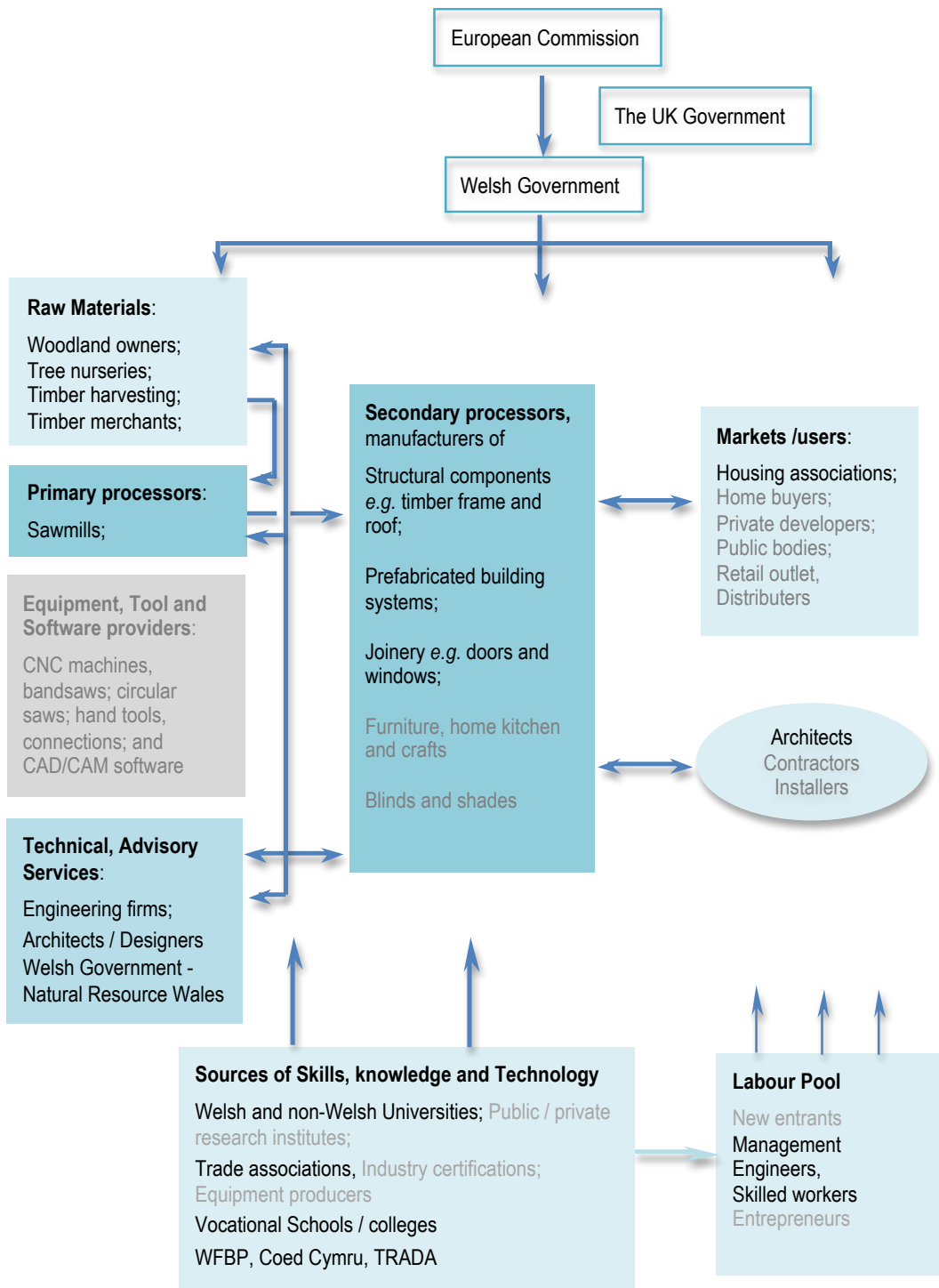


Figure 6.4: The formative phase of the network map of interactions between actors in the WTC TIS

[The actors in grey colour indicate that they have not emerged yet; the darker the blue colour of the box (or the links), the better those actor groups (or links) have performed to date.]

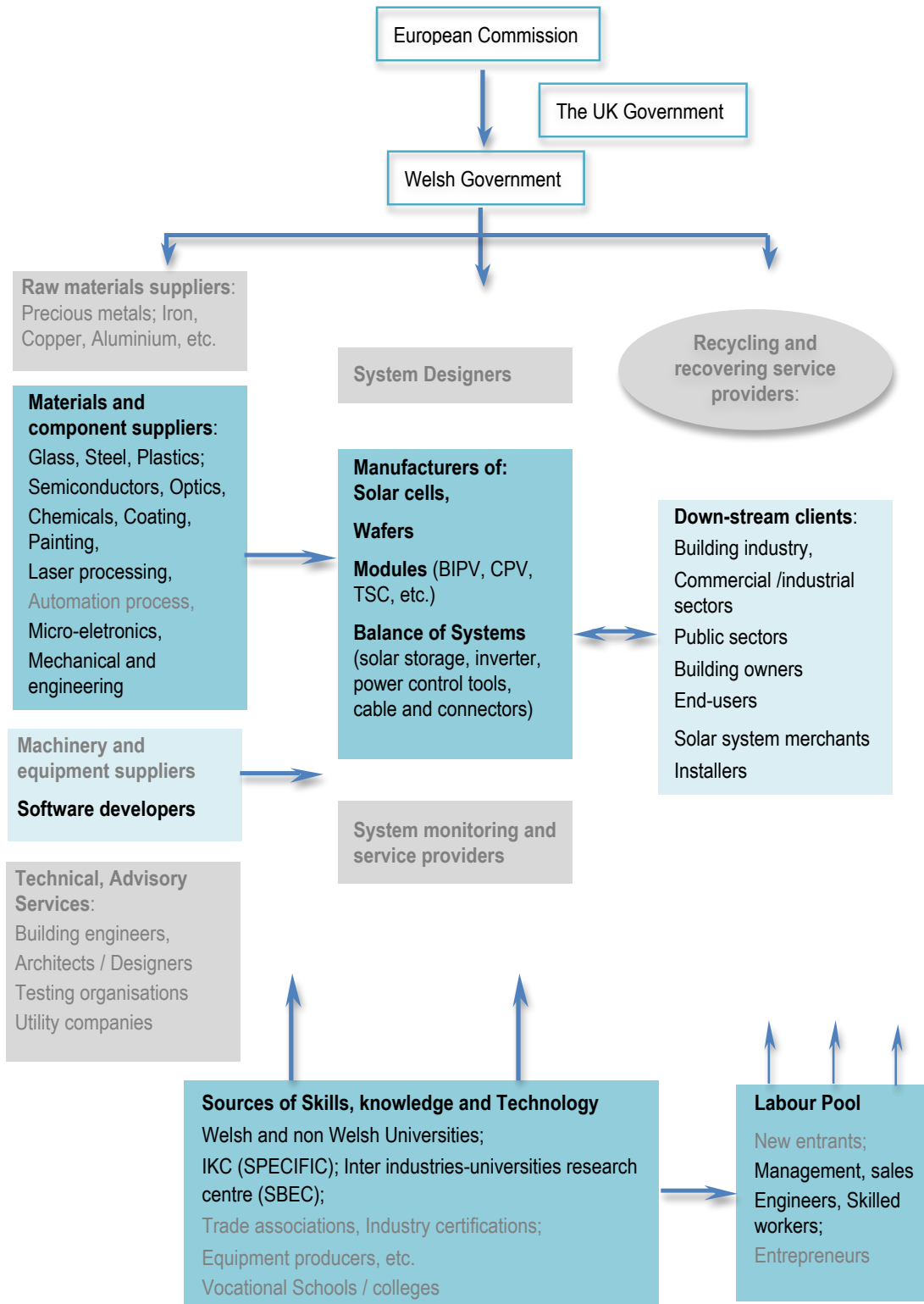


Figure 6.5: The formative phase of the network map of interactions between actors in the BISE TIS in Wales

[The actors in grey colour indicate that they have not emerged yet; the darker the blue colour of the box (or the links), the better those actor groups (or links) have performed to date.]

Chapter 7. Discussion and Conclusion

“I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail.” (Maslow, 1966: 15)

In the previous chapters, I have focused on addressing the first half of the research goal of this PhD study, *i.e.* developing theoretically informed and empirically grounded insights into the development of low carbon building technologies in Wales through examining how the functions of the innovation systems of two selected emerging technologies *i.e.* ‘Welsh grown timber for construction’ (WTC) and ‘building integrated solar energy systems’ (BISE) have been fulfilled. In this chapter, I will go on to address the second half of the research goal, *i.e.* discuss how the findings of the function analyses can offer a bottom-up perspective on how the regional governance in Wales can help to alter the functional pattern so the two TIS may reach the phase of market growth. In other words, Research Questions Three and Four that is outlined below are addressed here. This is followed by a conclusion to this PhD thesis.

Q3: What does the comparative study of functional patterns of the WTC and BISE TISs tell about the relevant innovation capability in Wales?

Q4: Subsequently, what are the policy implications for regional governance in Wales in terms of altering the functional patterns and improving the innovation capability of relevant Welsh organisations?

This chapter consists of three sections. In section 1, the function patterns of the WTC and BISE TIS are further investigated in a comparative manner, and the intention is that, through exploring the ‘similarities’ and ‘differences’ arisen, some ‘system weaknesses’ and ‘system strengths’ can be generalised in relation to the relevant innovation capability in Wales (addressing Q3). This subsequently leads to the object of Section 2, *i.e.* to postulate, from a bottom-up perspective, possible policy measures at the regional level that may help to alter the function patterns, and lead the two emerging technological systems to a ‘market growth’ phase respectively, while also improving the innovation capability of relevant Welsh organisations (addressing Q4). In section 3, I draw conclusions to this PhD study, which includes an evaluation of the contribution of this PhD study, and suggestions for future research.

7.1 Assessing the functional patterns

Rather than simply reiterating the function analyses that were carried out in Chapter 6, a comparison of the similar and different functional patterns emerging from the WTC and BISE TIS is outlined in Table 7.1. By exploring the similarities and differences that have arisen, it is expected that a variety of the 'system strengths' and 'system weaknesses' would be identified, with respect to the development of low carbon building technologies in Wales. This subsequently helps to build a better understanding of the relevant innovation capability in Wales.

As discussed in Section 3.4.2, Chapter 3, the comparison is functions-based, *i.e.* for each of the seven functions of the innovation system, similar and different patterns are assessed, on the basis of the way in which and the extent to which each function has been carried out in the WTC and BISE TIS respectively. Meanwhile, the similar and different functional patterns are drawn mostly in line with the performance indicators proposed for the IS functions assessment, as listed in Table 6.1; in other words, the similar and different patterns drawn largely reflect the way in which these performance indicators have been fulfilled respectively in the two systems, derived mainly from the function analyses carried out in Chapter 6.

As follows, a comparison of the functional patterns of the WTC and BISE TIS are provided in Table 7.1.

Table 7.1: A comparison of the functional patterns of the WTC and BISE (in Wales) TIS

Functions	Similarities	Differences
<p>Knowledge Dev. & Diffusion</p>	<ul style="list-style-type: none"> ▪ The R&D has been primarily financed by public funding. ▪ The R&D has largely built on ‘imported’ technologies or knowledge, and focused on the application-specific knowledge, and manufacturing processes, etc. ▪ There is the presence of formal and informal knowledge networks or partnerships in both systems, involving a range of actors e.g. universities, manufacturers (or wood processors), architects, building engineers, government agency, industry-led voluntary bodies and local councils, which saw inter-firm and inter-organisation (university) collaboration on specific projects. ▪ Demonstration projects are used for the purpose of both knowledge diffusion and marketing. ▪ Non-Welsh research institutes have been actively engaged in the R&D activities. 	<ul style="list-style-type: none"> ▪ No patent has been filed within the WTC TIS, whereas around 20 patents have been registered by the Welsh actors in the field of solar technology; ▪ Intermediary organisations <i>i.e.</i> Coed Cymru and the WFBP played an integral role in facilitating R&D in the WTC TIS, whereas industrial actors are essentially steering the R&D agenda and direction of BISE TIS in Wales; ▪ In the WTC TIS, there is a lack of coordination between similar research projects, while no dedicated research institutes or group specialises in the WTC, with very few full-time researchers employed by the Welsh actors, whereas, ▪ In the BISE TIS, research programme are better jointed, as shown in Figure 6.3, and a considerable number of full-time researchers, engineers or PhD students are employed by both industrial actors and Welsh universities, largely due to a large amount of funding secured by the actors; ▪ The knowledge exchange mechanisms are more established and diversified in the BISE TIS, whereas in the WTC TIS the effort of knowledge diffusion seems to be fragmented and ineffective.
<p>Entrepreneurial Experimentation</p>	<ul style="list-style-type: none"> ▪ Most firms involved are existing businesses who sought to diversify into new market segments; ▪ There is a lack of new ‘start-ups’ in both systems; ▪ The number of firms involved in both systems is still limited. ▪ One or more new products (new to firms in a sense) have been introduced to market by Welsh firms. 	<ul style="list-style-type: none"> ▪ The commercialisation of the Ty Unnos only became possible after Elements Europe (EE, a Midland-based firm) took over, and subsequently formed an ‘open’ value chain involving several Welsh firms, while more may be included in the value chain if the housing market is picked up. ▪ The Welsh wood-based sector predominantly consists of small and micro-businesses who do not have required time and resources to innovate, whereas most of the Welsh firms involved in the BISE are large firms with the resources and necessary know-how to diversify into new market segments, while exerting considerable lobby power over WG.

Functions	Similarities	Differences
Guidance of the Search	<ul style="list-style-type: none"> ▪ Both TISs are largely driven by the global trend toward sustainable construction, and the growing need to meet the carbon reduction target in building required by building codes and regulations; ▪ However, at the current stage, both TISs are primarily influenced by the policies or regulations set at the UK and EU levels, despite the regulatory powers for both planning and building regulations having been devolved to WG; ▪ Moreover, some institutional changes or policy status quo by the WG have caused uncertainties for both TISs, whereas the new Part L of Building Regulations for Wales has set 8% carbon reduction target for domestic new builds, significantly lower than originally proposed, and has done little to stimulate the application of WTC and other low carbon building technologies in construction, to say the least. ▪ Affordability, or cost parity to conventional building materials is another driver for innovations in both TISs, although this can be achieved only after manufacturing scale-up becomes possible. 	<ul style="list-style-type: none"> ▪ Innovation (e.g. Ty Unnos) in the WTC TIS was also driven by the need to accommodate the low quality of Welsh grown timber, and the existing skill sets and production capacity of Welsh wood processors, therefore setting barriers for entry low. ▪ The BISE market remains policy-driven, e.g. FIT, RHI and Green Deal in the UK, whereas no such policy has been introduced for timber construction in the UK in general. ▪ “Turning buildings into power stations” has become a vision that unites key industrial and academic actors in the Welsh BISE TIS, whereas in the WTC TIS there is no such vision proposed either by the industry or the government.
Market Formation	<ul style="list-style-type: none"> ▪ Certain level of demand articulation has been formulated for the technologies of both TISs, e.g. Ty Unnos for the affordable housing market, and TSC for large commercial and industrial buildings. ▪ A number of building projects using e.g. Ty Unnos or TSC have been built in Wales, and England as well. However, both systems have been inhibited by the overall lack of demand in the UK construction sector since the onset of the recession, which led actors in both systems to view WG’s role to generate demand through its procurement or other policy measures. ▪ Actors of both TISs used demonstration projects to market the products. ▪ There are no specific policy incentives for the market uptake of both WTC and BISE technologies in the UK and Wales. 	<ul style="list-style-type: none"> ▪ Overall, BISE products remain a niche presence in the solar and building market, whereas market shares of timber construction in the UK and Wales have seen steady increases in recent years. ▪ As already a market leader in the off-site construction solution, the involvement of EE has seen a more strategically focused marketing approach for the Ty Unnos, which is different from the traditional practices of the Welsh firms, who tend to invest little in marketing, with hardly any strategy. ▪ The BISE producers face a different sort of marketing challenge: a policy-driven market that makes the usual marketing strategy somehow ineffective; no longer about selling physical building components, but energy generation capacity that leads to an entirely different proposition. To this end, demonstration projects are seen as the single most effective marketing tool for BISE.

Functions	Similarities	Differences
<p>Resource Mobilisation</p>	<ul style="list-style-type: none"> ▪ There is a general concern among the firms in both systems with regard to recruiting employees equipped with the right skill sets. Different measures have been adopted by the firms to meet their respective training needs e.g. apprenticeship (WTC), on-job training (both), and specifically designed under- and post- graduate programme at the Welsh universities (BISE). 	<ul style="list-style-type: none"> ▪ While both TISs offered CPD courses, in the BISE TIS these courses are more systemically setup and diverse than in the WTC TIS. ▪ At the higher educational level, in recent years a number of BSc, MRes and PhD degree programmes in the related subject fields have been set up in the BISE TIS, with industrial partners involved in course design, and are taught in Swansea and Glyndwr universities respectively. It is expected that these degree programmes may lead to the emerging of a talent pool in Wales in future. In contrast, the WTC TIS has no such specifically designed degree course in any Welsh universities. ▪ The long-term availability of Welsh grown timber is important for the WTC TIS, but the current wood management regime in Wales is unable to secure the sustainable supply of the required raw materials, due to inherent institutional and cultural setbacks in Wales, whereas in the BISE TIS the availability of raw materials poses a less challenging problem as the R&D works towards the use of earth-abundant materials. ▪ Even though governments at all levels remain main financial providers to Welsh businesses, the BISE actors have shown a better capability to attain funding to support R&D activities; on the other hand, when the WTC actors felt financial strains, they were also reluctant to borrow due to the lack of demand.

Functions	Similarities	Differences
Legitimation	<ul style="list-style-type: none"> ▪ The public acceptance of timber construction has steadily improved in UK, while solar technology remains the most approved renewable technology by the UK publics; ▪ However, the perceptions of both technologies among key actor groups (e.g. building practitioners and policy makers) require further changes, with respect to system quality and performance, and cost. ▪ There are varied lobbying efforts by the actors of both systems at regional level, but they often appear to be individual and fragmented. 	<ul style="list-style-type: none"> ▪ The inclusion of solar PV in the UK renewable energy mix and BIPV identified as one of the key market segments in the UK Solar PV strategy are a much-needed policy boost for the market development of the BISE technologies, but these changes have not affected WG's position on solar energy, despite WG having invested considerably in the R&D of the BISE technologies. ▪ WG has shown a certain level of interest in timber construction. Meanwhile, the Ty Unnos has achieved some legitimation through winning a number of design and wood innovation related awards, and through display at high profile public events and trade shows. However EE and other WTC producers face a “chicken and egg” or “catch 22” dilemma: in order to compete with incumbent construction methods and materials, they need a ‘decent’ sized order to make the production running and cost effective; but before they can produce cost effectively they may never be able to land such a order.
Dev. of Positive Externalities	<ul style="list-style-type: none"> ▪ Both systems have seen inter-firm and inter-organisation (university) collaborations that have led to knowledge spill-overs between the partners; ▪ There are potentials for the emergence of pooled labour markets due to the industrial histories in their respective fields. 	<ul style="list-style-type: none"> ▪ A number of research programme (e.g. SPECIFIC and COATED) set up in the BISE TIS will foster a legion of highly qualified specialists in the functional coating in near future. ▪ Wales has seen the emergence of some specialised intermediate providers for the market deployment of solar energy in BISE TIS. ▪ None of the above aspects has emerged in the WTC TIS.

Derived from the findings in Table 7.1 and the materials in the preceding chapters, following propositions are made, with regard to the development of low carbon building technologies and the relevant innovation capability in Wales.

As concluded in Section 6.3, Chapter 6, both TISs are seen to reach their formative phases, though to different extents, which nevertheless suggest that a certain degree of innovation capability⁸¹ has been established in Wales. This is characterised by the general presence of local knowledge networks or partnerships, formal or informal, which often involve a range of actors e.g. universities, manufacturers, architects, building engineers, governmental agencies, industry-led voluntary bodies, and local councils. Such inter-firm and inter-organisation collaborations have unmistakably led to knowledge spill-overs, and some market-ready innovations e.g. the *Ty Unnos Modular™*, the *Welsh Brettstapel*, the *New Welsh House*, and the *Colorcoat Renew SC®: integrated solar air heating solution*.

Welsh firms and organisations have also shown willingness to work with non-Welsh actors, mostly English firms, universities and organisations, while in some cases Scottish universities and overseas companies as well. This has allowed the Welsh actors to widen their knowledge bases, and compensate for system weaknesses, e.g. the involvement of Element Europe, the Midland based firm, has made the commercialisation of the Ty Unnos possible. On the other hand, the function analyses suggested that both technological systems have been built on 'imported' technologies or knowledge. In the WTC TIS, as timber engineering is a mature technological field at the global level, the Welsh actors have focused on assessing different 'existing' solutions, and subsequently adapted the imported technologies to accommodate local needs and conditions (or constraints), as shown in the development of the Ty Unnos. For the BISE TIS, the focus of knowledge development and diffusion has been applied R&D, engineering design and manufacturing processes, which are largely, although not entirely, built on the fundamental researches originally developed by actors based outside Wales.

External sources of knowledge are widely considered to be critical to the innovation process. Cohen and Levinthal (1990) have gone so far as to call the ability to exploit

⁸¹ Dahlman et al. (1987) see 'innovation capability' as part of 'technological capability', and define it as the ability to improve technology or to develop new products or services that better meet specific needs. In line with Dahlman et al.'s definition, I use the term here in the context of 'innovation systems and the function approach', and thus view it loosely as the ability of actors to generate, diffuse and utilise technology.

external knowledge a vital component of a firm's 'absorptive capacity', whereas Freeman (1987b) has credited Japan's approach to imported technology, (i.e. reverse engineering such that local firms took full charge of 'unpacking' imported technologies, which subsequently led to 'systems' thinking and total systems improvement), as an integral feature of its national innovation system, and one of the reasons propelling its post-war catching-up success. Nevertheless, the benefits of using 'borrowed' technologies and knowledge rely on firms' capability to assess, assimilate and apply them in a way that can lead to creating new knowledge and innovations. To this end, it is this capability that has set the BISE TIS in Wales apart from the WTC TIS (at this stage, to say the least), which is reflected in the functions of both *Knowledge Development and Diffusion* and *Entrepreneurial Experimentation*.

As suggested, *Entrepreneurial Experimentation* has grown to be the motor of innovation for the BISE TIS in Wales, despite the number of Welsh firms involved limited. However, due to the size and nature of these firms, as well as their presumed significance towards the Welsh or local economy, they are able to mobilise the necessary resources, lobby for government grants, and practically drive the agenda and direction of the search. In contrast, in the WTC TIS, the non-firm actors, e.g. universities and government agencies (e.g. Coed Cymru), have been responsible for assessing, assimilating and applying the 'imported' technologies and knowledge. This is not to say that Welsh firms within the wood based sectors do not possess such ability, rather that a lot of firms are confined by their sizes (as the sector predominantly consists of micro- and small enterprises) and do not have the required resources and also time to do so. After all, "the acquisition of innovation capability – like the act of innovation – comes from explicit allocation of money and people to solve technological problems" (Dahlman et al., 1987: 766), not to mention the risk involved as well. This gives rise to one of the challenges facing regional innovation governance in Wales, i.e. how to improve the innovation performance of small businesses.

This concern over the innovation performance of small businesses is nothing new. In their report to the European Commission's Directorate General for Enterprise and Industry, Thomas and Henderson (2011) single out a dearth of innovative and R&D performing SMEs in Wales as one of the main weaknesses in Wales' regional innovation system. This is against the backdrop that 99.3% of the enterprises in Wales are SMEs, among which 94.6% are micro-enterprises employing less than 10 people, 3.8% are small businesses employing

up to 50 people, and 0.9% medium-size firms with up to 250 employees (Welsh Government, 2014c). These figures reflect the scale of the challenges, as well as the necessity to lift the innovation capability of small businesses, for the sake of the Welsh economy. As indicated, the development of the Ty Unnos system could serve as a model of innovation process involving small firms, but, as the analysis revealed, a more systematic approach is needed. This is because the development of innovation capability depends on long-term effort and evolution of both physical and social technologies. I will elaborate this further in Section 2.

In terms of *Guidance of the Search*, the function analyses have suggested that the development of both technological fields is positively influenced by the global trends towards sustainable construction and carbon reduction in the built environment, and the growing need to meet building codes and regulations for low carbon and low energy buildings. However, at the regional level, some institutional changes or policy direction (or a lack of direction) undertaken by the WG have created some uncertainties for the development of the two systems; for instance, the creation of Natural Resources Wales, through the merger of Forestry Commission Wales, Countryside Council for Wales and Environment Agency Wales, has raised the concern that the commercial interest of the Welsh forestry sector might be undermined; WG's arguably somewhat indifferent position on solar energy even after solar PV has been elevated to be one of the eight key renewable energy technologies by the UK government, whilst at the same time the WG itself has invested handsomely in the R&D of the technology.

Furthermore, despite the emergence of a distinctive Welsh transitions narrative⁸² during the late 2000s (as depicted in Section 4.3.2, Chapter 4), this vision seems to, in recent years, have been lost in translation, which is particularly reflected in the development of the amendments to the *Part L (Conservation of Fuel and Power) of the Building Regulations* for Wales, and has caused a serious setback for the *legitimation* of the low carbon building technologies in general. As mentioned, since 31 December 2011, the responsibility for building regulations has been devolved to the WG. It took about two years for the WG to

⁸² Much of the Welsh transition narratives took shape during the previous administration. After the 2011 Welsh election, both Rhodri Morgan (the then First Minister) and Jane Davidson (the then Minister for Environment and Sustainability) who was credited to champion the sustainability agenda in Wales, left office. Their departures have been linked to why the low carbon and sustainability agendas have a lower profile in the current administration.

release the new Part L for Wales in February 2014, with changes coming to force on 31 July 2014. The new regulation requires all new domestic buildings to achieve a mere of eight per cent reduction of greenhouse gas emissions based on 2010 level, which is significantly lower than the 40% originally consulted upon. While some saw it as a sensible and proportionate response to the current tough economic situation (Chapman, 2013), or a small step in the right direction (Davies, 2013), the outcome nevertheless dealt a major blow to WG's credibility on sustainability (its statutory duty). Friends of the Earth Cymru (2012) states that WG is, in effect, transferring and magnifying the financial outlay from developers to future householders, which is in contravention to the basic tenets of sustainable development. This 8% reduction target sets to be an interim step, because of Wales' statutory obligation to conform to EU directives, *i.e.* the European Energy Performance of Building Directive on Nearly Zero-energy Buildings (Directive 2010/31/EU, in this instance); that requires all new buildings to be virtually carbon neutral by 1 January 2021 (all new public buildings to be nearly zero-energy by 1 January 2019); so, a further round of consultation and regulatory changes will likely take place in 2016 (Sargeant, 2013a).

The Welsh Minister for Housing and Regeneration has justified the decision on the grounds of avoiding unintended impacts on the property and employment market while securing the target of 7,500 affordable homes to be built during this administration (Sargeant, 2013b). Whereas some have questioned whether a lower reduction target would stimulate more building development in Wales (George, 2014), the environmental groups *e.g.* WWF Cymru and Friend of the Earth Cymru claimed that the WG simply "*capitulated to the well-financed housebuilding lobby*" (Henry, 2013; Mark, 2013), while wasting an important opportunity to drive innovation and enable Welsh businesses to capture an 'early-mover' advantage (Friends of the Earth Cymru, 2012). Given that the authority for both planning and building regulations has been devolved to the WG, the current administration seems to exhibit a lack of vision, or rather has deviated from the original aspiration, in terms of how a transition to a low carbon built environment in Wales can profoundly help to solve Wales' entrenched social and economic problems, as introduced in the Welsh transition narratives.

It is undeniable that the current tough economic situation poses challenges for policy-makers at all levels, although there is the suggestion that 'jobs' has remained as the main

driver of the Welsh policy-making process (Civil Servant Interviewee N.3, 2013), the single most important criterion for the regional policy intervention in Wales since 1944 as pointed out in Chapter 4. It does raise the question of whether Welsh policy-makers are capable of breaking from this path-dependence, and look beyond narrowly defined goals e.g. 'jobs' and short-term socio-economic outcomes, as they to date have not seemed to have delivered the economic results intended. Instead, it has been suggested that regional governance should be inspired to creatively use policy intervention to promote multiple policy goals (Ashford and Hall, 2011), e.g. innovation, the creation of jobs and business opportunities, and low carbon transition etc., and help shape the long-term structural change (Thomas and Henderson, 2011) that is needed for the Welsh economy.

Such intervention might consist of a congruence of varied policy measures, including not only e.g. stringent regulations that can simulate the entrance of new products and processes into the market (Ashford and Hall, 2011), and give *Legitimation* on which the development and deployment of low carbon technologies can thrive, but also those aiming to create domestic demand for the low carbon technologies, a main bottleneck identified in the function analyses. They combined could help to increase the market uptake of the WTC products at once, while, in the case of the BISE TIS, they could help to create a 'lead market' or 'test bed' for the BISE products and services. I will further discuss this in the next section.

With regard to *Resource Mobilisation*, there is a general concern among Welsh firms in both systems over the difficulty of recruiting employees equipped with the right skill sets. While firms have adopted various measures to meet their respective training needs, e.g. on-job training (in both systems), apprenticeships (in the WTC TIS), specifically designed university degree programmes (in the BISE TIS), it again raises the question of how the Welsh educational system can better serve the needs of its economy, since education is one of the fully devolved subjects.

As reviewed, Abramovitz (1986) links the 'social capability' of a nation with its relative economic status i.e. 'forging ahead', 'catching-up' or 'falling-behind', and denotes the state of education embodied in a nation's population and its existing institutional arrangements as part of the 'social capability'. In this sense, some parallel can be drawn between the substandard state of Welsh education and the lagging status of the Welsh economy,

especially in the case of the quality of the Welsh primary and secondary education system which is falling behind (Dixon, 2013), fortified by the latest PISA⁸³ result that places Wales' education as the worst in the UK (BBC News, 2013c). While it is beyond the scope of this study to go further into detail on the Welsh educational system, one point raised by OECD in its recent review of the Welsh school system has struck a chord with this study, i.e. in the report OECD points out that the lack of “*a compelling and inclusive long-term education vision to steer the education system and its reform efforts* is an overarching challenge to improve the quality of education in Wales” (OECD, 2014: 11). Again, the importance of a long-term vision is stressed. On the other hand, just as Nelson (2004) points out, when the reform of particular institutions, e.g. the educational system, is required, it is likely far easier to advocate institutional reform, or mount programmes aimed at reform, than actually to deliver them. Even so, I will make an attempt in the next section to discuss how a long-term vision might be developed and subsequently delivered, by drawing on insights from successful experiences elsewhere.

As for the Welsh higher educational institutions, the function analyses have shown the active involvement of Welsh universities in the processes of *Knowledge Development and Diffusion* in both systems. Providing that Wales does not have any public sector research and development institutes (Thomas and Rhisiari, 2000; Thomas and Henderson, 2011), it is expected that Welsh universities and university-led research institutes will continue to play an important part in fostering the innovation capability in Wales. In theory, the university-industry interaction likely involves different facets. First, it is the basic university role of educating and supplying suitably qualified human capital for the Welsh firms; second, it is the role of research activity which increases the stock of codified knowledge that may have useful or commercial values; third, it is a role in problem-solving in relation to specifically articulated business needs; and, the fourth includes a wide range of interaction mechanisms between university staff and business, formal or informal (Hughes, 2007).

In this regard, all such four facets were observed in the two systems, to varied extents. While the university-industry interaction in the WTC TIS was akin problem-solving, what

⁸³ The Programme for International Student Assessment (PISA) is a triennial international survey carried out by OECD, and set to evaluate educational systems worldwide by testing the skills and knowledge of 15 year-old students. First introduced in 2000, students from randomly selected schools take tests in three subjects – reading, mathematics and sciences. The most recent assessment took place in 2012. More information is available from the official website <http://www.oecd.org/pisa/>.

is going on in the BISE TIS (in the case of SPECIFIC) has its emphasis on R&D, alongside activities designed to educate and supply a future pool of suitably qualified human capital. However, it needs to be pointed out that, in the WTC TIS, the university-industry interaction only took place because of the involvement of the intermediary bodies e.g. Coed Cymru and the Welsh Forest Business Partnership (WFBP); they played an important part in articulating the technical problems and research demands; otherwise universities may not be high on the list of knowledge sources that Welsh firms likely go to, an impression I collected throughout the interviews. In addition, the WTC TIS also encounters the reality that there are very few full-time researchers working in the field, when external actors, e.g. Edinburg Napier University, have been involve in order to complement the relative weak R&D capacity in Wales. To this end, it again raises questions about whether some long-term arrangement should be made in Wales to work closely with the Welsh businesses and raise the R&D and technological capacity in areas at which Welsh universities may not be specialised. I will discuss this in the next section.

7.2 Implication for regional governance in Wales

The emergence of the innovation system approach has much to do with a belief that the innovative prowess of national firms is determined to a considerable extent by government policies (Nelson, 1993), whereas the Functions approach provides a means to decipher the institutional, technological or economic factors that can influence the rate and direction of innovation processes, exposes 'system weaknesses', and thus may guide the development of specific policy measures. In this regard, following the comparative assessment of the functional patterns of the WTC and BISE TIS, I next discuss possible policy actions alongside four streams of thinking: 'technology foresight', 'the regulation-induced innovation hypothesis' (Ashford and Hall, 2011), 'demand-oriented policy measures', and 'support for small business innovations'.

The inspiration and authority for these recommendations are derived from different sources. As reviewed in Section 2.4, Chapter 2, one main origin is the literature on technological catch-up, in that most technological and economic progresses in Wales involve a catching-up process. This may not be so obvious in the case of the BISE TIS in Wales, but when it comes to institutional arrangements and regional governance that facilitates these changes, considerable competence building is needed in Wales. As already argued, while good practices in advanced regions can offer inspirations, Wales may not

have the right social technologies and institutional infrastructure to deliver these good practices. However, by drawing insights from countries and regions who have previously lagged behind, but have since successfully caught-up at either country or industrial level, Wales might learn how the required institutional capability can be built up.

7.2.1 Technology foresight: setting long-term visions

As discussed in the previous section, the development of innovation capability depends on long-term effort, and the guidance of well-defined long-term visions (in terms of *Guidance of the Search*). This may include, for instance, a long-term policy commitment to *Knowledge Development and Diffusion* as to a specific technological field such as low carbon building technologies, whereas necessary *resources* (e.g. human, financial and materials) are *mobilised* to help deliver such a commitment. On the other hand, Wales' recent experience with the amendments to the Part L of the Building Regulations for Wales also seemed to attest the importance of a regional consensus in formulating long-term visions (linking to *Legitimation*), in order to ensure the support of important regional actors (e.g. home-builders, in the case of the Welsh Part L). To this end, I next discuss the implication of 'technology foresight' as a useful regional governance tool, in terms of developing well-grounded long-term visions while forming regional consensus.

As introduced, in his 1987 book on Japan's national innovation system, Freeman (1987b) credited Japan's technological forecasting system with providing long-term 'visions' of the future that were able to influence decision-making throughout its national system in relation to R&D, investment, markets and structural change; moreover, this long-term vision charted broad directions of advance for the economy and for technology, and gave firms sufficient confidence to make their own long-term investment decisions. By the 1990s, similar technology forecasting or foresight exercises have been observed, to varied extents, in many emerging economies that tried to close technological gap (Shin et al., 1999), as well as in many Western European countries that wished to optimise resource allocation in the S&T policy (Brandes, 2009; Meissner, 2012). In recent years, an increasing number of studies have also looked into technology foresight as an effective regional governance tool to build up regional innovation potentials, in terms of developing common visions about the future, enhancing the cohesion among regional actors and enabling coordinated action towards common goals (Koschatzky, 2005; Hanssen et al., 2009; Keller et al., 2014; Vecchiato and Roveda, 2014).

A successful foresight process often involves a top down beginning but can be extended in addition by a bottom up approach (Meissner, 2012). For instance, in Japan a quinquennial technology foresight has been conducted since 1971, with aims to forecast long-term trends in various fields of S&T for the next 30 years; the most recent one (*i.e.* the ninth survey) was completed between the fiscal year (FY) of 2008-09, which consists of 12 interdisciplinary panels covering 832 topics; the methods used include the 'Delphi survey' of 2900 experts to outline areas of key S&T importance, 'scenario writing' based on group discussions to explore the path towards the future (which involves both experts and younger generation in separate discussions), and 'regional workshops' involving local populations to help assess the capability of local regions for green innovation and the creation of new industries and services (NISTEP, 2010). As shown, the Japanese system has become very sophisticated, resulting from a continuous forecasting exercise for more than 30 years, learning from the past (*e.g.* a social dimension was included in 1999 in order to reflect the social needs on the technology development (Kameoka et al., 2004)), as well as a whole-hearted belief that foresight can prepare Japanese society to face future challenges (NISTEP, 2010).

While it is unrealistic to assume that Japan's technology foresight exercises can be entirely imitated in Wales, they nevertheless provide a different model of doing things that allows a policy-making process based on long-term visions. On the other hand, Wales is a much smaller nation, so the content and process required likely need not to be as complicated as what took place in Japan. Since four technological fields have been identified in the latest Welsh innovation strategy, while nine key industry sectors have been set up under the Department for Business, Enterprises, Technology & Science (Welsh Government, 2013d), these could certainly form the basis for initiating a foresight exercise in Wales. However, the exercise would have to address two challenges facing regional innovation governance in Wales. First, it would need to avoid the 'top-down' and overbearing nature of governance that is often observed in Wales in the past two decades. It has been argued that "*everything is within the Welsh Government itself, and there is no innovation governance system of a wider nature*" (Academic Interviewee N.5, 2013). In this sense, a foresight exercise might offer an opportunity for the Welsh innovation governance to engage a wide range of stakeholders, including industries (both small and big businesses), local authorities, general publics, and universities in an equal partnership, and to build regional consensus.

Second, once a foresight exercise is started, it needs to be carried out in a systemic and continuous manner. As introduced in Section 4.4, Chapter 4, Wales was once among the first four EU regions to pilot a regional innovation strategy, *i.e.* the Regional Technology Plan (RTP), introduced in 1996, when the Welsh RTP process was valued as engendering the “*path-breaking forms of dialogue anticipated by theorists*” (Henderson, 2000: 347). But, Wales has since fallen away from the front of the field (Academic Interviewee N.5, 2013). It is thus interesting to speculate whether, had Wales followed a more consistent and coherent approach, the long-term structural change that is much needed in the Welsh economy might have been taking shape. As Cuhls (2001: 567) comments, “*what we do know is that the foresight studies in Japan do have an impact—just because they are continuing*”. When linking this statement to the study of innovation systems, such continuity can be interpreted as allowing an uninterrupted, interactive ‘learning’ process – the most important process in the modern economy (Lundvall, 2007); in the meantime, it may be argued that this continuous process and the relevant institutional setup enable all actors involved (e.g. firms, experts, policy-makers and general publics) to grow and deepen their knowledge bases of both science-based and experience-based natures⁸⁴, while facilitating the formation of networks and strategic alliances (Cuhls, 2001).

7.2.2 Regulation-induced innovation hypothesis: why stringent regulations?

In more than one occasion in this thesis, I have discussed how the new Part L of the Building Regulations for Wales dropped the originally intended 40% reduction target for domestic new builds, and instead adopted a much lower reduction target of 8%, even though it is clearly understood that all new builds must be virtually carbon neutral by 1 January 2021 in compliance with the relevant EU Directive. Such an institutional behaviour shows the shadow of a conventional assumption that stringent environmental regulations always increase the costs of compliance and harm firms’ competitiveness. However, since the late 1970s such an assumption has been challenged by a number of studies conducted by Ashford and colleagues⁸⁵ (Ashford, 1976, 2000; Ashford et al., 1985), and by Porter and van den Linde (1995a,b), which respectively led to the proposition of the ‘regulation-induced innovation hypothesis’ (RiiH), and the ‘Porter Hypothesis’ that is seen as a weak

⁸⁴ According to Jensen et al. (2006), science-based knowledge is the one produced through the science-technology-innovation (STI) mode, whereas experience-based knowledge is developed through learning by doing, using and interacting (DUI) mode.

⁸⁵ Ashford and colleagues are the research team based at the Massachusetts Institute of Technology (MIT), USA.

form of RiiH (Ashford and Hall, 2011).

As reviewed, RiiH postulates that stringent regulations, aiming at achieving sustainability, can stimulate fundamental changes in technology, often by new firms or entrants, through the introduction of entirely new products and processes into the market, thereby displacing dominant technologies; for incumbent firms, only those who have the willingness and capability to innovate can survive, while the remaining are likely displaced from the market. Consequently, they lead to the Schumpeterian 'wave of creative destruction' (Ashford and Hall, 2011). While the development of RiiH shows the clear influence of evolutionary theories, e.g. Nelson and Winter (1982) and Schumpeter (1939, 1943), some parallel can be drawn between the theory of RiiH and the Functions approach, e.g. in 'functional' terms, RiiH can be seen as a result of cumulative causation – *Guidance of the Search* coupled with *Legitimation* (in the form of introducing stricter regulations) is expected to have strong effects on *Entrepreneurial Experimentation* (in the form of either new entrants who see opportunities in new markets or incumbent companies who diversify into new segments).

In the case of the two technological systems examined in this study, it becomes obvious that a level playing field could be immediately created for the market deployment of the Ty Unnos module and other WTC innovations, if the Welsh Part L were to adopt a carbon reduction target of 25%, equal to the level 4 of the Code of Sustainable Homes (DCLG, 2010). As for the BISE technologies, experience in Europe has showed that a combination of stricter building codes and modest BIPV incentives has promoted more innovative BIPV applications installed in France and Switzerland than in Germany and Italy (Heinstein et al., 2013). In this sense, an integrated approach is needed for RiiH to have an impact in Wales, as demonstrated by Japan's experience in promoting energy efficiency law after the oil crises of the 1970s (see Section 2.4.4, Chapter 2). This includes, apart from the stricter regulatory standards, complementary monetary incentives, and relevant R&D programme funded by government or/and private sectors, as will be discussed later.

On the other hand, the stance that the Welsh Minister for Housing and Regeneration took on the new Part L may be interpreted as a lack of understanding of and commitment to innovation. As one interviewee commented, "*what you would want to be looking at within Wales compared to say Ireland or compared to Scotland is the extent to which there was a real*

strategic focus upon stimulating innovation for particular ends...I think that has been missing within Welsh Government, and Innovation Wales⁸⁶ does not fully cover that gap...I am not certain at this stage that there is the strategic push behind facilitating innovation more strongly within Wales” (Academic Interviewee N.5, 2013). To this end, what the ‘regulation-induced innovation hypothesis’ offers is an alternative way of thinking and policy-making, as opposed to allowing the incumbents to capture the regulatory agenda (e.g. how homebuilders successfully lobbied for the lower carbon reduction target adopted in the Welsh Part L); it calls on policy-makers to set higher regulatory standards, thereby stimulating innovation to facilitate changes, which could eventually lead to a breakout from ‘path-dependence’, or ‘lock-out’. This is, in my view, particularly important for the post-devolution Wales.

7.2.3 Demand-orientated policies for innovation

‘Demand’ or lack of it has emerged in this study to be an important matter, and it seems to be at the core of the problem this study aims to address, while at the same time part of the solution. In Chapter 2, I have theoretically explored the role of market demand in affecting the direction and rate of technological change as either an *priori* directing or an *ex post* selecting device, whereas the user-producer linkage could act as an important source of knowledge and ideas for innovations. The review of Wales’ industrial past in Chapter 4 also suggested that, as the Welsh economy is so often driven by external demand, and capitals, a frequent disintegration between the Welsh production systems and the local demand profiles have done little to improve technological capability in Wales, and partly contributed to the peripheral status of the Welsh economy. In this sense, the building environment seems to be an ideal testing ground to facilitate Welsh innovations and develop new industries, products and services based on low carbon technologies, simply because a Welsh market is already here.

However, since the recession the recovery in the housing market has been slow, which was seen as a main bottleneck for the market uptake of WTC products, as indicated by the function analysis. Hence, simply relying on consumer or market-driven demand will be unrealistic for these emerging technologies, whereas the lower than expected standards adopted in the Welsh Part L do not help the situation either. An alternative way to create

⁸⁶ The latest Welsh innovation strategy

market demand is needed. In recent years, there is an increasing call for demand-based policies, as a way to tackle bottlenecks of demand for innovation, and contributing to the innovation process (Edler, 2009; European Commission, 2009).

Demand-based policies for innovation were adopted as early as the 1970s. The rationale for introducing such policies lies with: a) overcoming system failures, e.g. high entry cost; b) serving societal goals and policy needs; c) modernising industrial assets leading to productivity gains, and d) pushing local innovation production and creating Lead Market potentials (Edler, 2009). In addition, some sector-specific conditions also makes demand-based policies relevant for promoting innovation in construction. First, a majority of the construction industry serves national and local markets due to the typical division of responsibilities and relationships along the supply chain differing from country to country (European Commission, 2009), and thus there is little risk that public procurement could lead to suppliers with best value for money coming from 'abroad' (Edler, 2009). Second, public sector has always been an important source for building demand e.g. schools, social housing, and hospitals, which largely explains why the Welsh construction sector has remained relatively stable during the economic downturn (Welsh Economy Research Unit, 2012). All these elements thereby ideally place government or public sector clients in a good position to lead the demand for innovations in the field of low carbon building technologies.

The most direct way for governments to influence innovation through demand-pull measures is as a purchaser. Public procurement policy is generally considered to be a more efficient instrument to stimulate innovation than R&D subsidies (Geroski, 1990), while triggering greater innovation impulses in more areas than R&D subsidies (Rothwell and Zegveld, 1981). Through the procurement policy, governments can act as 'lead users' for new innovation (Edler, 2009), while helping to stimulate private demand through demonstration projects for example. However, as revealed by the function analyses in Chapter 6, the current public sector procurement process in Wales is often risk averse, tends not to support innovation, while always going for the cheapest bidder. To this end, if public procurement is to be used as a demand-pull measure, the WG will have to adopt higher standards for public procurement for building projects, or more specific requirements, e.g. stipulating minimum threshold percentages for using locally sourced materials (or BISE) in the project, or to include requirements for the assessment of the

embodied energy, or for life cycle assessment (Business Interviewee N.11, 2013).

Doing so may also link with the vision to create a 'lead market' for e.g. BISE technologies in Wales, as I already proposed. EU launched the *Lead Markets Initiative for Europe* in 2008, and both sustainable construction and renewable energy are among the technological fields selected for the Initiative; the aim of this Initiative is to enable European enterprises to have better chances of entering new fast growing world-wide markets with a competitive advantage as lead producers (European Commission, 2008). As reviewed in Section 2.4.3, Chapter 2, the concept of 'lead market' is built on the hypothesis that particular characteristics of local demand can lead local innovations to be commercialised in the global market (Beise, 2004). It is closely linked to Porter's Diamond model (Porter, 1990), in which demand in a home market is seen as one of the four determinants influencing the innovativeness and competitiveness of local firms. While it was initially seen to only exist in economically advanced countries due to its emphasis on customer sophistication and affluence as the inducers of innovation, the theory has since been extended to include the 'lead market for frugal innovations' in emerging economies, where innovations are characterised by high affordability, robustness, and 'good enough' quality in a volume-driven market (Tiwari and Herstatt, 2012).

In this sense, both WTC and BISE innovations examined in this study fit well these profiles, even though it might sound odd to categorise BISE components or systems as frugal innovations. Nevertheless, it may be argued that to be affordable is undoubtedly high on the agenda of SPECIFIC, which will be delivered through manufacturing scale-up while using Earth abundant raw materials, thereby significantly reducing the cost of BISE production (Business Interviewee N.9; Academic Interviewee N.7, 2013). Meanwhile, as noted, what is happening in the solar energy market as well as in the field of solar technologies has shown that solar energy is becoming ever so close to be cost-parity to fossil fuel options; thus, it is not so far-fetched to consider that BISE components or systems can become affordable and compete with conventional building materials in near future, if the right innovation strategy is put in place, for instance, a 'lead market' initiative.

Here, a more pressing question may be raised with regard to the size of local demand in Wales. In other words, is Welsh market substantial enough to formulate a 'lead market' for e.g. BISE innovations? Porter (1990) has suggested the quality rather than the quantity

of the home demand to be crucial, and pointed out that demand is often segmented in many industries while some segments are more global than others. Although this thesis has run out of space to further discuss whether and how a lead market might take shape in Wales for e.g. BISE innovations, it seems to be an interesting topic that may benefit from a separate study. Moreover, lead market or not, governments or public sector bodies can still act as sophisticated or stringent buyers to enable and push the innovation performance of local firms.

Apart from public procurement, the other policy measures that may be used to stimulate demand for innovation include a) providing financial incentives for private demand, through direct payment or tax credits or exemptions; for instance, through e.g. providing finance to individuals who seek self-build in Wales (Chapman, 2013), the WG can help to create demand for the WTC products, in that the STA figure has shown that timber frames dominates the market segment of self-build, as indicated; b) providing information and enabling initiatives; this can be linked to the technology foresight exercise that I have discussed in Section 7.2.1; and c) using regulation and standardization, to alter market conditions to redirect efforts in innovation (Edler, 2009; NESTA, 2010; Izsak and Edler, 2011); similarly this can be linked to the 'Regulation-induces Innovation Hypothesis' that I discussed in Section 7.2.2, and again the point here is that an integrated approach is required for using policy to influence innovations aiming at sustainable development, an argument I already touched on, but more study is needed.

7.2.4 Support for small business innovations

As indicated, just like the Welsh wood-based sector, a majority of enterprises (99.3%) in Wales are small businesses, or more precisely are dominated by micro-enterprises, standing for 94.6% of all Welsh firms. These figures reflect the importance of improving existing small businesses' innovation capability for the Welsh economy (Jones-Evans, 2001). Recently, as introduced, WG launched a two-year Open Innovation Development Award initiative, and three firms from the BISE TIS have been selected as anchor companies (out of the seven in total) assigned the task to bring new product or process expertise to small businesses in Wales, and develop open innovation networks (Welsh Government, 2013c). Whereas 'open innovation' can certainly form a path for improving the innovation capability of small firms in Wales, here I intend to explore a rather different path, partly because none of the wood based firms is part of this 'Open Innovation' initiative, and

partly because, as explained, the path proposed has been proved to be effective in facilitating technological catch-up elsewhere.

In the technological catch-up literature, as introduced in Section 2.4.2, Chapter 2, Taiwan's catch-up success in the 1990s is seen as being led by a large number of SMEs, a trajectory different from that of Japan and Korea's in which large firms are mainly responsible, or that of TNC- or FDI- based growth model. Underpinning this success is the distinctive cooperation forged between public and private actors, in the form of R&D Consortia, which were able to overcome the scale disadvantages of Taiwan's small firms, and demonstrate the power of public-private cooperation in one successful industry intervention after another (Wong, 1995; Mathews, 2002; Dodgson et al., 2006). As Mathews (2002: 634-635) elucidates,

Taiwan's R&D consortia were formed hesitantly in the 1980s, but flourished in the 1990s as institutional forms were found which encourage firms to cooperate in raising their technological levels to the point where they can compete successfully in advanced technology industries. Many of these alliances or consortia are in the information technology sectors,... But they have also emerged in other sectors such as automotive engines, motor cycles, electric vehicles, and now in the services and financial sector as well. Several such alliances could be counted in Taiwan in the late 1990s, bringing together firms, and public sector research institutes, with the added organisational input of trade associations, and catalytic financial assistance from government.

Some of these consortia have been more successful than others—but all seem to have learned organizational lessons from the early cases where government contributed all the funds, and research tasks were formulated in generic and overly ambitious terms for the companies to take advantage of them. The more recent R&D alliances formed in the 1990s have been more focused, more tightly organized and managed, and have involved participant firms much more directly in co-developing a core technology or new technological standard which can be incorporated by the companies, through adoption and adaptation, in their own products.

What can be taken away from Taiwan's experience is how networks of SMEs have been organised intentionally and effectively, while technological learning, upgrading and catching-up, and industrial creation have been the main object of such collaboration (Mathews,

2002; Dodgson et al., 2006). As noted, the formation of networks is an essential condition and structural component of innovation systems, whereas learning and capability building remain of central importance to the IS approach.

From the onset, Taiwan's experience (as well as Japan's) suggests that it is naive to assume that firms are naturally willing to work together in collaborative processes, and thus it is rather the case that institutional frameworks need to be constructed in which firms find it to be in their interests to collaborate while they can still compete in the marketplaces (Mathews, 2002). In Taiwan, at the heart of such institutional framework is the public sector research institutes (PRI), especially in the form of the Industrial Technology Research Institute (ITRI), which has been integral to instigating R&D consortia since 1973, through not only conducting R&D directly but also acting as the coordinator of multi-partner consortia. Because of its neutral position, ITRI has been able to lead participating firms to work cooperatively and productively on a specific project while allowing them to remain competitors elsewhere (ibid; Dodgson et al., 2006).

A slightly different sort of intermediary actor can be found in the WTC TIS where both Coed Cymru and WFBP have been involved in the development of WTC products, and knowledge diffusion. However, while they played an indispensable part, neither of them are PRIs and have the resources and capacity to form an effective organisational structure to provide R&D support to Welsh firms both sustainably and systemically. Coed Cymru employs around 25 staff (with no designated R&D staff) and has an operational budget over £1.2 million (around 25% used for R&D) in FY 2011-12 (Coed Cymru, n.d.), whereas WFBP is currently, as a voluntary organisation, financed by the WG with an annual operational budget £235,000, and employs three full-time staff (with no designated R&D staff either) in FY 2012-13 (WFBP, 2012; Business Interviewee N.7, 2012); moreover its budget is approved on a year-to-year basis (WFBP, 2012; Welsh Government, 2014e).

As already questioned, how can an effective mechanism be set up in Wales which is able to provide R&D support to small businesses in a systemic and consistent manner? Should, for example, a PRI (similar to Taiwan's ITRI but probably in a more compact format⁸⁷) be set

⁸⁷ Established in 1973, the ITRI employs more than 5000 R&D staff (over 1300 with PhDs) and has an operational budget around NTD 18,490 millions (around £370 millions) in 2013, while its R&D activities focus on six major fields, with innovations and applications targeting three domains: Smart Living, Quality Health and Sustainable Environment (ITRI, 2013).

up in Wales since Wales does not have one at present? Whereas the Welsh universities remain the big R&D performers within the region, it needs to be reckoned that universities and PRIs are often operated with different priorities; for instance, while universities also perform the important function of teaching, PRIs usually solely provide direct R&D support to businesses, and public authorities (Innovation Policy Platform, 2014). Meanwhile, the Welsh regional innovation governance, as noted, is very top-down with most decision-making processes kept within WG, to the point that the governance arrangements are not clear beyond it being the responsibility of the WG (Academic Interviewee N.5, 2013). In this regard, it may be argued that, by establishing a Welsh public sector research institute, a horizontal coordination mechanism might be added to the current overly top-down arrangement while enhancing the innovation infrastructure in Wales. As a relatively independent research entity, and a focal point for small businesses in particular, the proposed PRI could focus on, across selected technological fields, facilitating technological learning, networking, problem-solving, technology generation, innovation management, access to (overseas) R&D and information on patents and licenses, training and commercialisation, etc. (Cooke, 2001; Tödting and Kaufmann, 2002). Where funding is concerned, the estimated £2 billion European structural funds for the period of 2014-20 might come to play an essential part after all.

Taiwan and its institutions are seen to demonstrate pragmatism and the ability to learn from mistake, which saw the ITRI evolving from its early role in which it assimilated imported technologies and then passed them onto the local companies, to an arrangement where the ITRI now acts as convenor and coordinator of projects with works jointly done by both the ITRI and participating firms (Mathews, 2006; Wong, 1995); and in the meantime the object of the R&D consortia has become more strategically focused, as described. In this sense, it is worth noting that a similar experience also happened to the WFBP, which saw the Partnership setting very ambitious organisational goals initially while trying to do everything at the same time but without clear direction. However, by learning from these early mistakes, the WFBP has since become more focused and specific, mainly involving WTC and local supply chain development etc. (Business Interviewee N.7, 2012). The point here is that, while Taiwan's experience shows how long-term commitment to innovation by its government has led to an improved institutional capacity that have contributed to Taiwan's successful catch-up in industrial sectors e.g. electronics, uncertainty over its future running may greatly weaken WFBP's capability to continuously

learn and improve, seeing that its future operation is determined annually by whether the WG is willing to continue the uncertain sponsorship. For the WTC TIS, the possibility that the WFBP might be dissolved due to funding shortages could very likely set the system into the motion of a vicious cycle.

7.3 Conclusion

This PhD study was set out to, first, develop theoretically informed and empirically grounded insights into the development of low carbon building technologies in Wales through investigating the extent to which the functions of two selected emerging technological innovation systems – ‘Welsh grown timber for construction’ (WTC) and ‘building integrated solar energy systems’ (BISE) – have been fulfilled respectively. To do so, a bespoke analytical framework for the assessment of the IS functions was developed (see Section 3.3, Chapter 3, and Table 6.1), which comprises seven functions of an innovation system with each function assigned a set of performance indicators (addressing Research Question 1).

The analytical framework was subsequently used to analyse how the functions of the WTC and BISE TIS have been fulfilled (addressing Q.2). Overall, the function analyses have led insights into how the institutional, technological and market factors at various levels have interacted and affected technological developments as well as the market deployment of the WTC and BISE technologies. The analyses also shown that, despite the assessment that both TISs have reached the formative phase respectively (as explained in Section 6.3, Chapter 6), there is no guarantee that both systems will eventually reach the stage of successful market diffusion, due to uncertainties likely arising in the spheres of technology, policy-making, and market demand.

To certain extents, as discussed above, the Welsh Government with its devolved power can introduce intervention mechanism to help the market diffusion of these technologies, especially since both planning and Building Regulations are devolved matters. Meanwhile, it is believed that the use of the innovation system and functions approach can help identify system weaknesses, and subsequently allow the regional governance to introduce policy measures that matter the most, and become, in a way, more responsive to local circumstance. This therefore arrives at the second half of the research aim of this PhD study, *i.e.* having compared the functional patterns of the WTC and BISE TIS and analysed

the similarities and differences that have arisen (see Table 7.1, addressing Q.3), this study explored the extent to which the findings of the function analyses offer a bottom-up perspective on regional governance in Wales that might help to alter the functional pattern, in terms of leading to the successful market diffusion of these low carbon building technologies, while improving the relevant innovation capability within the region.

The comparison of the function patterns of the two systems has suggested that a certain degree of innovation capability has been established in Wales, characterised by the general presence of local knowledge networks or partnerships often involving a range of actors (see Figure 6.5 and 6.6). Such inter-firm and inter-organisation collaborations have led to knowledge spill-overs, resulting in the emergence of a number of market-ready innovations. On the other hand, several system weaknesses were also identified, one of which is a lack of innovative and R&D performing SMEs in Wales; given that over 99% of the Welsh firms are either micro-enterprises (≤ 10 employees) or small businesses (≤ 50 employees), this just shows the scale of the challenges as well as the necessity to lift the innovation capability of Welsh small businesses. Also, the comparative analysis of the functional patterns suggested that the development of low carbon building technologies in Wales, as well as a possible low carbon transition in the Welsh built environment, may enter the virtuous cycles, or the right development paths or trajectories, if Welsh ministers are willing to whole-heartedly commit to the promotion of innovation, and the low carbon agenda, for both matters have seemed to slide into relative obscurity in recent years, as vividly illustrated by the development of the new Part L of Building Regulations for Wales.

More so, what lies beneath is a matter of 'path-dependence', or, in other words, whether the Welsh regional governance can break out of the old 'way-of-doing-things'. In Chapter 4, I discussed how '*maintaining high levels of employment*' became the single most important guideline for regional policy intervention in Wales since the 1930s. From then to now, with the establishment of an elected Welsh Government in-between, the distance travelled, in terms of the way of policy-making, does not seem to go very far, for 'jobs' still dominate the Welsh policy-making process. In the meantime, this old 'way-of-doing-things' has seemed to cause that the policy-making processes within the WG are less able to produce, or implement, well-defined long-term vision, policies or strategies, in a consistent, coherent manner.

As an attempt to address this 'path-dependence' while help to alter the functional patterns, a number of policy measures were recommended above (in Section 7.2, addressing Q.4), in line with four streams of thinking, *i.e.* 'technology foresight', 'the regulation-induced innovation hypothesis', 'demand-oriented policy measures', and 'support for small business innovations through *e.g.* R&D Consortia'. While borrowed, these recommended measures not only address both 'technology push' and 'demand pull' side of policy needs, but also represent different pathways out of 'lock-in' and 'path-dependence'.

7.3.1 Contribution of this study

This study contributes to two strands of literature. First, most of the literature on the low carbon built environment has focused on the supply side, *i.e.* the development of new technologies, systems and products, as well as methods of design, planning or evaluation etc. Few have approached the subject from an evolutionary, socio-technical perspective. As demonstrated, using the innovation system and functions approach has enabled to reframe the problem with respect to the development of low carbon building technologies, and to study it through the exploitation of interactions between economic, institutional and technological factors, thus opening a different problem space for alternative solutions.

Secondly, while the Technological Innovation System and functions approach have been increasingly used for analysing emerging technologies, most literatures have focused on the emergence of renewable energy technologies. To this end, this study is an attempt to study emergent technologies in some more traditional sectors, the *e.g.* agro-forestry, construction and steel industries. In general, the IS and functions approach has proved to be useful, and provided a much-needed structure that allow empirical findings to be organised and analysed in a systematic and coherent manner. In addition, such a structure has also made the comparison of different TISs involving different industrial sectors, actors and technologies possible, and somehow relevant, in that the focus of the comparison is functions and factors that affect the performance of the functions.

Meanwhile, this study has shown that the relevance of the function analysis was largely determined by how the functions are measured, and, in a way, how the different functions are interpreted. When the performance indicators were used to assess the extent to

which the functions have been fulfilled, the selection of indicators posed a major challenge for this study. Based on the reasons provided in Section 3.3, Chapter 3, a set of more generic indicators (see Table 6.1) was eventually proposed, with considerable inputs from some more established innovation assessment practices e.g. the EU Regional Innovation Scoreboard, largely because some of the indicators proposed in the existing TIS and functions literature (see Table 5.2) seem to be more specific towards assessing the emergence of renewable energy technologies, and less relevant to assess e.g. building technologies. To this end, the development of methods for functions assessment remains an important area of future research. If performance indicators are used as one of the methods, it may come to the question on whether separate generic indicators or sector-specific indicators should be adopted.

In addition, this research has explicitly studied TISs in the regional context, *i.e.* in Wales, which may help to address comments on how there is a lack of territorial embeddedness in the existing TIS literatures (Coenen and Truffer, 2012). As shown, while factors at the national, super-regional (EU) or international level are able to affect the innovation processes at the regional level, institutional settings at the regional level sometimes have more direct influence over the development and diffusion of emergent technologies in a given field. This can be ascribed to the power distribution and interaction between the regional, national and EU level e.g. WG's fully devolved authority over the planning and building regulations, or the nature of market formation, as some sectors or market segments (e.g. construction /housing market) are seen to be more local than others, which gives regional and local governments considerable discretion in stimulating demand through policy intervention.

On the other hand, this study has taken a close look at firm level activities and behaviours, e.g. small businesses vs. large firms in terms of their respective abilities to innovate, market and mobilise resources. As a result, firms are no longer treated as 'abstract' and 'homogeneous' entities, and a bottom-up, 'micro-to-macro' perspective is provided, where alternatives for regional institutional configuration were recommended, allowing policy-making to be more responsive to local needs and circumstances. Furthermore, as explained, this study has incorporated the literature on technological catch-up, which similarly enables to reframe the problem, and subsequently broadens the possible

solutions that can be applied to system weaknesses identified in the function analyses, as discussed.

Finally, as already pointed out in Section 3.5, Chapter 3, a methodological novelty of this study is the design of '*network maps of interactions between actors*' to help visually identify actors and their networks (the structural components of an IS) in a given TIS as it evolves (see Figures 5.2 and 6.4; 5.5 and 6.5). This contains a two-phase process: at first, a 'perceived' network map of a well-functioning TIS is developed, which is then used as the basis for examining which actors and networks have actually emerged in the generation, diffusion and utilisation of relevant innovations, subsequently resulting in the formation of a 'present' network map of a given TIS. In this respect, firms are visually no longer some 'abstract' and 'homogeneous' entities within an innovation system, while, from an actor-network interaction perspective, the network maps provide a supplementary interpretation of the status of a TIS, e.g. whether a TIS has reached the formative phase.

7.3.2 Issues for future research

As follows, a number of issues are identified, and subject to further research, some of which have been explored, to some extents, in this thesis, but better understanding is required.

First, there are some theoretical issues in relation to the innovation system and functions approach that need to be researched further. They include: (a) 'the development of methods for functions assessment', providing that performance indicators are used, whether separate categories of generic indicators and sector-specific indicators should be developed and used; (b) 'the system boundary of an IS', apart from spatial or sectoral boundaries, the functions of an IS is considered as a third way to define the boundary; the function analyses of the WTC and BISE TIS have shown varied 'open' (innovation or value chain) elements arising from one or more of the functions respectively, and at the meantime the nature of the multi-governance model operated in Wales has seen varied factors at national and EU, as well as international levels that can also affect the innovation processes at the regional level; this raises the question of whether all factors identified from all functions should be considered while defining the system boundary, or whether the focus should be placed on more specific factors e.g. technology-specific, economic-specific, or institution-specific factors.

Second, as reviewed in Chapter 4, the economic development in Wales has often seemed to be predominantly driven by external demand, from the age of coal and steel to the development of the modern manufacturing industry. This frequent disintegration between the Welsh production systems and local demand profile was seen doing little to improve the innovation capability of Welsh firms. To this end, it will be interesting to study the role of demand, especially that of domestic demand, in influencing the innovation capability of local firms. In relation to the theme of this study, two potential research topics were identified: (c) the extent to which domestic demand can affect the innovation performance of local firms in the context of technological catch-up within a region⁸⁸, with findings to be further linked to the development of low carbon technologies in a catch-up region such as Wales, and (d) whether and how a lead market may take shape in Wales for e.g. BISE innovations, through the introduction of demand-oriented policy measures with government or public sectors acting as sophisticated or stringent buyers to enable and push the innovation performance of local firms.

Finally, when four different streams of policy measures are recommended in this study, it is believed that (e) an integrated approach is required; however, how this might work requires further research, because it is not just about the policy and programme, but also how the regional governance is organised and how governance capability should be built up to deliver these policies and programmes, in a multi-level governance model which affects Wales in every aspects.

⁸⁸ I submitted a research proposal on this subject for the EU Marie Curie International Outgoing fellowship Programme in 2013, although my application was unsuccessful.

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Appendix A:

Lists of the organisational affiliation of the interviewees

In accordance with good ethical practices, before the interviews took place, the relevant ethical approval was formally sought, and subsequently obtained. Here, only the organisational affiliations of the interviewees are given as follows, whereas the identities of individual interviewees are anonymised, in order to respect and protect their privacy.

For the case study of Welsh Grown Timber for Construction (WTC)

- Benfield Att Group
- BRE Wales
- BSW Timber
- Coed Cymru
- Confor Wales
- Country Land and Business Association, Wales
- Design Research Unit Wales, Welsh School of Architecture, Cardiff University
- Forest Products Research Institute, Edinburgh Napier University
- Elements Europe
- Holbrook Timber Frame Ltd
- IBI Nightingale
- Kenton Jones,
- *Previously* Forestry Commission for Wales
- Scott Brownrigg Associates
- Thomas Joinery
- Wales Forest Business Partnership
- The Welsh Government
- Wood Knowledge Wales

In total, 20 interviews involving 22 interviewees were carried out between March 2012 and February 2013. One of the early interviews was conducted involving a small group of three participants.

For the case study of Building Integrated Solar Energy Systems (BISE) in Wales

- BayWa r.e Solar System Ltd.
- Centre for Solar Energy Research, Glyndŵr University
- Dyesol UK Limited

- Emerson Control Techniques Ltd., European Headquarter
- GB Sol
- IQE
- Low Carbon Research Institute, Cardiff University
- Pure Wafer International Ltd.
- School of Planning and Geography, Cardiff University
- Sharp Manufacturing UK/Wales
- The SPECIFIC Innovation and Knowledge Centre
- TATA Colour
- The REGAIN project, Blaenau Gwent County Borough Council
- The Welsh Government

In total, 14 interviews involving 14 interviewees were carried out between December 2012 and July 2013.

Appendix B:

An example copy of the interview questions

As described, the interview questions were devised to reflect how the functions of an innovation system may have been performed, which in turn provided some structure and direction for the interviews. Since the two selected case studies involve different technologies, some related questions were composed differently so to accommodate the technological field involved. As follows, an example copy of the interview questions that were specifically prepared for the case study of Building Integrated Solar Energy Systems (BISE) in Wales is provided.

Interview questions devised for the BISE case study

About the company:

- When and how did you start your business?
- Business activities / products (do you sell any system); Are they different from when you first started (new product / service)? How many product innovation (improvement on exist products / new products (process) have you developed in the last two years?
- Do you regard your company a hi-tech company?
- Annual turnover;
- Why do you choose this site to set up your business?

How many people does the company employ at present? Any changes of number in the last 5 years? In which division? The share of highly-qualified people? Any problem to recruit?

What is the target market for your products / services (local, national, international/ sector)? Who are your users /clients?

How do you market your products and services? Do you use any external (paid or free) agents to promote your products and services?

In term of R&D, is there any particular department or persons who is responsible for research and development of new products and services?

Are you a member of any trade association? If so, how does it benefit your business?

Do you have contacts or co-operate with the following institutes / organizations? If yes, in which way do you collaborate?

- Public research institutes (university) [Welsh Opto-electronic forum PV group]
- Private / other firm (other renewable technology companies)
- Business consultancy
- Local authorities / chamber of commerce / business enterprises?

How important is for your business to keep updated with the latest information, development and knowledge with regard to solar technologies? In which way do you normally acquire the latest information and technological development?

Have you been invited to conference, new product launch event or training program, or trade events? How useful do you think they are?

Do you provide any in-house training?

Who are your main competitors? What is the key for your company to stay competitive?

Do you use any suppliers / sub-contractor for products and services?

How is the company financed (own / foreign invest/ venture capital)? Does the company have difficulties to find capital? Does the company use any governmental grant? If yes, which programme? How are you aware of it?

What are the reasons for the company to invest in the solar energy market? If so, whether do you think that the solar technologies (PV, solar thermal) are mature technologies? If not (If yes, in order to compete with other low carbon technologies) what more needs to be done, in term of both technology and market development, [without government subsidy]?

In your opinion, what is the potential for solar energy development in Wales? A lot of policy-makers are talking about the energy policy's "trilemma", how do you think that solar energy development can meet the challenges posed by the 'trilemma? At moment, most of installation of PV are driven by FIT, without the subsidy scheme, how can solar energy /PV market grow?

In your opinion, will a strong home market for solar energy help the Welsh solar company, especially at the early stage? If yes, in which way? What need to be done to develop a strong home market?

In your view, what is the direction for solar technology development? Whether will any current technologies / products still exist or be replaced in 5 years (by what)?

Some have suggested that the Welsh research on solar technology lacks of break-through innovations, do you agree this view?