An Investigation into the Determinants of Diffusion of Renewable Energy

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I would like to dedicate this thesis to my mother, Eirini.

Declaration

I, Konstantinos Delaportas, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Konstantinos Delaportas

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Abstract

The aim of this work is to examine the mechanisms and the factors that influence the diffusion of renewable energy technologies (RETs), in particular Solar PV and Wind power. To understand them, three theoretical approaches are used together: the neoclassical approach to diffusion, Rogers' Diffusion of Innovation (DOI) framework, and the Technology Innovation System (TIS) approach. A key problem with the first two approaches is that they take a static view of this dynamic process, while the latter fails to do so adequately. Thus, we recognised that in the literature there is a gap in the understanding of how the diffusion determinants vary across time. To deal with this, we use life-cycle models in conjunction with these theories, so that we can identify theoretically meaningful points in time and try to examine how the diffusion determinants vary as the technology evolves. In more details, we separate the time of diffusion of a technology into four distinct periods, and for each try to identify what factors make the potential users more likely to adopt the RET. Driven by the complexity and the multifaceted nature of diffusion, we use a variety of methodological approaches to identify the mechanisms and factors of diffusion. These include quantitative techniques (survival models, and panel data econometrics), qualitative techniques (case studies), and a third methodology designed to bridge the qualitative-quantitative divide, known as Qualitative Comparative Analysis (QCA). We find evidence supporting the varying nature of the diffusion determinants, independently of which theory we examine. In line with the mainstream literature on the diffusion of RETs, a key factor which was found significant across all time periods was government intervention; however, its importance tended to decrease as the technology matures. Additionally, our research illustrated that diffusion cannot be solely explained by looking at individual factors but rather it is better understood as the outcome of an evolving system, which includes a wide variety of institutions, which vary across country but also according to the country's distance to the technological frontier.

List of Abbreviations

CRES Centre for Renewable Energy Sources
CZ The Czech Republic
DECC Department of Energy and Climate Change
DOI Diffusion of Innovations Framework by Rogers
DD Dominant Design
EE Entrepreneurial Experimentation
ETS UK Emissions Trading Scheme
HELAPCO Hellenic Association of Photovoltaic Companies
ILC Industry Life-Cycle
IRENA International Renewable Energy Agency
KD Knowledge Development Function
MF Market Formation
NIMBY Not In My Back Yard
PLC Product-Life Cycle
RETs Renewable Energy Technologies
RES Renewable Energy Sources
RM Resource Mobilisation
TIS Technology Innovation Systems

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Chapter 1

Introduction

1.1 Aim of this PhD

I have been under the impression that people generally were rational, always adopted the most efficient technologies, and always tried to find the best way to achieve a given objective. At least, this is what I was taught when I started my education in economics, a discipline aimed at finding ways to maximize the largest number of needs using the lowest amount of resources. However, these were the assumptions of neoclassical economists, describing an idealized version of the world which could be explained through mathematical modelling. Later, I familiarized myself with an alternative literature on economics, which challenged the traditional assumptions of neoclassical economists on rationality, and introduced new concepts such as bounded rationality and path dependence. There was also another stream of literature which challenges rationality not on an individual basis, but at a social level; it argues that even if individuals are rational, we cannot assume that the rationality will persist if we look at them as whole.

At the same time, I became interested in the issues of climate change and renewable energy technologies (RETs). These technologies clearly are superior to conventional ones from a sustainability perspective, since they exist in unlimited supply, and cause no visible environmental harm to society. Their drawback is their intermittent supply, although this applies primarily to solar and wind technologies. On the basis of all these parameters, one would expect the diffusion of these technologies to be widespread (Shama, 1983). However, what we observe is a world decarbonization at a very slow pace. At the same time, threats related to global warming, climate change, nuclear accidents, and geopolitical concerns have increased the importance of transformations to the energy sector, especially towards independence of energy supply. In response, countries worldwide have been investing vast sums in renewable energy research and development (R&D) and subsidies for the deployment of these resources. However, the global rate of adoption remains very slow (Negro et al., 2012).

Driven partly by my aspirations to make the world a better place, I decided to embark on a PhD project that would shed some light on why people are not trying to protect themselves and the environment in which they live. In particular, this PhD research is my attempt to understand the reasons for the slow diffusion of renewable energy, and I hope that it provides a few interesting new perspectives on the process and the design of more effective policies.

It should be noted that RETs are not the only path to decarbonization. To achieve this transformation, two main approaches in the scientific and public domains have been proposed: increasing the energy efficiency of non-renewable sources, and/or increase the use of renewable energy sources. The first option could be viewed as implying incremental innovations to electricity production, while the second refers to radical innovation since it involves radical transformation to the way electricity is produced. I considered exploring the diffusion of radical innovations to be more fascinating than studying incremental innovation.

In this work, we are interested in examining the diffusion mechanisms of two RETs: wind electricity systems and solar photovoltaic systems. Arguably, among the RETs (i.e. excluding hydro and geothermal), these two technologies are the most widespread and are the most cost competitive with conventional oil resources. At the same time, public perception of RETs tends towards solar and wind energy, rather than biomass, etc.

After taking the decision to pursue a PhD project to try to understand the adoption of new technologies, I began to look for examples in history of how radical innovations get adopted. Personally, one of the most exciting case studies came from the maritime industry, where the adoption of the steam ship was a very gradual process. In particular, steam ships were more efficient than sailing ships (Gilfillan, 1935), but the market instead of immediately adopting them, responded by trying to make sailing ships more efficient, which led to a series of incremental innovations of these ships, before they were eventually abandoned for the more efficient steam ones.

To understand this resistance to change, I decided to delve more deeply in academic research. There, I came across evolutionary economics, and the notion of routines, which are established behavioural norms and patterns of behaviour that organisations follow, and are unwilling to change (Nelson & Winter, 2009). Moreover, I found that the idea that people and organisations are not rational agents who strive to find more efficient ways to do things, was shared widely by the academic community (Davis, 1989; Venkatesh et al., 2003; Rogers, 2010). In particular, i discovered that there was a whole field in innovation research, diffusion studies, which tries to understand how does adoption of a new technology take place.

Diffusion studies as a field seemed very exciting and intellectually stimulating as it encompasses several disciplines in the social sciences. In economics, linear models of diffusion are proposed to formalize theoretical patterns in mathematical models (e.g. Griliches, 1957; Stoneman, 1983). There were examples also in the field of sociology of more integrative methods to describe the process (e.g. Rogers 1962). Similarly, the marketing literature has tried to understand the factors that influence the decisions of consumers to purchase certain items, which is another description of a diffusion process. However, most of these studies can be considered to be complementary, rather than competing to each other in attempting to explain the diffusion "phenomenon".

In the late 1980s, the diffusion process was reconceptualized and an attempt was made to view the whole process as part of a system. This approach has its origins in the concept of innovation systems (Lundvall, 1985; Freeman, 1995), and the idea that innovations do not arise within a linear process, but rather that the whole process involves two-way interactions and feedback loops among the various elements of the system. This group of theories was a response to simplistic views of the innovation process that took no account of the various networks of agents and the institutions that determine the process.

This thesis concurs with the view that innovation and its diffusion is not a linear process, and is better understood if viewed as a systemic process. However, we try to expand this view, by looking not just at the system elements, but also at the dynamics of the system and how these evolve with time.

This systemic approach cannot be examined by focusing solely on the economics of the new technology. An approach is needed that combines analysis of the evolution of each of the elements of the system and how they interact, which can only be achieved by looking at the framework that incorporates all these different interactions. I decided in this thesis to try to understand how the diffusion of an innovation can be explained as an outcome of the development of an innovation system. To achieve this, I decided to focus on the major diffusion theories, and to complement the analysis with those theories that have been used almost exclusively in the field of renewable energy.

In the course of a deeper investigation of the work on diffusion, I came across the S-curve, which is the most common pattern of the spread of an innovation in the market. However, a similar pattern can be found in the evolution of industries, which is investigated by a whole literature on industry-life cycle models. In some ways, both diffusion theories and life-cycle models can be said to start from an S-curve, but they develop along different paths. However, I believe that there are complementarities between these theories and life cycle models, and they can both be used together to provide a better understanding of the diffusion process. Therefore, the three main theoretical pillars upon which this work is based on are: diffusion theories, technological innovation systems, and life-cycle models.

In the remaining of this chapter, I start by presenting the main diffusion theories, then review the literature on life-cycle models before finally discussing technology innovation systems. Then, I present the main findings and the contributions of this doctoral research, as well as some issues for policy research. Before proceeding with the analysis, I provide a technological overview of the two main RETs that constitute the basis of the empirical research in subsequent chapters.

1.2 The Technological Context of this work

1.2.1 Solar Photovoltaic (PV)

The first technology considered is solar PV. In particular, we examine the diffusion of solar PV electricity systems, which are electrical installations which use energy from the sun and convert it to electricity. For simplicity and reader-friendliness, we use the term solar PV. In layman terms, a "solar PV system is one which can use light energy and generate electricity, using semiconductors. Semiconductors are materials whose conductivity can be enhanced through energy input in the form of heat or light" (Brüns, 2010, p.162).

Solar energy was exploited as long ago as in ancient Rome, where citizens exploited the heating properties of the sun in residential installations. Its next use did not occur until the 18th and 19th centuries, when scientists began to exploit the sun's heating properties[1] and to convert heat power into kinetic energy[2]. It was not until 1886 that the American inventor, Charles Fritts, created the first solar cells from selenium which managed to convert a minimal amount of sun into electricity (Biggs, 2012). The efficiency of electricity production began to increase dramatically in the early 20th century, when scientists started to use silicon as the material for solar panels. One of the best known scientists exploring this effect was Albert Einstein, whose work on photoelectricity and relativity won him the Nobel Prize in 1921.

Practical and commercial use of PV cells started first in the USA in 1954 in the Bell Laboratories, where scientists managed to increase their efficiency to as much as 4%, which was sufficient to power various electrical devices. This discovery was taken up by the US government and used it to power satellites and, in 1959, solar cells were available for private users. However, until the 1960s, their cost was prohibitive (around $100 per watt) and, as a result, their adoption in other than in space related missions was relatively minor[3]. For example, by 1976, NASA's Lewis Research Center had installed "83 photovoltaic power systems across the globe, to provide vaccine refrigeration, room lighting, medical clinic lighting, telecommunications, water pumping, grain milling and classroom television" (BPVA), 2010. By the 1970s, due to the work of Elliot Berman, the price of solar had dropped to $20 per watt, which was till expensive for most residential uses, but

[1]See e.g. the work of Horace-Benedict de Saussure (1796) in making a solar oven.

[2]See e.g. Augustin Mouchot's work on solar energy (1869).

[3]See e.g. the satellite Vanguard, Explorer III, Vanguard II, and Sputnik-3, which used solar cells to generate electricity in 1958, and Explorer VI in 1959, Telstar in 1962, and Nimbus in 1966.

made economic sense for some commercial applications such as navigational warning lights and horns in lighthouses and rail-road crossings. It became standard practice to use solar modules to operate signalling systems and offshore oil rigs (Brüns, 2010, p.171).

The most significant technological breakthrough in solar PV came in 1985, when the University of South Wales managed to break the 20% efficiency barrier for silicon solar cells, suggesting that solar PV technologies were sufficiently price competitive to allow their wider adoption and potentially enough efficiency to justify grid integration (Renewableenergyhub.co.uk, 2016). However, up to the late 1980s, there were no significant projects beyond quasi-experimental ones, demand and production volumes remained low, and thus the cost too high for mass adoption. It can be argued, that until the end of the 1980s, the global PV industry was in the early emergent technology stage. Figure 1.1 depicts the evolution of prices and capacity, and Figure 1.2 focuses only on the most recent evolution of the prices.

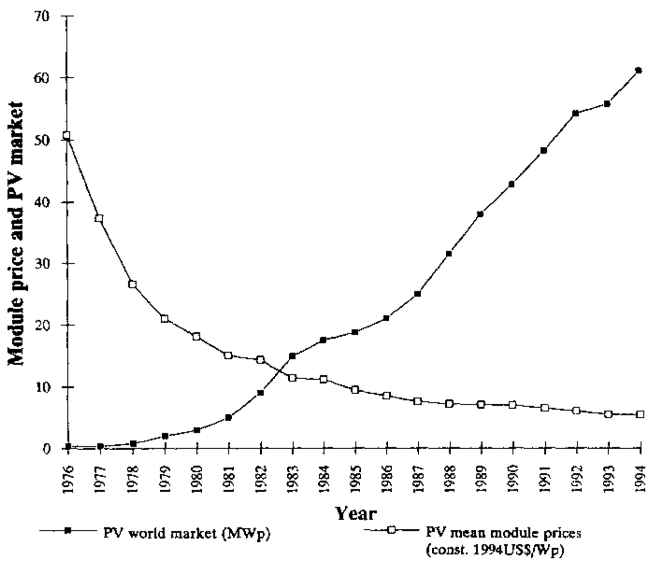


Fig. 1.1 Solar PV capacity and Module prices (1976-1994)

Source:Ayres et al., (1998)

The 1990s was a key decade for the development and successful commercialization of solar PV; the first commercially viable technologies became operational and various niche outlets were created. Examples include the integration of the first grid-supported photovoltaic systems in California (1993) and Germany (1994), the first flight made by a solar powered plane, Icare, over Germany (1996), and an increase in the efficiency of solar cells to up to 32.3% (1999). This phase was characterized by the emergence of various niche markets across the world, accompanied by a worldwide production of PV in excess of 200 megawatts.

The next major period that can be identified started in the early 2000s, when the technologies become standardized, and costs started to stabilize, potentially pointing to the establishment of a dominant design. These developments were accompanied by a surge in global demand for solar PV, fuelled primarily by generous subsidies in Europe, which caused a boom in the market for solar PV. Demand outweighed supply, leading to an increase in the price of PV modules. However, by then, the manufacture of solar panels had become standardized and they were being produced in vast quantities in China, which was the world's largest producer in the early 2000s. The increase in the production of solar PV was so dramatic in China that it led to a massive collapse in the price of panels after 2007 (see Figure 1.2). By 2010, global use of solar PV had reached almost 140,000MW, suggesting that the technology had entered the mass market phase (see Figure 1.2).

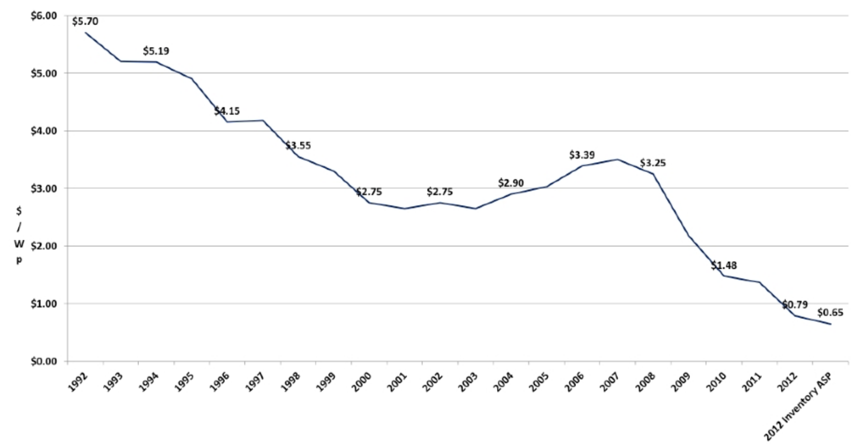
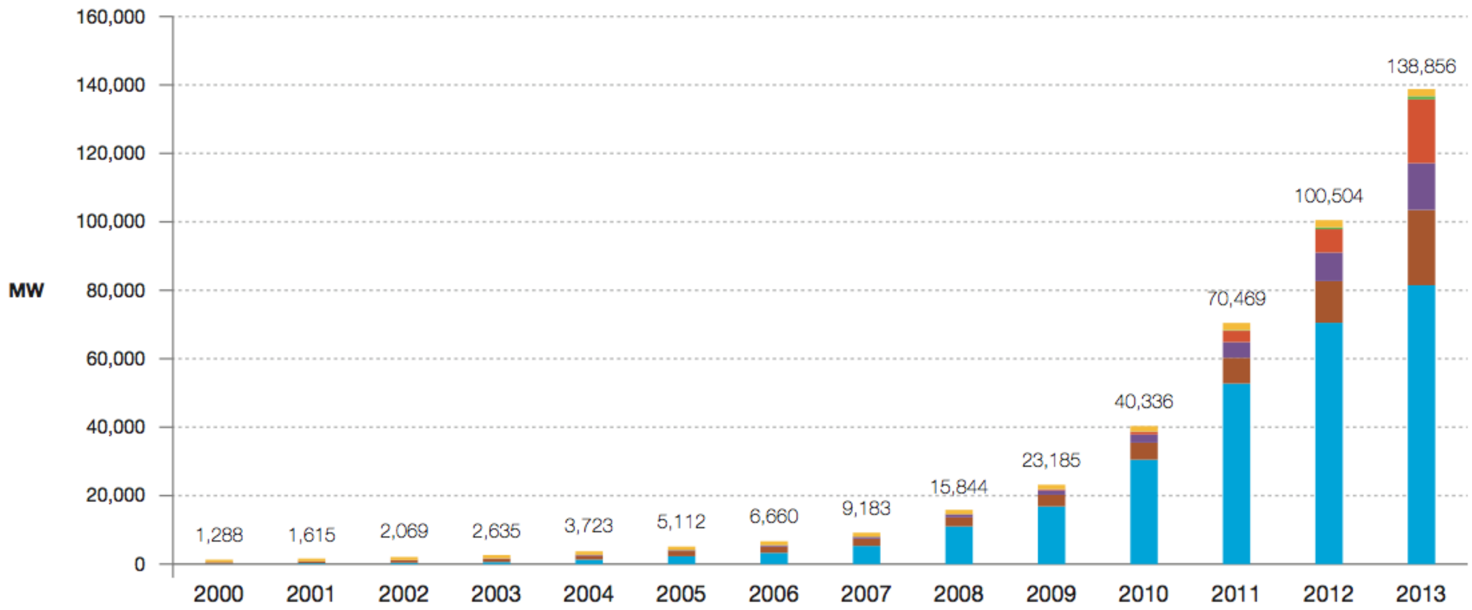


Fig. 1.2 Solar PV Module prices ($ per W) (1992-2012)

Source:Mints, 2013



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
RoW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,590	2,098	2,098	2,098
MEA	n/a	n/a	n/a	n/a	1	1	1	2	3	25	80	205	570	953
China	19	24	42	52	62	70	80	100	140	300	800	3,300	6,800	18,600
Americas	21	24	54	102	163	246	355	522	828	1,328	2,410	4,590	8,365	13,727
APAC	368	496	686	916	1,198	1,502	1,827	2,098	2,628	3,373	4,951	7,513	12,159	21,992
Europe	129	265	399	601	1,306	2,291	3,289	5,312	11,020	16,854	30,505	52,764	70,513	81,488
Total	**1,288**	**1,615**	**2,069**	**2,635**	**3,723**	**5,112**	**6,660**	**9,183**	**15,844**	**23,185**	**40,336**	**70,469**	**100,504**	**138,856**

RoW: Rest of the World. MEA: Middle East and Africa. APAC: Asia Pacific.

Fig. 1.3 Evolution of global PV cumulative installed capacity 2000-2013

Source:EPIA 2013

The data suggest that the majority of installations are in Europe, followed by Asia Pacific and China. Surprisingly, the USA, which dominated the market in the 1980s achieving a 21% share of the global PV market in 1983 (Brüns, 2010, p.171) is currently lagging behind Europe and China. Table 1.1 provides a breakdown of the capital costs required for a typical solar park based on standardized PV systems. A PV system consists of modules, inverters, batteries and all the installation and control components for the modules, inverters and batteries. Table1.1 shows that half of the capital investment is directed towards the modules[4], with connection to the grid the next most important capital cost.

Table 1.1 Breakdown of Costs for a Solar System (2012)

Breakdown of Solar PV Capital costs	**Share of Total Cost as %**
PV modules	50%
Electrical Engineering-supply (inc. grid infastructure)	18%
Mechanical Engineering	15%
Civil Works	6%
Electrical Engineering-installation	4%
Site Security	3%
Misc.	4%
Source: IEA-RETD	

What the future holds for the evolution of the solar PV industry is uncertain. The current research emphasis is on the development of more effective storage solutions, which would help to alleviate the main problem related to solar of intermittent supply; quite simply, if the sun does not shine, no electricity is produced, which implies that electricity can be generated for only half a day at best. So long as this major issue of intermittent supply remains unresolved due to lack of effective storage solutions, solar PV cannot be considered a perfect substitute for conventional non-renewable energy sources.

1.2.2 Wind Energy

Human beings have tried to harness the power of wind since ancient times, mainly in the form of kinetic power for sailing ships. Around 2000BC, the ancient Babylonians created the first windmills, and by 200BC windmills were being used in China to pump water and to grind grain (Energy.gov). Around the 11th century AD, crusaders and merchants brought the idea of windmills to Europe, whose use spread rapidly especially for

[4]The importance of this component explains why it was the focus of the previous section, and why the literature mostly focuses on the evolution in these prices.

milling grain. However, after the industrial revolution, windmills began to be replaced by steam engines.

Professor James Blyth can be credited with discovering the first windmill which could be used to produce electricity in 1887 in Glasgow, Scotland (Nixon, 2008). At approximately the same time (1890), the Danes started installing vast wind turbines to generate electricity and by 1904 they had founded the Society of Wind Electricians. By the 1940s, they had managed to construct a turbine that could produce 1.25MW of electricity from 30mph wind speeds, which then was fed into the grid.

The interest in this technology remained localized, primarily in Denmark, until the 1970s oil crises, which drove the quest for alternative sources of energy with minimal risk. From all the alternative sources available at that time, the technology closest to commercialization was wind, which suddenly became affordable due to the huge increase in the price of conventional electricity sources. The US then began to invest heavily in R&D and demonstration projects, and 10 years later (1980) had manage to manufacture the largest wind turbine (7.5MW) and had the world's largest wind farm (in New Hampshire). In 1980, the US was the largest market for wind turbines. However, the technology remained at an experimental stage, with no major diffusion in any country, due primarily to its prohibitively high cost (Figure 1.5).

The 1990s can be considered the period of standardization of wind technologies with most turbines in the range of 1MW (Figure 1.4), and cost stabilization (Figure 1.5). Also in the 1990s, Europe began to be an important market, driven partly by its excellent wind resources, but also by high energy costs (Ackermann & Söder, 2002).

By the mid 2000s, the industry had taken off on a global scale (see Figure 1.6), and turbines continued to get bigger and bigger (Figure 1.4). In 2012, the largest wind capacities were in China, the USA, Spain and Germany (Figure 1.7). Denmark had dropped out of the group of top wind producers, probably because of its relatively small size compared to the other actors.

Over time, various designs were proposed and competed to harness wind power, as well as many other differences related to the materials used for turbines and blades, etc. However, the two main differences related to wind generator designs were the vertical/horizontal orientation of the axis and the number of blades. Vertical axis machines are a simpler design, but are less efficient than horizontal axis machines. There have

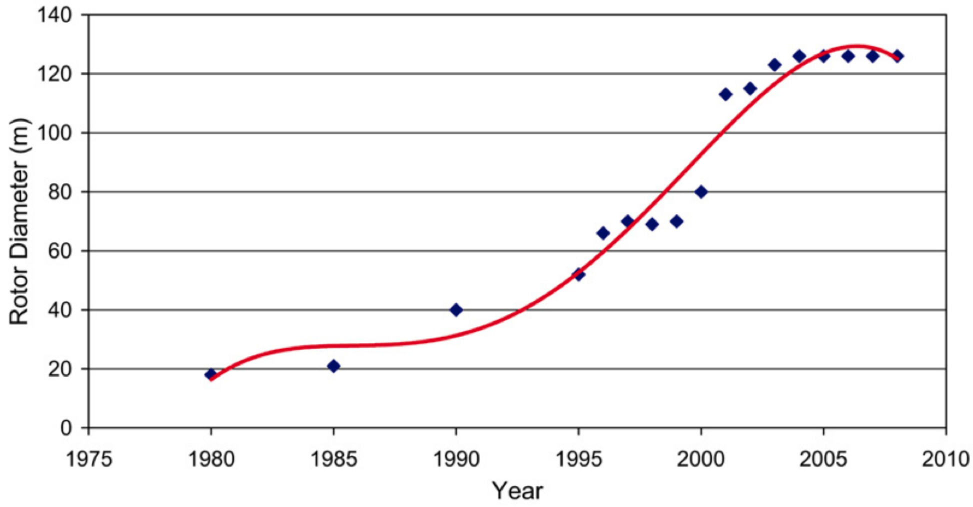


Fig. 1.4 Contemporary Wind Turbines' Diameter (1980-2010)

Source: Source: Kaldellis & Zafirakis 2011

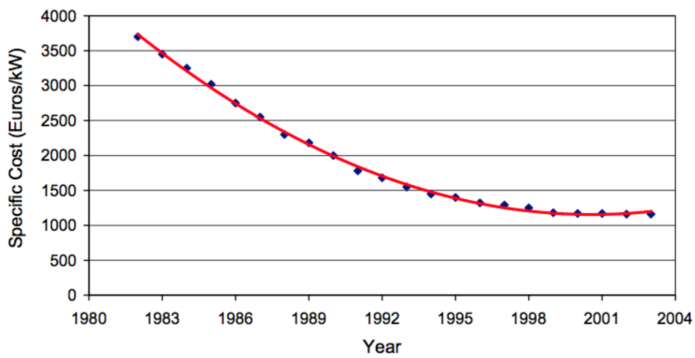


Fig. 1.5 Time Evolution of the Specific Turnkey Cost of Onshore Wind Farms(1980-2004)

Source: Kaldellis & Zafirakis 2011

been several competing designs, such as the Post, the Tower, the Smock, the American windmills, etc. (Gasch and Twele, 2012). Eventually, in the 1990s, the typical horizontal three blade turbine became the industry standard. The typical wind mill consists of a mechanism to catch the wind (the arms or blades), a mechanism that rotates the blades so that they can follow the wind, and a gear system which transfers the energy to an electrical generator (Ragheb, 2014).

The future for wind is twofold. On the one hand, there is a continuous quest for increased

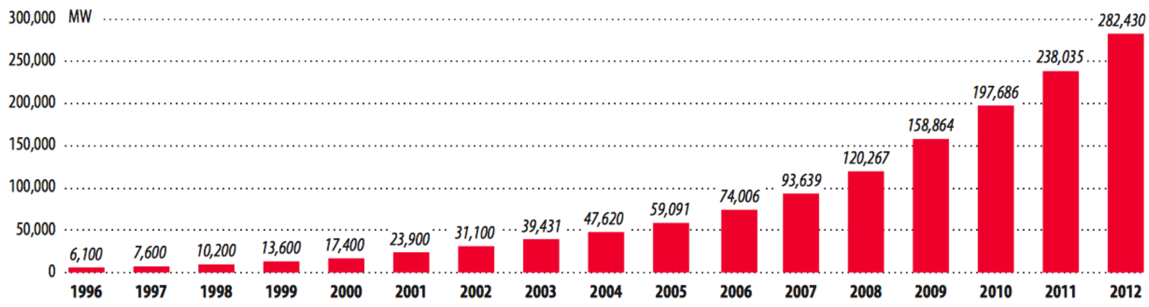


Fig. 1.6 Global Cumulative Installed Wind Capacity (1996-2012)

Source: GWEC 2012

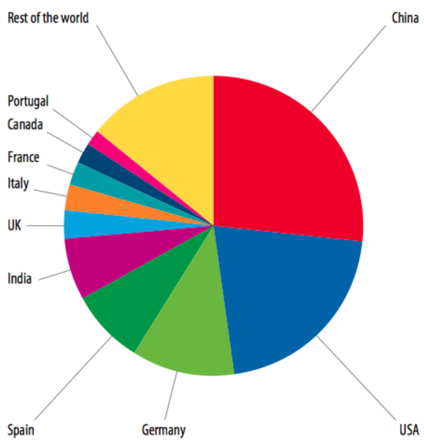


Fig. 1.7 Top 10 Cumulative Wind Capacity Countries (2012)

Source: GWEC 2013

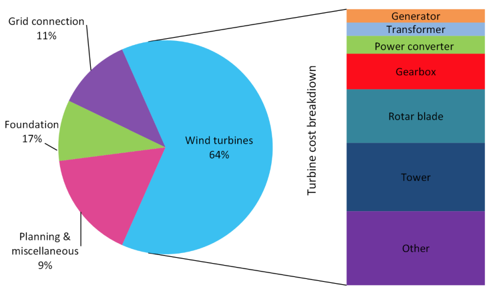


Fig. 1.8 Breakdown of Wind capital costs

Source: IRENA

efficiency[5] of wind turbines. On the other hand, the reduced availability of land and space suitable for onshore wind installations has driven the location of to the sea, and triggered the a new industry of offshore wind. This technology has been around since 1991 when the first offshore wind farm was established in Vindeby, Denmark. The idea is very similar to onshore wind, but there are also many parallels with offshore oil rigs, because the turbines are built in the out at sea. Offshore has various advantages in terms of efficiency since there is more wind and fewer "Not In My Back Yard" (NIMBY) problems since the turbines are almost invisible to the naked eye.

[5]Efficiency in the context of wind turbines can mean two things; first, there is a capacity factor, which is the percentage of time that the wind turbines are active; second, there is a load factor, which is the percentage of the turbine's potential output that is actually achieved.

1.3 A Summary of the Theories on Diffusion of Innovation

In the field of diffusion studies various theories have been proposed by various academic traditions ranging from rural sociology and clinical epidemiology, to marketing and organization studies, and different academic disciplines[6] ranging from sociology and psychology to anthropology, political science and economics. All have tried to explain this process (Greenhalgh et al., 2005), with each discipline providing a different interpretation of diffusion, different success criteria and different theoretical frameworks. However, since the 1970s, there have been no radical changes or hugely innovative approaches (Meade & Islam, 2006), apart from the new systems of innovation approach which we discuss next. The remainder of this section presents the key conceptualization of the diffusion process and then focuses on the neoclassical and the sociological approach to its determinants, the former because it is the concept that has dominated policy making in RETs, and the latter because it is the most common approach in the field of diffusion studies.

1.3.1 The Diffusion Process

To understand the factors that influence the diffusion of innovation, we need first to understand what diffusion is. Wejnert (2002) employs Rogers's (1962) definition of diffusion "as the spread of ideas, concepts, practices, within a social system, where the spread denotes flow or movement from a source to an adopter" (Wejnert, 2002, p. 297). Mansfield (1961) proposes a three-level characterization of diffusion as: imitation/interfirm diffusion, which is the spread of new processes among the firms in any industry; intra-firm diffusion, which points to the adoption of a technology within a firm; overall diffusion, which is the spread of an innovation throughout the whole industry. The difference between the first and last types is subtle, but can be best understood by looking at the metrics; for the first we look at the proportion of the firms in the industry which use the innovation, and for the second we study the proportion of all output in the industry produced by the particular technology. In the context of this work, none of these definitions is perfectly appropriate, but the one that is closest is overall diffusion, and in our case, in the electricity production industry.

The literature suggests the existence of three stages between the moment of informa-

[6] For an extensive reference list of the work done in different disciplines, see MacVaugh and Schiavone (2010

tion about the existence of the innovation, and the decision to adopt it[7] (Burt, 1973, p. 126). The process starts with the potential adopter becoming aware of the innovation and beginning to gather information on it in order to form a decision about whether or not to adopt the innovation. The final phase of adoption by the user is the process of behavioural adoption, which involves a change of behaviour in the user in order to accommodate adoption of the new technology. The length of this process is described by Rogers as the rate of adoption. Formally, Rogers views it as the relative speed with which an innovation is adopted by individuals and organizations (Rogers, 2010, p. 232). It is generally measured as the number of individuals who adopt a new idea in a specified period. So the rate of adoption is a numerical indicator of the steepness of the adoption curve for an innovation[8].

The dominant stylized fact for the diffusion of a product across time is that it follows an S-curve, if we envisage it on a set of axes where x is time and y is the number of adopters. This means that the proportion adopted is an increasing function of time which initially is convex and eventually turns concave (Jensen, 1982, p.182). This is depicted in Figure 1.9.

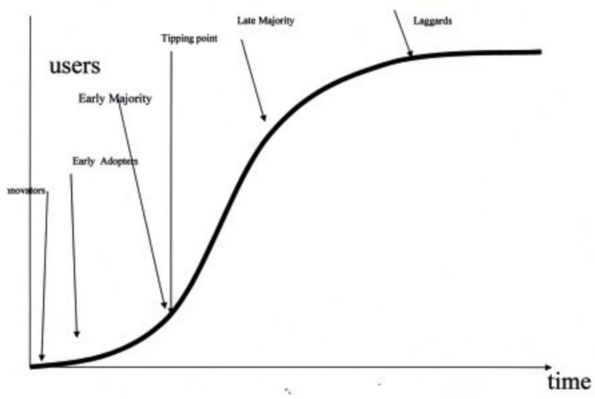


Fig. 1.9 The Diffusion Process

Source: Rogers 1962

The main idea is that when an innovation first emerges, it has relatively few adopters - the innovators. Gradually, over time, the number of users increases until a point in

[7]The simplistic view of diffusion adopted by the early theorists is clear; they assumed that innovation was a well-defined homogenous phenomenon rather than an imprecise and incomplete technology which is under constant development and subsequent improvement.

[8]The explanations for different speeds of adoption vary and are discussed in the next section.

time referred to as the tipping point when the number of adopters starts to increase exponentially. Following that period, the speed of diffusion decreases as the technology eventually penetrates the whole of the market. Based on time of adoption, adopters fall into one of five categories: Innovators, Early Adopters, Early Majority, Late Majority and Laggards[9] (Rogers, 2010). The leading explanation for the S-shape is the epidemic model, which suggests that the differences among groups of adopters is explained by the amount of information they have on a product, the way they use it, and the impact of this information. Differences in the timing for different users in relation to the acquisition and processing of this information explains the existence of different groups.

There are many potential explanations for why some technologies diffuse faster than others (e.g. complexity of the technology, switching costs, etc.); however, in all of these, the research assumes that agents are identical. This assumption is the main point of criticism of competing explanations for the S-curves, and in particular the probit model (Geroski, 2000). The key premise behind this model is that diffusion does not depend solely on product characteristics, but is also a function of the incorporation of differences in the goals, needs and abilities of firms.

As summarized by MacVaugh and Schiavone (2010), the diffusion process can be seen as taking place at three distinct levels: micro, meso and macro. Work on the micro level examines the learning conditions and the individual domain of a single adopter, and belongs mostly to the economics (e.g. Griliches, 1957) and marketing disciplines (e.g. Moore & Benbasat, 1991). Work on the meso level investigates how different users interact, and how this interaction influences the process. Finally, the macro level includes the economic system and the market within which the innovation diffusion takes place. The benefit of this three-tier classification is that it allows us to group the various determinants into different levels: at the micro level, the adoption decision is based on the preferences of the individual; at the meso level, the decision is determined by the interrelation between the community of users; at the macro level, the decision is shaped by the interplay between the users and the market. The weakness of this classification is that it does not allow for interactions across these levels[10].

The multidimensionality of the process explains why it has attracted the attention of so

[9] 2.5%, 13.5%, 34%, 34% and 16% of the population is predicted to fall into these respective stages.

[10] An exception to this can be found in the work of Fok and Franses (2007) who use a multi-level nonlinear regression for a panel of time series to examine the diffusion of scientific publications. Nonetheless, this approach has yet to be adopted in the field, probably due to the difficulties related to collecting appropriate data.

many distinct academic disciplines. The diffusion of innovations has its origins in the work of Tarde (1903) on the "Laws of Imitations" and his attempt to understand why among a certain number of inventions that exist at the same point in time, some are imitated and others are not. However, this work is rather general, and the subjects of investigation range from linguistics and mythological ideas to industrial processes. In the discipline of economics, diffusion was first investigated by Ryan and Gross (1943) who studied the diffusion of hybrid seeds. Later, Coleman, Menzel and Katz (1955) tried to understand how a new drug becomes diffused among physicians, and even later, diffusion was investigated in the context of political ideas among states (Walker, 1969), policy innovations (Berry & Berry, 1992; Valente 1995), and political reforms (Starr, 1991). It could be said that this represents the diffusion of diffusion theory across all the disciplines in the social sciences.

1.3.2 Neoclassical Economics Perspective

One of the earliest approaches to explaining diffusion was proposed by the neoclassical economists, who believed that the only factor influencing the diffusion of an innovation was its profitability; the cheaper the product, or the higher the expected profitability, the faster would be its rate of adoption. The characterization as neoclassical is based on the assumptions made by the authors of this literature[11]. Firstly, they viewed all individual adopters as similar in every way, whose sole objective was to maximize utility which was a function of their wealth. Secondly, they assumed that the preferences of individuals and the technology they were investigating remained constant across time. Thirdly, all models assume that diffusion depends exclusively on the characteristics of the innovation, especially its perceived profitability. Fourthly, that the innovation is readily available to all users.

The first work in the neoclassical field was Griliches' pioneering research on hybrid corn[12] which showed that part of its increased adoption rate was attributable to profitability (Griliches, 1957). Griliches argued also that the decision to adopt depends primarily upon the "availability of the innovation in the region in question" (Griliches, 1957, p. 507); in other words, one should not try to understand the reasons why an innovation

[11] This list of assumptions comes from the author's own summary of the literature. For the interested reader, Geroski (2000) makes a thorough literature review of the various models that have been used, and their assumptions

[12] Although investigation of the topic of hybrid seed might not sound an attractive research subject, this research is of particular interest because of the importance of hybrid seeds to farmers in that period. Seeds are the main input to a farmer's production process, and farming, at that time, was the major source of income in the US economy.

has not diffused in a particular region, if the innovation is simply not yet available in the region. Thus, availability served as a proxy for the supply of the innovation, which, in turn, depended on the perceived profitability of the region by these suppliers. In its turn, this depended on the size of the market, the marketing costs, the cost of innovation in the area, and the expected rate of acceptance by consumers. Griliches concluded that the expected pay-off to suppliers was the major factor influencing their decision to introduce the product to the market.

Similarly, in another of the earliest works in the field, Mansfield (1961) found that the decision to adopt a new technology at firm level is a function of the technology's profitability, the investment required, and the number of competitors using it, a finding that he verifies empirically by looking at 12 different innovations in different industries. Similar approaches which emphasize profitability can be seen in the work of Smith (1961) and Hinomoto (1965). All these authors take as given the fact that profitability is the main incentive, and then try to predict the time to adoption; they argue that this depends either on the status of the capital stock of the company (in terms of how much time it needs to deteriorate completely), and/or the level of profitability promised by the innovation

The neoclassical approach to the diffusion of RETs focuses primarily on the double externality problem. According to this approach, theoreticians suggest that the lack of innovation and diffusion can be attributed to the failure of the market to internalize the effects of positive knowledge externalities and the negative environmental externalities (see e.g. the work by Jaffe & Stavins, 1994, and Jaffe et al., 2002). The positive externalities come from the fact that the environmental innovation can lead to positive effects to other firms and the rest of the economy, as the RET innovations can lead to further technological improvements and act as a foundation for the generation of new technologies. However, these benefits might not be captured by the original innovator, so this might lead to an under-provision of the RET. The negative environmental externalities might lead to an over-production of non-RETs since the price does not reflect the negative environmental impact these might have on the environment. Both these effects together can be seen as responsible for the reduced diffusion of RETs. This approach has translated into two types of policies: one aimed at supporting R&D, and one aimed at increasing the costs of pollution. Neither is technology specific, and rather lead to the adoption of the technology with the lowest marginal costs.

The weakness of the neoclassical framework comes from its oversimplifying nature and its reliance on profitability and externalities. This has been recognized by those academics who argue that results for the importance of profitability seem inconclusive when more control variables are introduced in the models (Mansfield 1961). This argument could not be investigated in depth until much later, due primarily to lack of data and the difficulties involved in measuring effects such as firms' promotional efforts and firms' beliefs with respect to the risk of adopting the innovations.

In later work, Mansfield (1969) provides further empirical evidence that the main reasons why companies adopt and argues that diffusion is positively related to the proportion of firms which have already adopted the innovation, and the characteristics of the adopters (esp. their education level). In other words, he points not only to the characteristics of the innovation but also to those of the adopter and the environment. These critiques appear in Jensen (1982, p. 183), which argues that profit-centred approaches ignore "the effect of information about the product and management attitudes on the firm's adoption decision". Later work also confirms the importance of profitability, but points to the importance of the other characteristics of a product, as well as the characteristics of adopters (Nabseth & Ray, 1974; Gold, 1981; Davies, 1979).

1.3.3 Rogers' Diffusion Framework (DOI) and The Sociological Approach to Diffusion

One of the most complete alternatives to the neoclassical framework was proposed by the sociologist, Everett Rogers, who suggested a conceptual framework to explain diffusion by looking at factors additional to profitability. Rogers is considered by many to be the father of diffusion of innovation research (McGrath & Zell, 2001), and his prominent book *Diffusion of Innovations* has received 57,473 citations (Google Scholar July 2014) and has been published as six editions (1962, 1971, 1983, 1995, 2003, 2010). Rogers studied farmers' decisions to adopt agricultural innovations based on the influence of neighbouring farmers and, by looking at the non-adoption of profitable innovations, he realized that something more than profit explained this process. In an interview in 2000, he admitted that his aim was to construct a general framework that would explain this process irrespective of the industry, culture or economic system in which the diffusion process was taking place (McGrath & Zell 2001), since he believed that some elements of the diffusion process were universal.

In examining his framework in more detail, we see that it is based on rational theories of organizational life adopted from economics, sociology and communication theory

(Lyytinen & Damsgaard, 2001 p.174), and that it suggests that diffusion takes place in five stages: knowledge acquisition, persuasion, decision, implementation and confirmation. All these stages are shaped by five main characteristics of the innovation, which, according to Rogers, explain 49%-87% of the variance in the rate of its diffusion. These are relative advantage, compatibility, complexity, trialability and observability (Rogers, 2010). The remaining variation can be attributed to a spectrum of factors such as "the type of innovation-decision[13], the nature of communication channels diffusing the innovation at various stages in the innovation-decision process, the nature of the social system, and the extent of change agents' promotion efforts in diffusing the innovation" (Rogers, 2010, p. 232). A graphical representation of his diffusion framework is provided in Figure 1.10.

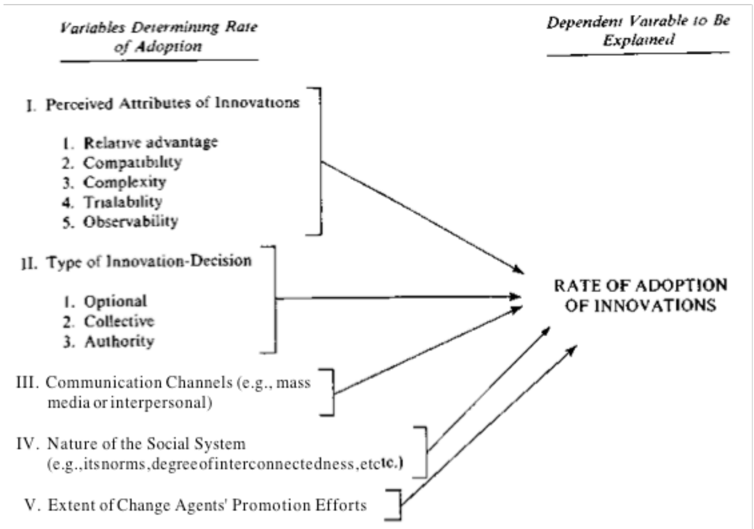


Fig. 1.10 Rogers' Diffusion Framework (DOI)

Source: Rogers 1961, p.225

The first characteristic is relative advantage and it is defined as "the degree to which an innovation is perceived as being better than the idea it supersedes" (Rogers, 2010, p. 213); that is, it is the extent of an innovation's technical novelty. This is the most straightforward measurable diffusion parameter, and can be expressed in either monetary terms or in terms of social advantages, depending on the nature of the innovation. The higher the innovation's relative advantage, the faster its rate of diffusion. Compatibility is "the degree to which an innovation is perceived as consistent with the existing values, past

[13]This refers to whether the decision to adopt is made collectively by a social group, or individually, and whether it is an optional or mandatory adoption.

experiences, and needs of potential adopters" (Rogers, 2010, p. 223). The greater the compatibility of the innovation with already established practices, the lower the uncertainty and, thus, the higher the potential for diffusion.

Rogers defines complexity as "the degree to which an innovation is perceived as relatively difficult to understand and use" (Rogers, 2010, p. 230), and argues that it is negatively related to the rate of adoption. Trialability is "the degree to which an innovation may be experimented with on a limited basis" (Rogers, 2010, p. 231); the higher the degree of trialability, the lower will be the uncertainty surrounding the innovation and the greater the likelihood of its adoption. Lastly, observability is "the degree to which the results of an innovation are visible to others" (Rogers, 2010, p. 232). Rogers argues that the more visible the technology to members of a social group, the faster will be its rate of diffusion.

In relation to other factors that determine diffusion, type of innovation decision suggests that we should pay attention to the number of potential agents involved in the adoption decision. The more agents that are involved, the slower will be the adoption process, *ceteris paribus*, suggesting that an adoption decision by an organization is more difficult than the decision of a single agent. To facilitate this process, Rogers' suggests that the analysis should take account of the particular individual/institution responsible for facilitating the change. This so-called "change agent" is defined as "the individual who influences clients' innovation-decisions in a direction deemed desirable by a change agency" (Haider & Kreps, 2004, p. 5). An example of a change agent might be a health education office within the ministry of health, whose aim is to educate potential adopters and facilitate the change brought about by the potential adoption of the innovation. Lastly, the communication channels and the way they operate in a given social system play a definite role in the rate of diffusion since they determine how the change agent communicates with potential adopters.

This is the most frequently applied framework in the field of diffusion, probably because of its ability to provide concrete strategies for the introduction of technologies (Ling, 2002). It has been used to explain the diffusion of innovations related to a wide range of technologies from Aids treatments (Crystal et al., 1995) to online games (Cheng et al., 2004). Utterback's (1974) review of the literature on innovation and diffusion suggests that Rogers' work has been accepted by the economics field. Utterback uses the concept of relative advantage to capture the idea of profitability, but combines it with the cost of the innovation. He stresses the importance of information and communication and, also, compatibility. In a way, he makes a selective use of Rogers's framework. The main interest in his thesis is to examine the impact of firms and what drives their decision to adopt an innovation, and not to examine what makes the innovation diffuse through the whole system.

In the field of RETs, this theory is not often applied. Kaplan (1999) uses DOI to analyse the decisions of electric utility managers towards the adoption of solar PV. Haas et al. (1999) examine the socio-economic aspects of the Austrian 200kWp PV-rooftop programme and the prospects for further dissemination of this technology. Another use of DOI comes from Mallett (2007), who evaluates the impact of social acceptance of RETs in Mexico, while Völlink et al. (2002) use Rogers' framework to predict the intention to adopt energy conservation interventions. Faiers et al. (2007) test the importance of the characteristics of an innovation and how they vary, based on the adopter category, using domestic solar-power systems as a case study.

Nevertheless, work on RETs and DOI remains scarce. Probably, the absence of studies on Rogers's application to RETs is related to the framework's inability to account for the impact of the environment on the diffusion process, which is somewhat surprising given Rogers's sociological background. The institutional environment is key to understanding RET diffusion. For example, the concept of carbon lock in (Unruh, 2000) shows that industrial economies become locked into fossil fuel-based energy systems through a process of technological and institutional co-evolution, which prevents the diffusion of RETs.

However, this theory is limited, primarily because it takes no account of the interactions among the determinants of diffusion and looks only at the direct effects on diffusion of individual elements. Other criticisms, some of which have been acknowledged by Rogers, are related to the implicit assumption that an innovation should always be adopted by all members of the society and can never be rejected, known as the pro-innovation bias (Robertson, 1967; Rogers, 2010).

Another issue related to Rogers's framework is related to the way the actors are perceived. It tends to assume that all agents are rational and conduct similar cost benefit analyses when deciding whether to adopt an innovation; in other words, it assumes agents are not heterogeneous (Rogers, 2010). However, this only applies to the agents within each of the individual adopter categories (innovators, early adopters, early majority, late majority and laggards); the agents of each of these groups differs with respect to the timing of the adoption and their appetite for risk and degree of opinion leadership. For example, early adopters have very high social and financial status, while laggards have the lowest social status and are very resistant to change. Therefore, we can argue that this is an improvement with respect to the neoclassical framework, where all agents are homogeneous. However, the framework still does not account for non-maximizing behaviours such as satisficing (see e.g. Winter, 1971, 2000; Schwartz et al., 2002).

A similar issue arises in relation to the way the product/technology is perceived. In contrast to evolutionary economics, DOI assumes technologies are easily codifiable and time invariant. In other words, both product and technology are fixed across time (Tomatzky & Klein, 1982; Premkumar et al., 1994; Rogers, 2010). This is clearly an oversimplification that ignores the socially constructed nature of large technological systems (Lyytinen & Damsgaard, 2001). It also assumes that the determinants of diffusion will be the same across time, which is obviously not realistic. For example, as the product is in the early phases, relative advantage might be more important, since this will be necessary to compensate for the risk and uncertainty for early adopters. Later in the process, when the product becomes standardized, other features such as compatibility of the innovation with existing user practice, might become more important.

In addition, the framework assumes that diffusion takes place in an orderly sequence of events, which is falling in the same trap as those who assume that innovation is a linear process (Lyytinen 1991; Lyytinen & Damsgaard 2001). In this context, the DOI is built upon the idea that there is little or no feedback between the stages of the diffusion process (Nolan, 1973; 1979; Rogers, 2010). The idea of validity of the S-curve again becomes contestable; the diffusion process might come to an end before the innovation reaches maturity, and the technology might be superseded by a different innovation[14]. Moreover, Rogers's assumptions about the distribution of the agents across the phases is very idealistic[15], and rarely observed in social science (Ling, 2002), where the distribution pattern of diffusion deviates from the S-curve (Mahajan et al., 1990).

[14]For a review of different types of adoption curves see Mahajan and Peterson (1985).

[15]The separation of the population of adopters into categories is based on a simple formula of the mean time of adoption and its standard deviation, under the assumption that the adoption curve is bell-shaped. Rogers argues that the proportion of adopters that lie 2 standard deviations to the left of the mean are the innovators, those at 1 standard deviation are early adopters, etc.

1.4 Life-Cycle Models

The above discussion of the literature on diffusion shows that the S-curve is a stylized fact (see the work of Brown & Cox, 1971), probably because it makes conceptual sense, is relatively easy to model, and has achieved wide empirical support. This stylized picture can be found in the literature on life-cycle models, although in a different context. Clearly, there is an implicit connection between diffusion studies and life-cycle models, since both have the same starting point, but different aims. I was surprised not to discover any explicit connection between these two streams[16]. This is perhaps explained by the fact that the diffusion literature focuses solely on a particular product, while life-cycle models are more interested in the industry evolution, which naturally passes through its life cycle which contains dimension of diffusion among others. In my view, the key advantage of integrating the diffusion model with life-cycle models is the latter's ability to explicitly incorporate the element of time, which is only implicitly accounted for in traditional S-curve models.

In this work, we do not aim simply to unify these two streams of literature. Rather the objective is to exploit the diffusion theories within these frameworks so as to identify key points in time and see if and how the diffusion determinants vary at these different points. Before proceeding with our new framework, we conduct an extensive review of the literature on life-cycle models in order to get a clear understanding of the aims of each theory and the key findings. The review of work on the product-life cycle comes first and is followed by the literature on the industry life cycle model.

1.4.1 The Product Life-Cycle (PLC)

The rationale for PLC theory comes from biological sciences and the idea that an organism's life starts with its birth, continues with its growth and maturity, and ends with its death. Transferred to the field of industrial economics, the theory stipulates that products across industries go through at least four distinct phases (Wells, 1968): introduction, growth, maturity, and decline. The theory was pioneered by Kuznets (1930) and Dean (1950); Kuznets investigated the production patterns of various commodities, and observed that initially production levels rise at an increasing rate, but that over time their rate of growth decreases and eventually becomes negative. His observations were tested

[16] In fact, the first work on the industry life-cycle by Gort and Klepper (1982) made an explicit link with the topic of diffusion, but had no relation with either the DOI or the neoclassical approaches presented above. Later work on life-cycles, instead of looking in more depth at the issue of diffusion, investigated issues related to strategy and industry evolution, which we discuss in more detail later in this section.

by Hirsch (1965), who classified products, and thus industries, as growth/growing and maturing/mature, within a framework that he justified by applying it to the US electronics industry.

Based on this work, a stylized bell-shaped curve emerged[17], which was split across various phases, the number varying according to the author (Polli & Cook, 1969). However, the consensus leans towards the existence of four phases, which are visualized in Figure 2.1.

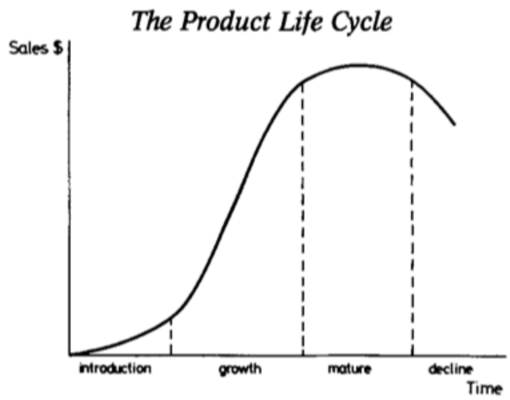


Fig. 1.12 Product Life-Cycle Models

Source: Audretsch, 1987, p.299)

The graph in Figure 2.1 plots the sales of a product and time, from the moment the product goes onto the market until it is removed. In the first phase, the product is new to the market, so there are few users and very small numbers of sales. In the second phase, the number of sales increases exponentially, and in the maturity phase, sales go up, but at a decreasing rate, before eventually stabilizing. In the final phase, the level of sales is declining. Therefore, the characteristic of the PLC model is the importance of sales as the distinguishing factor across the different stages (Vernon, 1966; 1979; Hirsch & Bijaoui, 1985).

The logic of the curve is based on Rogers' DOI framework (Robertson, 1967; Polli & Cook, 1969). Initially, the product meets with resistance since it represents new rou-

[17] There are at least 15 different PLC patterns proposed in the literature (see Rink & Swan, 1979). These are based on research on different industries from consumer durables to industrial goods. However, there are no major studies that discuss how different conditions can explain the varying shapes of the PLC curve; this is a largely under-researched area.

tines and a new modus operandi. Then, as more people adopt it, the information on the product's value spreads, leading to higher levels of adoption. Eventually, the market potential becomes smaller, and sales growth reaches a maximum. Then consumers start to abandon product for newer substitutes, and sales start decreasing until eventually the product is removed from the market.

Most early works focus on validating the existence of the PLC (Rink & Swan, 1979). The PLC has been used as a core analytical tool in a range of the economic literature, particularly in the fields of micro/industrial/innovation economics and management. The framework was developed initially as a marketing tool (Cox, 1967) to help managers identify the most appropriate price of a product according to the phase of the life cycle. The theory was aimed also at facilitating managers' understanding of the links between industry dynamics and various aspects of firm performance across time and space, and helping them to devise the firm's strategy. In a sense, the PLC's distinction of different stages across times suggests that a firm's optimal strategies differ across these stages: "Specifically, a leadership strategy is adopted at the introduction and growth phases and is then followed by the niche strategy at the maturity stage. Finally, when decline sets in, a harvest strategy is implemented" (Thietart & Vivas, 1984). Some authors go so far as to suggest that the PLC is the most fundamental variable determining firm strategy (Hofer, 1975, p. 798). Similarly, in the field of logistics, practitioners use the concept of PLC to forecast the resources necessary to deal with the product across the life-cycle.

Another major area of research based on the PLC is the impact on various aspects of innovation. The key idea is that, in the initial phases of a product's life, the product is the most technologically advanced compared to the existing knowledge stock (Audretsch, 1987). However, across time, the innovations related to this product decrease (Gort & Konakayama, 1982), and it loses its comparative advantage. This brings about a decrease in sales and eventually eradication of the product.

Others attempt to investigate how a firm's location decision varies according to its position in the life-cycle, the most prominent study being Vernon (1966). Vernon proposes a link between the PLC and the location of its production. Initially, the focus is on innovation, so production needs to be located in a knowledge- intensive country. As the product matures and the technology becomes standardized, the emphasis moves to cost reduction, and production moves to a lower cost country. Following Vernon's work, there is a body of literature that attempts to integrate the geographical element into the PLC analysis. For example, Campi et al. (2004) find that in the initial stages of the PLC, when the focus is on product innovation, firms tend to be located in diversified environments in big cities with good access to human and knowledge resources. As the product matures and the emphasis shifts to process innovation, firms tend to be more geographically dispersed in order to achieve lower costs.

However, the findings on the PLC are no longer applicable to the international location of technology (Cantwell, 1995). For latecomers, we see a reversed version of PLC emergence known as the reverse product life cycle (RPLC), which provides an alternative evolutionary explanation for the catching up process of latecomer firms (Hobday, 1995; Hobday et al., 2004; Choung et al., 2014). Here, we see that latecomer firms can also be technology innovators, not just adopters. An example of this is the renewable energy industry in China. Clearly, China was not a pioneer of any of the technologies, and was a latecomer in the field, joining in the 2000s; however, it managed not only to catch-up with the western economies, but to become the leading producer and a pioneer of these technologies.

Despite its advantages, the applicability of the PLC framework to the context of RETs is limited. The first problems arise when trying to identify what constitutes the product of RETs. In strict terms, the product of RETs is the electricity produced. However, the PLC of electricity is not directly relevant for this work. Thus, we need to rethink the issue of the PLC in the context of RETs and provide a wider definition of what constitutes a product. Ideally, one might conceive of a technology life cycle rather than a product (Haupt et al., 2007), the technology being the wind energy or solar PV energy system. This provides more flexibility for discussing the periods of introduction, growth and maturity in these technologies which, as discussed in previous sections, are collections of products rather than uniquely identifiable products.

Moreover, when trying to link Rogers's DOI explanation for the PLC to the empirical findings on RETs, more difficulties arise. The explanation predicts that consumers will start substituting the new technology with an even better one as the RETs mature. However, most RETs are designed to have very long lifetimes, with only minor maintenance costs. Moreover, they are expensive to remove and substitute with something completely different (see, e.g., wind turbines and solar panels from 1991 which are still operational)[18]. Rather, the substitution will likely take place only if a dramatically new and improved technology emerges. Another particularity of renewables is the fact that they will have to be substituted by new technologies when the physical/land limits of RETs are reached,

[18]For more information see Goodall (2014) and Chianese et al. (2003).

something also not predicted by PLC. Adding this extra element of time could potentially lead to a truncated version of the PLC.

Lastly, an issue that needs to be considered when applying the PLC framework in this work is its predictions about the nature of innovation. The theory predicts that initially the product is technologically superior to existing technologies, something which clearly does not apply to RETs. Some might argue against this, assuming externalities are priced in.

If we look at the development of the innovation process after the dominant design according to the PLC, we should expect a decrease in the number of product innovations, and a greater emphasis on process innovation. However, in the case of RETs, even after the dominant design emerged, we see continuity in the number of product innovations, with larger and larger turbines and more and more efficient materials for solar panels. This is not to imply that process innovations do not exist (e.g. in improving the performance of gearboxes for wind installations, and establishing more reliable inverters for solar systems), but that product innovations remain significant.

Using the Technology Life Cycle for Wind and Solar PV

Given the aforementioned weaknesses of the PLC framework, we decided to use a more general term in this work: technology life-cycle (TLC). This is more an issue of terminology than a major theoretical suggestion, and is based on the idea that solar PV and wind technologies are not just products but are technologies. In this context, and based on what was discussed in the previous section, we suggest the following two categorizations for the TLC for wind and solar PV[19].

For Wind, we can identify four phases:

1. Phase 1: Emergence of Technologies - from 1960s until late 1980s
2. Phase 2: Niche Markets - early 90s
3. Phase 3: Dominant Design - from mid 90s until early 2000
4. Phase 4: Mass Market - from early 2000

Similarly, for solar PV, we can identify the phases of:

[19] It should be noted that, given the status of these two technologies, we do not identify any other phases related to maturity and decline.

1. Phase 1: Emergence of Technologies - from 1970s until early 1990s
2. Phase 2: Niche Markets - the 90s
3. Phase 3: Dominant Design - early 2000
4. Phase 4: Mass Market - from middle of 2000s onwards

Identifying the Dominant Design

Given the importance of time in our work, particular emphasis needs to be given to the categorisation we just presented, especially for the period of the dominant design. Anderson & Tushman (1990, p.616) define the dominant design as "the cumulative product of selection among technological variations". In other words, "a dominant design is a specific path, along an industry's design hierarchy, which establishes dominance among competing design paths" (Utterback and Suarez, 1993, p.1).

As we illustrate in the later chapters, the dominant design (DD) represents a critical point in the life-cycle of the technology as it shows the transition from an experimental technology to one which is commercially viable. In other words, until the emergence of the dominant design, there are no assurances to the entrepreneurs and the users of the technology that it has the potential to compete with the already established ones. Moreover, it is not necessarily the most advanced and superior technology of its time, but rather a technology that does best in reducing technological uncertainty (Anderson, & Tushman, 1990). As a result of the DD emergence, the dynamics of competition in the industry as well as the nature of innovation change (Utterback & Abernathy, 1975).

It is, therefore, evident that there is no clear cut set of indicators or measures that can be used to identify when a particular dominant design has emerged in a technology. Rather, a way through which we can identify the emergence of the DD is by looking at the market and the system, and see whether the market behaviour is congruent with those effects that the theory predicts will take place as the result of the emergence of the dominant design. For example, the literature suggests that after the appearance of the DD the following stylised facts occur[20]:

- a shift in the emphasis from product to process innovation

[20] Key works in the literature upon which this list of stylised facts is suggested are: Utterback & Abernathy (1975), Anderson & Tushman (1990), Utterback & Suarez (1993) Agarwal et al. (2002), Jacobides (2005); Argyres & Bigelow (2007); Stuerz (2014)

- standardisation in technology
- reduction in the speed of technological advances
- firms emphasise cost reductions
- a shake-out of firms in the industry in which the technology belongs to
- a wave of mergers and acquisitions, typically leading to a wave of vertical integration

From all the above discussion it is evident that the emergence of the dominant design is hard to predict and can only be observed after its emergence and after some significant period has passed. Moreover, in none of the empirical work on the topic, there has been any attempt to identify an exact or approximate date in which the DD emerges.

Nonetheless, there is still scope for methodological robustness when trying to examine the DD's emergence. In particular, from all the stylised facts presented above, the ones that are the easiest to capture are those related to the entry and exit of firms, the mergers and acquisitions in the industry, and the costs.

Looking at the feasibility of gathering data on the entry and exit rates, we have to point out that since we are referring to a technology rather than to a particular product, we would have to investigate the entry and exit rates of all companies that are involved in the production process of the technology. The problem with this line of analysis is that the companies that make the components for the technology are usually making components for other technologies as well. Moreover, given the international nature of the technology, we would expect that the industries would be of a global nature, and thus, this type of data would need to be gathered on the international scale. For similar reasons, measuring the M&A activity would be virtually impossible.

The other stylised fact that could be used to capture the emergence of the DD is related to the standardisation of the technology. One way to capture this is by looking at the costs of the technology and identify periods at which the costs have largely stabilised, after a continuous and significant fall. Cost stability could be perceived as indicating a period of no major technological breakthroughs, and, therefore, a shift from product to process innovation. Again there are issues with this approach, as the technology consists of various products, and thus, many prices have to be examined. To deal with this matter, we decided to look at the breakdown of the costs components of the technology, aiming to identify which components constitute the larger proportion of the technology's costs. In this way, we would then be able to look at the evolution of costs of that particular element and thus, identify the DD emergence.

In the context of this work, we have identified that for the wind the major cost component is the wind turbine (Figure 1.8), although various subcomponents complicate the analysis. To deal with this, we use "turnkey cost", which is "the specific investment cost per kW", a measure frequently used in the wind energy industry (Kaldellis, & Zarakis, 2011). By looking at Figure 1.5, we can observe that in the late 1990s, and early 2000s, the turnkey costs of operating a wind farm have stabilised after a period of significant decline. For this reason, we can infer that this was a period during which the dominant design for this technology emerged.

For solar PV, the key component is the module, which as we discussed previously (Table 1.1), represents 50% of the total capital costs of a PV system. From Figure 1.2 we can see that the prices of the modules followed a downward trend until the late 1990s, and then remained virtually at the same level during the early 2000s. Therefore, we can argue that during this three year period, the technology was standardised denoting the emergent dominant designed.

Moreover, given the international nature of the technology we can argue that the emergence of the dominant design in one country would imply that, with a relatively short lag, it would become available in other countries for diffusion. Therefore, we can be confident that the emergence of the dominant design takes place in similar times across the countries in the world[21].

Regarding the work in this Ph.D., the classification of the dominant design emerging over a period rather than at particular date has no adverse implications due to the methodologies used. For Chapter 3, there is no dynamic element in the analysis, so this discussion is not applicable. Chapter 4 follows a case-study method which allows for some flexibility in the way time is dealt with, in contrast to Chapter 2, which follows a purely quantitative approach. In this chapter, we faced some difficulties with our approach to the DD since the methodology demands precision regarding the timing of the DD emergence. As we discuss in the chapter, to address this problem, we run multiple models,

[21] Of course there are examples of technologies which is not the case, as there is unwillingness from the producers to share them internationally (e.g. innovations in the defence sector), but for RETs there should be no reason why they would not be internationally available.

each assuming that the DD for wind emerged during one year from this period, and then check our results for robustness. Lastly, for Chapter 5, the model that we constructed allows for the assumption that the DD does not emerge at a single point in time, but rather over a period.

1.4.2 The Industry Life-Cycle (ILC)

The evolution of industries and the different stages that can exist simultaneously in different areas in an economy have for long been recognized by the field of economics. Marshall (1879; 1890) identified the existence of different economic sectors with different growth rates. Schumpeter (1939) in his work on business cycles also recognized that industries follow a period of emergence and decline, while Kuznets (1930) linked economic growth to the emergence and decline of various industries. Rostow (1959; 1960) observes regularities of industrial dynamics, with a process of take off accompanied by a period technological maturity and mass consumption.

In other words, a similar S-shaped curve has been observed in the context of firm entry and exit, which in its turn gave rise to new models of industry evolution. This S-shaped stylization of the evolution of an industry came to be known as the industry life-cycle (ILC) model. This theory of industrial dynamics was proposed by Williamson (1975, pp. 215-216), who recognized that there are three stages in the development of an industry: the exploratory stage, the development stage and the mature stage. Later, Clark (1985) followed Williamson's approach to industry evolution, and suggested the two stages: "fluid" and one that is highly "specific" and rigid. (Clark, 1985, pp. 235-236). His research aims at explaining how technological change influences an industry's evolution, and suggests that initially there is a great deal of uncertainty and, thus, variety in product designs and processes. This high variation period is followed by a standardization phase, and the emergence of a dominant design, significant reduction in uncertainty, and an emphasis on process rather than product innovation. Similarly, Drew (1987) in a study of technological developments in medical imaging products, recognizes the existence of four stages in the evolution of an industry: embryonic, growing, mature and aging.

However, the work of Gort & Klepper (1982) is the defining model in the field, a model which originated from the diffusion literature. In their original work, Gort and Klepper (1982) investigate the time paths in the diffusion of product innovations. They observe the development of 46 product histories, and proposed a new theory of development of industries for new products, suggesting that the way the diffusion process takes place influences the market structure of the industry. Their model identifies five stages in the development of the industry as visualized in Figure 2.2.

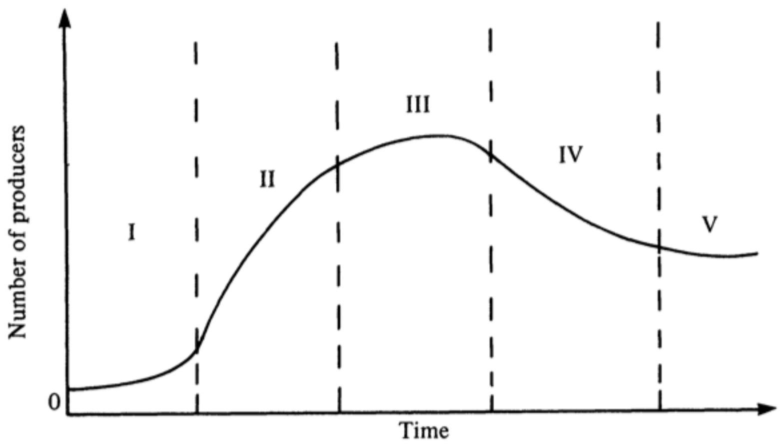


Fig. 1. The five stages of new product industries.

Fig. 1.13 Industry Life-Cycle Models

Source: Gort & Klepper 1982, p.639

Their theoretical conceptualization was based on the idea of entry rates. In the first stage, there is only one firm which introduces the technology to the market in a period of high uncertainty since the technology is not well understood (Mueller & Tilton, 1969; Abernathy & Utterback, 1978). The first mover firm then grows and manages to retain its monopoly position until new firms are able to copy the technology. This results in increased entry rates as more and more firms are able to imitate the technology, which leads in turn to an increase in the number of producers and, thus, the beginning of a new phase. This new entry continues until the market reaches a peak for number of participants in period three. At that stage, some theoreticians suggest that the dominant design is established (Utterback & Abernathy, 1975; Anderson & Tushman, 1990; Utterback & Suarez, 1993; Agarwal et al., 2002). This brings about standardization of the technology, reduction in its complexity, reduction in the speed of technological advances, and a shift to process innovation. Firms start to find ways to reduce their costs and increase efficiency, which eventually results in a wave of vertical integration (Jacobides, 2005; Argyres & Bigelow, 2007; Stuerz, 2014) and a shake-out in the maturity phase. In period 5, the industry reaches a dynamic equilibrium where the number of producers stabilizes. Clearly, the timing of these phases varies for different products.

All of the processes described above and the reasons for the transitions between phases, have been studied by various authors who have proposed alternative theories and drawn on various streams of the literature. Most work focuses on the shake-out process (Gort & Wall, 1986; Jovanovic & MacDonald, 1994; Klepper, 1996; Barbarino & Jovanovic, 2007; Jovanovic & Tse, 2010). For example, Klepper (1996) formalizes the empirical regularities of industry evolution, and challenges the idea that the dominant design is the cause of a shakeout. He argues that, as the number of entrants increases, the emphasis shifts to R&D in process innovations to meet the objective of the firm to reduce costs. This causes the exit of less innovative firms and acts as a barrier to entry for new firms since the incumbents already have a cost advantage.

Some, such as Jovanovic and MacDonald (1994) emphasize the importance of information and know-how for shake-out; they argue that innovations take place outside the firm, and are then adopted by incumbent firms in the industry. The faster the incumbents adopt the innovation, the faster they can reap its benefits (e.g. cost reductions) and increase their competitive position. Those firms that are laggards will eventually exit and, thus, the industry will face a shakeout. Lastly, Barbarino and Jovanovic (2007) focus on the role of demand and supply conditions, where excess demand causes increased entry rates, leading to a huge and unsustainable expansion of the market, which eventually leads to a temporary slump and a shakeout process[22].

Others do not focus solely on the reasons behind an industry shake-out, but look also at how this process of exit influences the level of innovation (Mueller, & Tilton 1969) and firm behaviour[23]. Some exploit the ILC framework to explain the location of innovative activity, and how this varies as the industry shifts across stages (Audretsch,& Feldman 1996).

ILC models are a good representation of industries that produce consumer durables. However, various weaknesses emerge when the ILC logic is applied to a broader range of industries, as discussed in Malerba and Orsenigo (1996). Firstly, if the industry is narrowly defined (e.g. a typewriter), then the ILC becomes very similar to the PLC. However, if we take a broader perspective of a product and treat it as a sum of various subsystems

[22] A similar development can be seen in the market for solar panels, where excess demand for panels led to a boom in the global supply of panels led by Chinese companies, and eventual collapse of the industry.

[23] The ILC has been widely used in the strategy field, but this is beyond the scope of this thesis. For the interested reader. more information on this use of the ILC model is provided in Robinson and McDougall (2001), Lumpkin and Dess (2001) and Verreynne and Meyer (2010).

of products, then the ILC becomes less valid. Secondly, Malerba and Orsenigo are sceptical about the empirical validity of the initial product innovation, which then is followed by process innovations, and argue that this does not hold for capital intensive industries. Thirdly, the model assumes that the industry begins to form when there is a major product innovation, and then standardization of the technology leads to the emergence of a dominant design and stabilization of industry growth. However, the introduction of a dominant design might cause a new discontinuity in the industry and the emergence of a new one[24]. Lastly, the assumption that the initial innovation originates with one pioneer who then generates a flow of entrants is not supported empirically for a wide range of industries since pre- existing conditions vary significantly across industries.

With these criticisms in mind, it is easy to see that the ILC, by itself, cannot explain the evolution of RETs. The first criticism is highly applicable to the RETs. There is no real single product, but rather a system of technologies which together constitute an energy system. Therefore, many of the predictions of the ILC do not hold. For example, we do not see process innovations, but rather small product innovations; we see new more efficient inverters being introduced into solar PV systems, and more efficient gearboxes in wind installations. These are not process innovations, but are product innovations in a given technological system.

In addition, in line with the fourth criticism, we do not see the emergence of completely new firms and industries. Rather, we observe existing firms expanding their operations into RETs through a wave of mergers and acquisitions. For example, Vestas, one of the leading global producers of wind turbines started out as a steel technology company manufacturing household appliances, but by 1968 had became one of the leading exporters of hydraulic cranes. The first turbine was produced in 1979, but until the late 1980s, the company was still experimenting with different technologies, and lied in the brink of closure. It was not until the 1990s that the company started to establish its presence in the industry, by stabilising its designs, and by 1998 it became listed in the stock exchange, signifying its plans for growth and expansion, becoming at that time the industry's dominant player. In 1999, it merged with NEG Micon and became the global leader in wind turbines. Also in relation to the fourth criticism, in the cases of both wind and solar, there was no single pioneer who was followed by new entrants. Rather, each of the components of these energy systems traditionally were developed in industries

[24]An example of this is the semiconductor industry, where the emergence of the planar transistor as a dominant design led to the generation of a completely new dominant industry design (the integrated circuit) and a new industry.

that were always highly concentrated.

The second and third points of critique do not apply to the context of ILC and RETs. When the dominant design emerged in each of these technologies, we did not see the emergence of a completely new industry, but rather a series of incremental innovations which led to reductions in the costs of technologies and stabilization in the industry.

To conclude, work on the ILC produced various innovations in the field of industrial economics and bridged between neoclassical and evolutionary economics (Agarwal & Braguinsky 2014). Firstly, one advantage of the ILC approach was that it produced a model of endogenous industry evolution. Secondly, it introduced Schumpeterian style dynamics into a field traditionally dominated by the neoclassical economists' perceptions of industry dynamics, focused around market structure and competition. In particular, the ILC contribution is its endogenous model of industry formation, which is at the core of creative destruction, and which, according to evolutionary economics, is the key driver of economic development. Another advantage of using ILC models is that they bring a dynamic element into the analysis and allow examination of its impact on innovation, industry concentration and firm entry/exit rates. However, as we have illustrated above, it cannot be used on its own, and unmodified to account for the process of RET diffusion.

1.4.3 Distinguishing Between PLC and ILC

One of the main problems with both ILC and PLC theories is that they are not clearly delineated from each other. We consider that the distinction depends on the unit of analysis, which ultimately depends on the research aim. ILC clearly focuses on the evolution of the industry, while the PLC is aimed at the product. As Jovanovic (1998, p.331) accurately states "the ILC is a shift from a product cycle notion that viewed an individual product as the unit of analysis to an industrial organization approach dealing with the endogenous evolution of industry".

To understand this distinction better, we need to understand what is an industry, what are its limits and characteristics, issues that have not been clearly defined in the literature on ILC. Although there is no agreement on the definition of an industry, there is a general consensus on its characteristics. These are: the nature of technology (Chatman,& Jehn, 1994), industry growth potential (Chatman, & Jehn, 1994), intensity of competition, types of entry barriers, profitability, predictability of demand (Agarwal, & Gort, 2002). Using the ILC framework as a moderating variable, several of the above aspects have been examined. On the other hand, work on PLC focuses mostly on providing a guide for managers and/or answering strategy oriented questions related to using the PLC model in research on how companies should react to their product.

However, this distinction is not sufficient since various management and strategy scholars use the PLC framework to analyse strategic management practices over the industry life-cycle (Covin, & Slevin 1990). Furthermore, it is definitely not easy, and arguably not optimal, to analyse strategy without looking at the industry. Similarly, it is almost impossible to analyse industry wide topics without investigating and understanding what happens at product level. This interrelation, in my view, is the reason for the lack so far of an appropriate formal attempt to distinguish between the two concepts. Therefore, it could be argued that the two models are not so very different since they are complementary, and developments in the PLC could potentially be the reason for the patterns of industry evolution captured by the ILC model. In particular, industry dynamics are both micro or product and mezzo or industry level process and thus we can never have a separation of the two models, but solely interaction between them.

1.5 The Theory of Technology Systems of Innovation (TIS)

1.5.1 The Innovation Systems Perspective

The key consensus in the innovation literature is that innovations do not emerge within a linear process, but arise as the result of continuous interactions among different numbers of players, in a non-orderly way and that, more importantly, innovation is the result of both individual and collective action (Saxenian, 1996; Edquist, 2001). As Lundvall (1992) argues, the analysis of innovation should be based on the idea that innovation is an inherently social, interactive learning process. This evolutionary understanding of innovation reveals the complexity and uncertainty of this process, and the weakness of neoclassical models to guide innovation policy decisions. This realization led innovation scholars to turn their attention to other disciplines, particularly biology, and to adopt the idea of system. In other words, to perceive the actors and the various institutions involved in the innovation process as elements in a system whose outcome is the generation and diffusion of innovation. This realization gave rise to a whole new field within innovation research known as Innovation Systems (IS).

This constituted a major leap away from the neoclassical economic tradition, which focused primarily on how to correct market failures and guided policy making until the mid-1980s (Jacobsson, & Bergek, 2011, p.42). In particular, the key idea of neoclassical economists was that innovation is undersupplied, and the role of policy was to correct this shortage by providing subsidies for the process. However, this approach proved inappropriate in many instances; the policies providing large subsidies for R&D failed to yield satisfactory results, exemplified by the failure of the Soviet Union to catch up with the West. On the other extreme, there was the case of Japan, which had minimal R&D, but managed to advance technologically and economically (Freeman, 1987).

The innovation systems approach emerged as a response to this simplistic view of innovation and policy failure (Jacobsson, & Bergek, 2011, p.42); systems of innovation scholars argued that innovation depends on the interrelation and interaction of the various elements of the system, and a weakness in any one of them could obstruct the development of the system and, thus, the generation and diffusion of innovation (Malerba & Orsenigo, 1996; Carlsson & Jacobsson, 1997; Edquist & Hommen, 1999). The choice of technology is not determined simply by individual firms and prices, but depends also on the innovation system which both aids and limits the choices of the individual actors

(Jacobsson, & Johnson, 2000, p.629).

The IS approach was particularly useful because it gave a more general justification and direction for government intervention as a way to correct and improve the functioning of the system's various subcomponents, which would in turn facilitate the whole process of innovation and diffusion. Moreover, it suggested that the role of policy was not simply to provide more financial resources, but rather to use its resources to correct this "system failure" (Smith, 2000; Woolthuis et al., 2005).

A major issue related to the systems approach in general is the boundaries of systems (Markard & Truffer, 2008; Coenen & Díaz López, 2010), a problem identified in the IS literature. The boundaries to a system are crucial for identifying which factors are endogenous and which are exogenous to the innovation process. Some argue that the limits of the system are the country in which the innovation takes place, others suggest that they are regional and others claim that these limits are technology or sector specific. It could be said that every system serves a different purpose; therefore, it is to be expected that different systems will exist. We can identify four major subcategories of IS:

1. National innovation systems (Freeman, 1987; Lundvall, 1992, etc.)

2. Regional innovation systems (Saxenian, 1996; Maskell, 1998)

3. Sectoral innovation systems (Breschi & Malerba, 1996; Malerba, 2004)

4. Technological innovation systems (Hughes, 1987; Carlsson & Stankiewicz, 1991; Lundgren, 1991)

Although the system boundaries may differ, all these approaches build on the fundamental assumptions in the innovation literature, which Edquist (2005) summarizes as:"innovation and learning are key economic processes, an evolutionary understanding of innovation, a tight interaction between social and technological aspects of an innovation and a focus on different types of innovations".

1.5.2 Technology Innovation Systems (TIS)

Among the plurality of approaches to innovation systems, in this work we focus on TIS and the technology. We believe that this approach is best suited to understanding the process of diffusion of RETs, since our research question tries to identify how a technology (solar PV) rather than a particular product (e.g. monocrystalline PV panels) diffuses in the system. New technologies are dynamic and are characterized by continuous innovation; thus, the chosen IS framework has to account explicitly for this dynamism and focus on the technology rather than other institutional characteristics. Before expanding our discussion of the TIS, some reference needs to be made on two streams of literature which were potential candidates for this work: the sectoral systems' approach to diffusion, and the literature on technology transitions (TT).

Malerba's sectoral systems approach (2002) includes various technologies, and the system boundaries are defined by existing products; However, in the context of RETs, both the technologies and the products are in a process of continuous development; thus, it is difficult to set the boundaries to the system in advance, and the analysis runs the risk of overlooking the performance of important factors and actors that are still not formed (Nygaard et al., 2008; Coenen & Díaz López, 2010). In allowing the technology to set the system limits we manage to avoid these risks. In addition, sectoral systems are focused on understanding how innovation by firms can increase competitiveness, rather than how an innovation diffuses in the system. Last but not least, the sectoral approach has a strong emphasis on the development of knowledge, rather than the diffusion and use of the new technology (Geels; 2004).

Another popular approach comes from the literature on technology transitions (TT). This literature emerged as a criticism to the sectoral systems of innovation and its primary aim is to incorporate explicitly into the analysis the user side (Geels; 2004), an idea founded in Freeman's (1979) coupling concept of matching technology with the markets. The advantage of this approach is that it incorporates a broader range of stakeholders in the analysis such as the producers, the societal groups, the research networks, the user groups, the suppliers, each of which is a system which evolves and at the same time causes a broader evolution of the whole system/market. The key aim of this work is to explain how how technological innovations emerge, and how they are incorporated into the society.

To achieve this, TT theorists view transitions as a multi-level process, which is the outcome of the interplay between three levels: niches, regimes, and the landscape. Niches are the micro-level where radical innovations are generated. These can be R&D laboratories, demonstration projects, or market niches. Regime is an extension of the technological regime proposed in evolutionary economics, and points to the cognitive routines of an engineering community (Geels & Schot, 2007). In later work, this notion was expanded to include general rules that coordinate the activities of all the members of the social groups which influence the evolution of the socio-technical systems (Geels, 2011). Lastly, the landscape can be perceived as the exogenous environment, which is hard to change and sets the broader picture in which niche and regimes interact. The eventual transition is the outcome of the interplay between these three levels, each of which is a separate configuration of elements which evolves independently but also in combination with the other two.

TT can be seen as a very useful framework within which we can explain energy transitions, which occurs when there is "a shift in the nature or pattern of how energy is utilized within a system" (Araujo, 2014, p.112). In particular, the energy sector has been through various changes in the past 150 years. Across history, energy was primarily produced from biomass (especially wood), but with increased energy demand, and scarcity in wood supply, its price started increasing, which led to a need for a better/cheaper alternative. This came about with the emergence of the steam engine powered by coal. This was then used to generate electricity, which became the primary energy source both for domestic and commercial uses. Following Nakicenovic et al. (1998), historically electricity production was primarily fuelled by biomass, until the early 20th century. Then, this was largely complemented by coal, and by the 1950s, oil started becoming a major contributor in the world's electricity production. Since the mid-1970s, increased electricity production has been accommodated not only by oil, but also by gas, hydropower, and more recently other forms of renewable energy (e.g. wind, and solar).

A problem with energy sector transitions is that they take a very long term. As Smil (2010, p.148) points out, a complete shift from fossil fuels to RETs is "a generations long process", as massive changes in infrastructure, and great capital expenditures are necessary to create an energy sector which is completely carbon neutral. In this work, we are not interested so much as to investigate diffusion of RETs in such a wide context that they would completely substitute conventional fuels, since this is technologically infeasible. Rather, what we are interested in is how RETs can manage to penetrate the energy mix of a country, with a maximum of 20% of total energy mix, as this is the rate at which most successful cases have achieved. To achieve the 20% transition, it is not necessary to have such a drastic transformation of the energy system as it is proposed by the TT scholars and the one predicted by the TT theories. Therefore, we decided not to look at this approach in this thesis.

In a way TIS can be seen as a forerunner of the TT, since it focuses only on the evolution of a some of the elements of the broader system. In more details, the TIS approach follows Carlsson and Stankiewicz's (1991, p. 111) definition of technological systems as "network(s) of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilize technology. Technological systems are defined in terms of knowledge or competence flows rather than flows of ordinary goods and services. They consist of dynamic knowledge and competence networks".

This new theorising about the process completely changed the way of thinking, which until then had focused on identifying the key determinants of diffusion while ignoring the complementarities among these factors. Instead of trying to identify certain determinants of diffusion, which may be independent of each other, but matter for the diffusion of technology, TIS scholars proposed the examination of a system's three key structural elements: the actors and their competences, the networks, and the institutions (Jacobsson, & Johnson, 2000). The actors include the firms in the value chain (Porter, 1985) and all the organizations and agents that participate in the system and bring in specialized knowledge (Bergek et al., 2008). The networks can be either political, aimed at supporting or opposing the innovation and/or learning and linking suppliers-users-competitors-researchers. Institutions are at the core of the system as they set the background against which the actors interact through the networks, resulting in evolution of the system.

The interaction of these three structural processes leads to the development of the TIS, which, in turn, promotes the diffusion of the technology in the system. However, Bergek et al. (2008) pointed to the weakness of trying to directly link the structural components of the system with system performance. They suggested that in order to examine the performance of the system, the researcher needs to investigate the various activities that take place within the system, which most TIS scholars label functions or activities[25]. These are necessary as they shape the performance of the TIS.

To get a better understanding of the dynamics of system evolution, we need to base our analysis on the evolution of the functions and take a functional or activity approach. Looking simply at the structural elements of the TIS does not help our understanding of the dynamics underlying system formation. By taking a functional approach, we are forced to look at the evolution of each function across time; this provides a clearer understanding of how the importance of functions varies across time and depends on the evolution of the technology. For example, in the early phases of the technology, the development of knowledge might be more important than the formation of the market. Also, this functional approach can shed light on the issue of complementarities among

[25] This is a term used primarily by Edquist (2005)

functions, something which has been recognized as a key driver of the evolution of the system (Bergek, 2002; Jacobsson & Bergek, 2004; Edquist, 2005; Hekkert et al.,2007; Suurs, 2009).

Another reason for taking a functional approach to diffusion is related to the complexity behind performance assessment. The simplest way to compare the innovation diffusion performance of two systems is to look at the output of the system, in this case diffusion of RETs. However, as Jacobsson and Bergek (2004) point, a functionalist perspective allows comparison of the performance of each function in the system rather than a simple and unhelpful comparison of output figures (Suurs, 2009). This allows the researcher to develop a more complete understanding of the reasons behind the evolution of a given TIS.

Despite the importance of the functions in the process of TIS evolution, there is still no agreement about the names of functions or their exact number. Nonetheless, there is agreement on the core issues captured by these activities - knowledge, entrepreneurship, social acceptance, resources, public support and markets.

It is of crucial importance in this analysis to distinguish between technologies that are improving/complementing existing ones, and those that are entirely new to the system. Building a new system that would replace existing ones is a longer and more uncertain process, because of the need to break the path dependence and lock in of the already established system (David, 1985). To distinguish between incrementally improving and radically improving technologies, Jacobsson uses the criterion of substitution vs complementarity. If the new system complements the old one, this is a transition, but if the two systems are substitutes, i.e. based on competing technologies then a new system is created. In the case of RETs, the distinction is less clear cut. Although in the short-run, RETs complement existing electricity generation technologies, in the long-run the aim is to completely substitute non-renewable technologies. Nonetheless, for each MW of electricity produced from renewable sources, the non-renewable sector is losing customers since it could be the one producing that electricity. Therefore, we can argue that RETs are competing technologies.

The advantages of the TIS approach is that it combines the meso and macro levels of analysis by integrating both the market domain and the social system in which the diffusion takes place into the framework. In addition, TIS operates on the basic tenet of non-linear models of innovation, which in essence are transfused into non-linear diffusion processes. Thus, the theory recognizes the complex inter-dependencies among the elements and allows for multiple kinds of interactions among them. Moreover, it explicitly recognizes that the system might fail not just because of market failure, but because of various other system failures (e.g. Mytelka & Smith, 2002; Lundvall and Borrás, 2005; Edquist, 2005; Woolthuis et al., 2005; Chaminade & Edquist, 2006; Frantzeskaki & de Haan, 2009).

Another advantage of this approach is that it incorporates the idea of path dependence which is a key tenet in evolutionary economics and also key to understanding innovation. The importance of path dependence is crucial as there is a frequent assumption in previous models that new industries emerge from nothing (Krafft et al., 2014). This is a hugely oversimplifying assumption and fails to take account of the existing environment. David (1985, p. 332) defines path dependence or more accurately a path-dependent sequence of economic changes as

> one of which important influences upon the eventual outcome can be exerted by temporally remote events, including happenings dominated by chance elements rather than systematic forces

This approach challenges the assumption that the most technologically superior design is recognized by the market and adopted. However, a less efficient technology might achieve dominance following a series of stochastic processes of events[26]. This conclusion runs contra to neoclassical economics which takes for granted certain equilibrium conditions, and tries to examine which processes lead to that equilibrium. In the path dependence literature, the outcome is not determined ex-ante, but is uncertain and dependent on the various processes that occur until that equilibrium is reached. Moreover, these events are not simply random but also persistent, and cannot be changed by chance.

However, this approach is in its infancy; it was proposed less than 20 years ago and several of its elements remain to be investigated. For example, there is superficial treatment of the time element in the theory, and various ambiguities around the measurement, nomenclature, and interaction among functions [27]. Moreover, there has been some work that criticises the whole concept of lock-in, most famously by Liebowitz and Margolis (1995) argued against the idea of lock-in to inferior technologies. For example, they

[26]The characteristic example of sub-optimal technological choice comes from the keyboard industry, where the QWERTY version emerged as the dominant design, despite the fact that other versions such as the Dvorak Simplified Keyboard were more efficient (see David (1985) and Malerba et al (1999).

[27]A more in-depth discussion of this theory, and the criticisms and weaknesses are presented in Chapter 3

claim that the famous QWERTY lock-in is a market outcome and the result of lack of competition in the keyboard market, rather than a result of historical influences. A different critique comes from Reinstaller and Hözl (2009), who argue that path dependent outcomes are the result of small events with positive feedbacks, but the extent of the lock in depend on the "organizational, industrial, and institutional conditions in which they are embedded" (Reinstaller & Hözl, 2009 ,p.1025).

Initial work on TIS focused on factory automation in Sweden (Carlsson & Jacobsson, 1994; 1997). However, this literature burgeoned with work on renewable energy (Klitkou & Coenen, 2013). Some of the earliest earlier studies, such as Jacobsson and Johnson (2000), Jacobsson and Lauber (2006), and Bergek et al. (2008) take a broad selection of RETs and try to investigate how the systems evolve. However, later work focuses on single technologies. For example, Dewald and Truffer (2012) investigate the diffusion of solar PV in Germany, Guo et al. (2009) examine solar PV in China, Klitkou and Coenen (2013), look at solar PV in Norway. Suurs and Hekkert (2009) investigate TIS in relation to biofuels and Negro et al. (2007; 2008) investigate the biomass TIS.

1.6 Combining Diffusion Theories, Technology Systems and Life-Cycle Models

The main conclusion from the review in the previous three theoretical sections is that diffusion cannot be understood by looking only at one theory, or at products and their adopters independently, nor by looking only at the firms or the environment. Moreover, it could be argued that over time, none of these elements remains fixed, but evolve together. To get a better understanding of the diffusion process, we decided to combine all three theories to diffusion discussed above, since we believe that this should enable a more holistic understanding of the diffusion process. As illustrated above, the neoclassical and DOI approaches suffer from many conceptual problems, mostly stemming from their simplistic conceptualization of the innovation process. Nonetheless, the neoclassical approach revolves around the importance of profitability for adoption which is a necessary but not sufficient condition, and the DOI is useful since it focuses on the importance of the characteristics of the innovation. On the contrary, the TIS brings together a more systematic conceptualisation of the process, emphasising the complementarities between the various elements.

However, the neoclassical and the DOI approaches do not take a dynamic view of the process, while the work on the TIS is dynamic in theory, but in practice it fails to do so adequately. For this reason, we decided to combine these theories with the life cycle models, which provide us with some stylized facts in terms of industry, product and technology evolution, allowing the process of diffusion to be broken down into smaller stages. This enables a better understanding of which determinants are important in each phase, and how their importance varies across time. In each stage, we hypothesize that different factors will be important for diffusion. For example, in the early phases, when the technology is still expensive and the number of firms involved in the industry is small, the importance of the environment and the government might be higher, compared to later stages. Similarly, as the industry grows, the capabilities of firms increase, which means that some of the characteristics of innovation proposed by the DOI will be less important (e.g. trialability), while other factors might be more important (e.g. compatibility).

However, the PLC cannot stand on its own as industries cannot be simply reduced to products. Similarly, the ILC cannot be the sole focus of a diffusion analysis since we cannot look only at the evolution of an industry because the boundaries of an industry change with the evolution of the technology. Life-cycle models provide a limited generalization of industry dynamics. Therefore, the ILC has to be linked to the TIS. In the context of TIS, the ILC captures some of its structural components. However, to bridge the gap between the components and the outcome of the system (i.e. diffusion), we need to examine the processes/functions that produced this outcome. This functional approach is the key benefit brought by TIS to diffusion analysis.

Combining therefore the theories of diffusion with the life-cycle models will allow us to get a better understanding of the dynamic nature of the diffusion process, which is the key objective of this PhD. The rest of the PhD is structured in the following way: Chapter 2 investigates the determinants of wind power, Chapter 3 focus on the TIS literature and applies it to solar and wind diffusion in EU countries, Chapter 4 looks at the solar PV TIS in a more dynamic perspective in four countries, Chapter 5 formalises the TIS framework, and Chapter 6 provides the conclusions and contributions of this work.

Chapter 2

Determinants of adoption and diffusion of Wind Energy: competing theories and frameworks

2.1 Introduction

The primary aim of this chapter is to identify the determinants of the diffusion of wind energy technology. This is achieved by combining two theoretical perspectives in diffusion theory, and the application of the life-cycle frameworks. In particular, we are interested in understanding how the characteristics of the product/technology and its adopters influence the process.

In terms of the theories, we have decided to focus on the neoclassical approach to diffusion and Rogers' (1962) diffusion of innovation framework (DOI). The neoclassical approach to diffusion relies on the importance of profitability as the key driver of diffusion, and stresses the double externality problem for RETs. The DOI is a wider approach to diffusion. It does not focus only on profitability or relative advantage (as DOI scholars call it), but looks also at four more perceived attributes of the innovation: compatibility, complexity, trialability, and observability. It also includes other elements in the environment such as the nature of the social system, and the role and function of the change agent.

Our selection of these two theoretical approaches is driven by two main reasons. Firstly, the neoclassical approach which stresses the importance of profitability and market failure currently dominates the thinking of policy makers in the field of diffusion of energy technologies, while the DOI framework is the most widely used in scholarly research on the diffusion of innovation. Secondly, our choice was guided by the type of data that was available and the type of analysis. We want to conduct a large N analysis in an attempt to identify the general characteristics and determinants of the diffusion process. This requires an investigation of diffusion in a large number of countries (i.e. more than 30), across an extensive time period (20 years). From a methodological point a view, this type of data is best analysed using regression analysis. Regression analysis works nicely with the neoclassical approach to diffusion which usually stipulates a linear approach to diffusion, and thus avoid any potential collinearity problems with modelling.

However, we recognise that these theories have some very restricting assumptions with respect to variability of the determinants of diffusion across time. At the same time, one of our main drivers in this work is the idea that diffusion is a dynamic process in which each element evolves across time. To deal with this conflict, we use life-cycle models, which provide a theoretically sound way to break down the element of time into different phases. Although many scholars do not differentiate between them, life-cycle models can be separated into product life cycle (PLC) models and industry life-cycle models (ILC). The main difference is related to the unit of analysis, which ultimately depends on the research aim. ILC models focus on the evolution of an industry, while PLC models focus on the evolution of a product. Jovanovic (1998, p.331) states that "the ILC is a shift from a product cycle notion that viewed an individual product as the unit of analysis to an industrial organization approach dealing with the endogenous evolution of industry". In this work, we are interested in energy produced by wind. However, this is does not belong clearly in either an industry nor a product. It has elements of both; on the one hand, we have the wind industry (manufacturers of wind turbines, electricity networks, service companies, etc.) which should be analysed with the ILC, and on the other hand we have the elements of the wind generation systems (e.g. wind turbines, gearboxes, etc.) which are best analysed using the PLC. This difficulty in identifying which of the two frameworks can better explain wind diffusion points to the fact that wind diffusion cannot be analysed solely by either of the two frameworks independently. For this reason and for completeness, we decided to use both frameworks in this work.

Apart from the difficulty involved in understanding the differences between these two frameworks, the investigation in Chapter 1 revealed some other gaps and ambiguities in these underdeveloped, though frequently used frameworks. The ambiguities range from the boundaries that separate the PLC and ILC models, to the lack of a methodological framework that identifies the beginning and end of each stage. Since we plan to integrate these two approaches, we develop a methodology that helps to identify the boundaries between the different phases in the PLC and ILC models.

The remainder of this chapter is organized as follows. Section 2 starts by presenting some of the theoretical foundations of the diffusion theories we are planning on using, as well as the life-cycle models as frameworks for diffusion. Section 3 proposes a methodological approach to investigate the different stages of the life-cycle and discusses the econometric techniques used to model diffusion in the introduction and growth stages. Section 4 presents the results and Section 5 concludes.

2.2 Competing theories and frameworks for Diffusion of RETs

2.2.1 Theories of Diffusion

Neoclassical

One of the earliest theoretical approaches on diffusion of innovations was proposed by neoclassical economists[1], who view profitability as the main determinant of adoption. They argued that the lower the cost of a product, the higher its expected profitability is and thus the faster it would be adopted by users. Thus, the main argument is that the market is the one that is responsible for diffusion; if the price is low enough and the benefits high enough, then the innovation will diffuse.

Given that profitability was the main incentive, they tried to investigate how different sources of profitability can be used to explain time to adoption of an innovation. Some of these elements were the investment required for the technology, the number of competitors using it, firm size[2], and the concentration rates in the industry in question.

These findings were solid insofar as the assumptions these scholars made were true. In particular, they assumed that all individual adopters are similar in every way, and have as a sole objective to maximize utility which was a function of their wealth. Secondly, they assumed that the preferences of individuals and the technology they were investigating remained constant across time. Thirdly, all models assume that diffusion depends exclusively on the characteristics of the innovation, especially its perceived profitability. Lastly, the innovation is readily available to all users. These assumptions allows us to label this approach as the neoclassical approach to diffusion[3].

Turning our attention to how this theoretical approach has been used to explain the diffusion of RETs, we can observe that it has been used primarily with reference to the double externality problem. Neoclassical economists argue that the free market fails to internalize the effects of positive knowledge externalities and the negative environmental externalities (see e.g. the work by Jaffe & Stavins, 1994, and Jaffe et al., 2002). The positive externalities come from the fact that the environmental innovation can lead to

[1]See for example the work of Griliches (1957), Mansfield (1961), Smith (1961), and Hinomoto (1965).

[2]See e.g. work by Fellner (1951) and Reinganum (1981).

[3]This list of assumptions comes from the author's own summary of the literature. For the interested reader, Geroski (2000) makes a thorough literature review of the various models that have been used, and their assumptions

positive effects to other firms and the rest of the economy, as the RET innovations can lead to further technological improvements and act as a foundation for the generation of new technologies. However, these benefits might not be captured by the original innovator, so this might lead to an under-provision of the RET. The negative environmental externalities might lead to an over-production of non-RETs since the price does not reflect the negative environmental impact these might have on the environment. Both these effects together can be seen as responsible for the reduced diffusion of RETs.

The existence of this double externality problem is the primary justification for the active role of government in the energy sector (Rennings, 1998). The government can introduce policies which can help correct this market failure. Two types of policies are suggested: one aimed at supporting R&D, and one aimed at trying to increase the costs of pollution. Other authors discuss how different national support policies such as subsidies, taxes, renewable energy funds, green certificate schemes or FIT (Wüstenhagen & Bilharz, 2006; Gan et al., 2007) influence RET diffusion. However, not all types of regulation have an immediate effect on the adoption of RETs, and the impact of different policies is very much country-specific (Acemoglu et al., 2009; Popp, 2006).

Another element in the neoclassical school of thinking which has attracted attention in the literature on RET diffusion is price and costs. Some early work on RETs shows that energy prices are a significant determinant of technology adoption (Boyd, & Karlson 1993). Thus, it could be argued that prices are also significant for the diffusion of RETs. The only paper that investigated this phenomenon explicitly is Rehfeld et al. (2007), which stresses the importance of getting prices economically right in order to achieve maximum diffusion. The issue of costs is explored in Neij (1997), who uses experience curves to study the diffusion of wind and solar, and argues that the most important factor for their diffusion is how quickly their prices (measured as the cost of generating electricity) will fall compared to traditional electricity producing factories. Similarly, Nakicenovic (2002) illustrates the importance of learning by doing in the diffusion of new technologies, and conducts a case study of the decarbonization of energy. He proposes a theoretical model that shows that although it is more costly to invest in clean technologies, the learning effects from the diffusion of these technologies will allow for a prompt payoff of the investment and thereby facilitate even more the diffusion.

Although externalities and profitability are both key in the process, they are surely not the only factors that shape the diffusion of RETs (Dewald & Truffer 2011). In reality, the overemphasis on national policies has shifted the attention of diffusion scholars away from pivotal issues such as technology-specific characteristics or other systemic elements of the diffusion process, which later work has proven as crucial. Examples include the characteristics of the product other than profitability, and the characteristics of adopters (Nabseth & Ray, 1974; Gold, 1981; Davies, 1979). To deal with issue, we decided to also use the DOI framework (Rogers, 1962) in our analysis.

Rogers' DOI

The DOI is primarily a sociological approach to diffusion and suggests that five main characteristics of an innovation determine its rate of adoption. These are relative advantage, compatibility, complexity, trialability and observability (Rogers, 2010). The remaining variation can be attributed to a spectrum of factors such as "the type of innovation-decision[4], the nature of communication channels diffusing the innovation at various stages in the innovation-decision process, the nature of the social system, and the extent of change agents' promotion efforts in diffusing the innovation" (Rogers, 2010, p. 232).

Relative advantage is defined as "the degree to which an innovation is perceived as being better than the idea it supersedes" (Rogers, 2010, p. 213). Compatibility is "the degree to which an innovation is perceived as consistent with the existing values, past experiences, and needs of potential adopters" (Rogers, 2010, p. 223). The greater the compatibility of the innovation with already established practices, the lower the uncertainty and, thus, the higher the potential for diffusion.

Complexity is defined as "the degree to which an innovation is perceived as relatively difficult to understand and use" (Rogers, 2010, p. 230), and is negatively related to the rate of adoption. Trialability is "the degree to which an innovation may be experimented with on a limited basis" (Rogers, 2010, p. 231); the higher the degree of trialability, the lower will be the uncertainty surrounding the innovation and the greater the likelihood of its adoption. Lastly, observability is "the degree to which the results of an innovation are visible to others" (Rogers, 2010, p. 232). Rogers argues that the more visible the technology to members of a social group, the faster will be its rate of diffusion.

Another factor that influences diffusion is the type of innovation decision, which points to the importance of the number of potential agents involved in the adoption decision. The larger their number, the slower will be the adoption process, *ceteris paribus.* To fa-

[4]This refers to whether the decision to adopt is made collectively by a social group, or individually, and whether it is an optional or mandatory adoption.

cilitate this process, Rogers' suggests that the analysis should take account of the particular individual/institution responsible for facilitating the change. This so-called "change agent" is defined as "the individual who influences clients' innovation-decisions in a direction deemed desirable by a change agency" (Haider & Kreps, 2004, p. 5). An example of a change agent might be an economist with an economy's finance ministry, whose aim is to facilitate tax collection by promoting some new accounting methods. Lastly, the communication channels and the way they operate in a given social system play a definite role in the rate of diffusion since they determine how the change agent communicates with potential adopters.

Although this is one of the most frequently applied frameworks in the field of diffusion, its application in the diffusion of RETs is not as wide as one would expect. Some examples of such work comes from Kaplan (1999), who uses DOI to analyse the decisions of electric utility managers towards the adoption of solar PV. Haas et al. (1999) examine the socio-economic aspects of the Austrian 200kWp PV-rooftop programme and the prospects for further dissemination of this technology. Another use of DOI comes from Mallett (2007), who evaluates the impact of social acceptance of RETs in Mexico, while Völlink et al. (2002) use Rogers' framework to predict the intention to adopt energy conservation interventions. Faiers et al. (2007) test the importance of the characteristics of an innovation and how they vary, based on the adopter category, using domestic solar-power systems as a case study.

In this work, we see DOI as a great complement to neoclassical approach as this theory allows us to incorporate into the diffusion analysis technology specific characteristics. This is especially valid for RETs, and wind technologies in particular, which have some distinct characteristics compared to other mainstream industries, which need to be accounted in an analysis. Jacobsson and Johnson (2000) point to three particularities of this industry. The first is related to the size of the market, which is enormous and, thus, the length of time needed for a substantial transformation is extensive. The second relates to the subsidization of the incumbent/traditional energy sources, either in the form of R&D incentives or non-reflection of the environmental costs in the prices of energy produced. This helps keeps the costs of conventional electricity sources low and increases their price competitiveness.

Third, Jacobsson and Johnson (2000), but also other authors such as Nakicenovic (2002) and Unruh (2000), stress the fact that RETs are competing in a sector which is dominated by powerful lobbies and, thus, their diffusion faces excessive resistance. Although their introduction may be small scale, RETs, because of their lower energy densities than traditional energy production means, occupy larger physical space and, thus, are more likely to influence a larger number of stakeholders (Wüstenhagen et al., 2007, p. 2684). This can lead to the NIMBY (not in my backyard) effect, which is a situation where a certain service, in principle, would benefit the majority of the population, but fails to gain acceptance by local communities (Van der Horst, 2007). A typical example is the case of wind power, which enjoys great public support, compared to wind power projects. Wind turbines face significant opposition from various social groups, despite their clear environmental benefits, because of their appearance, noise pollution, and some evidence that wind turbines have a negative impact on bird populations. Some examples of countries where the NIMBY phenomenon prevails are the USA (Bosley, & Bosley, 1988; Firestone & Kempton, 2007), England (Devine-Wrigth, 2005; Jones & Elser, 2010), and the Netherlands (Krohn & Damborg, 1999; Agterbosch et al., 2004)[5]. From this discussion, it is evident that diffusion analysis simply on an economic basis might not be sufficient, which points to the potential weakness of the neoclassical approach in this context, and thus the complementarity offered by the DOI framework.

A problem with both theories that we reviewed is that they assume that technologies and products are easily codifiable and time invariant (Tomatzky & Klein, 1982; Premkumar et al., 1994; Rogers, 2010). These simplifying assumptions ignore the socially constructed nature of large technological systems (Lyytinen & Damsgaard, 2001), and can lead to conclusions which have little connection to reality. For example, if we focus on the DOI framework, Rogers claims that all five characteristics of the innovation are important across the innovation's life-cycle. In reality however some of these characteristics might be more important than others according to the phase of the technology. For example, relative advantage might be more important in the early phases of the technology, since the innovation has to deliver a reward high enough to compensate early investors for risk and uncertainty. As the technology matures, other characteristics might become more important (e.g. the compatibility of the technology with existing user practices).

This inability of the neoclassical and the DOI approaches to incorporate the time-varying nature of the factors that influence the diffusion is one of the major points of criticisms that this work addresses. To achieve this, we decided to use life-cycle models, in combination with the diffusion theories. Life-cycle models are useful since they manage to identify different phases of the evolution of a product, industry and technology. This

[5]Other examples can be found by looking at references in the media, but we preferred to focus here only on peer-reviewed work

separation of stages gives us a theoretical justification of different time periods in which we can examine how the determinants of diffusion vary. Therefore, our last step in this section is to present the life-cycle literature.

2.2.2 Frameworks of Diffusion

The Product Life Cycle (PLC)

Within the life-cycle literature two main models can be identified: product life cycle (PLC) models and industry life cycle (ILC) models. Starting with the PLC, its origin can be traced back to the work of Kuznets (1930) and Dean (1950) and Hirsh (1965) who investigated the production patterns of various products and identified some patterns. In particular, they observed that as the product was relatively new, the production rates were increasing at an increasing rate. After some point however, the production started increasing at a decreasing rate, and eventual fall. Based on these empirical observations, a bell shaped curved emerged, with time on the x-axis and sales on the y-axis. Time was then separated into four main phases. This depiction can be visualized in Figure 2.1.

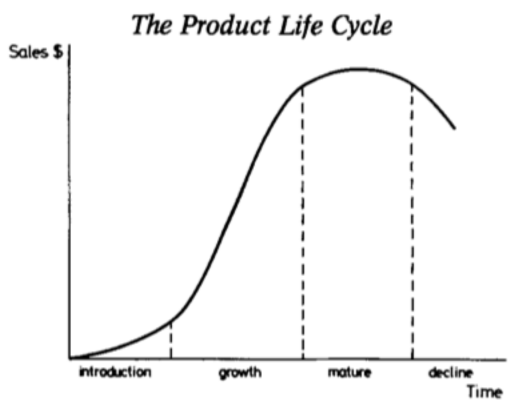


Fig. 2.1 Product Life-Cycle Models

Source: Audretsch, 1987, p.299

The main explanation for the PLC shape comes from the DOI theory (Robertson, 1967; Polli & Cook, 1969). At the time of its introduction, the new product does not get a great number of users as there is a lot of uncertainty around it, and also challenges the existing routines. Then, as the number of users increases, information around the product increases and thus uncertainty decreases, and the number of users increases at an increasing rate. Eventually, the market reaches its largest size and then adopters start to abandon this product for new better substitutes, leading to a decrease in sales and eventually the product's removal from the market.

The framework has been widely used in various strands of the economic literature, ranging from micro and industrial economics, to managerial economics and innovation (eg. Cox, 1967; Hofer, 1975; Thietart & Vivas, 1984; Gort & Konakayama, 1982; Audretsch, 1987). Its use extends also to international economics with Vernon's (1966) well-known work on location of international production, although this theory has more recently been invalidated (Cantwell, 1995).

The application of the PLC framework on RETs is limited. Maybe this has to do with some conceptual differences between the model's assumptions and the RETs' particularities. For example, the PLC suggests that the new technology is initially superior to the existing ones, and that is the reason why users start adopting it. However, this might not be the case for RETs, since initially they are too expensive compared to established technologies. Another example is related to when the framework suggests the new technology will be substituted by a newer one. In particular, according to the PLC, when a new technology emerges, the PLC suggests that it will start replacing the existing one. However, RETs have very long lives, relatively low maintenance costs, and are also expensive to substitute[6]. So, this process might be delayed. Lastly, the RETs might have to be substituted by new technologies even before they reach maturity since the physical limits might be exhausted. This will force their substitution by new technologies, which might lead to a truncated version of the PLC.

The Industry Life-Cycle (ILC)

The next major model in life-cycle literature is that of the Industry Life-Cycle (ILC). This framework examines the evolution of industries, which have traditionally been perceived as having periods of growth, maturity and decline (Marshall, 1879; 1890; Kuznets, 1930; ; Schumpeter, 1939; Rostow, 1959; 1960). More precisely, the ILC framework stipulates that the evolution of industries, as this is captured by firm entry and exit, follows a an S-Shaped distribution when plotted against time.

Various theoretical propositions have been made to explain the shape of the curve[7] However, the defining model in the field is proposed by Gort & Klepper (1982), who inves-

[6]For more information see Goodall (2014) and Chianese et al. (2003).
[7]See for example the work by Williamson (1975), Clark (1985), and Drew (1987).

tigated the development of 46 products and identified five stages in the development of the industry. Their framework is illustrated in Figure 2.2.

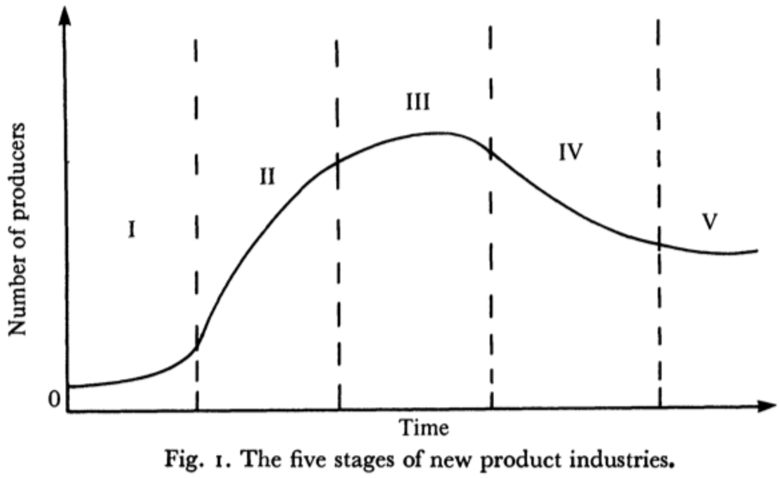


Fig. 2.2 Industry Life-Cycle Models

Source: Gort & Klepper 1982, p.639

Their model tries to explain the evolution of the industry based on entry rates. The key argument is that in early stages, the industry consists of a small number of firms, since the technology is not well understood by market participants (Mueller & Tilton, 1969; Abernathy & Utterback, 1978). Subsequently, the technology starts to be better understood, uncertainty gets reduced, and thus new firms enter the industry, until the market reaches its peak number of participants. Then, it is argued that the dominant design is established (Utterback & Abernathy, 1975; Anderson& Tushman, 1990; Utterback & Suarez, 1993; Agarwal et al., 2002). This brings about standardization of the technology, reduction in the complexity of the technology, reduction in the speed of technological advances, and a shift in process innovation. After the dominant design, the focus shifts into process innovation, and the number of participants starts decreasing through a shake out process (Jacobides, 2005; Argyres & Bigelow, 2007; Stuerz, 2014). In the final stage, the industry reaches a dynamic equilibrium where the number of producers stabilizes.

The ILC framework has been widely used by economists. Most of the work focuses on the shake-out process that takes place when the industry enters the maturity phase (Gort & Wall, 1986; Jovanovic & MacDonald, 1994; Klepper, 1996; Barbarino & Jovanovic, 2007; Jovanovic & Tse, 2010). Others focus on industry-level profitability, as well as firm performance (Robinson & McDougall 2001; Lumpkin & Dess 2001) and how these vary across the stages, while other scholars examine how the patterns of innovation differ as the industry moves into different stages (Mueller, & Tilton, 1969; Audretsch,& Feldman, 1996).

ILC models are a good representation of industries that produce consumer durables. However, various weaknesses emerge when the ILC is applied to a broader range of industries, as discussed by Malerba and Orsenigo (1996). One such industry is RETs. To be more precise with the problems of applying the framework to this industry, firstly, the RETs are not simply products but rather a system of technologies. Therefore, we cannot simply examine them as evolution of industries, but rather we should look at them as evolutions of systems. Another problem with using the ILC for RETs is that we are not looking at the evolution of an industry whereby completely new firms are established, but rather we observe existing firms expanding their operations into RETs through a wave of mergers and acquisitions. At the same time, we cannot identify a single firm which was a pioneer in wind technologies and then it was followed by new entrants. Rather, the different components of the RETs energy systems were developed in industries that were always highly concentrated, and innovation took place by incumbents.

Apart from the specific problems with the PLC and ILC frameworks, there is a general problem with using life cycle models in this work, which is related to the choice of the technology. Our empirical investigation includes wind technologies, which have not yet reached maturity. However, at this work the emphasis is on the determinants of diffusion in only the first two of the four stages of the life-cycle. Although this might be seen as a limitation of the present research, we argue that it remains relevant and interesting for at least two reasons. Firstly, given the increase in the rate of technological progress, technology life-cycles are getting shorter, and at the same time more new technologies emerge and substitute existing ones before existing can manage to reach their final phases in their life-cycles. Also, although there is an extensive literature that contests the number of phases in the life-cycle, there is a consensus about the introductory and growth phases. Therefore we can argue that the existence of the initial two phases of the life-cycle is generally accepted and presents a solid basis for research.

Despite these weaknesses the ILC can be seen as a good complement to the neoclassical approach to diffusion, since it introduces Schumpeterian style dynamics in the process by suggesting an endogenous model of industry evolution (Agarwal & Braguinsky 2014),

and can provide a useful dynamic framework for analysing industry evolution.
To conclude, the present work should be seen as an attempt to address some of the issues in the literature on diffusion theories recognised above. Firstly, it goes beyond the neoclassical approach which focuses only on the importance of regulation and profitability. Rather, by also using the DOI, it takes a broader view of the characteristics of the RET that influence the diffusion. Secondly, by using the DOI framework, we contribute to the literature on the importance of lobbying and lock-in to which the energy sector is exposed. Lastly, in this work, we recognize that wind technologies are constantly evolving and, thus, the factors that influence their diffusion should also vary, something not explicitly investigated in any prior work. For this reason, we use the PLC and ILC frameworks to identify key points in time in which changes in the determinants of diffusion might take happen.The aim of the next section is to explain how these theories and frameworks are operationalised in order to study the diffusion of wind.

2.3 Methods and Data

After proposing the combination of the two diffusion theories with the life cycle models, the next step is to discuss the methods we use to combine these elements together. We start by presenting the methodological issues around ILC and PLC, and then present and discuss the models.

2.3.1 Methodological Considerations in Life-Cycle Models

The problem with determining the actual shape of the PLC/ILC, the position at which a particular product is (Day, 1981) as well as the number of phases a certain product/industry has over its life-cycle, are all parts of the methodological difficulties when using life-cycle models (Wind, 1981). The next section presents some of the methodological approaches to classifying products and industries across their respective life-cycle. We propose two categories according to whether the focus is the product or the industry.

Classification of the stages in the PLC Context

In attempting to construct the PLC of a product, we need to think about the product life, i.e. when was the product introduced for the first time and when did consumers stop using it. Cox (1967) provides two definitions, Catalogue Life and Commercial Life, for how a product's life can be perceived. Catalogue Life suggests that the product is born when it is listed in the company's catalogue for the first time, and is dead when it is removed from the catalogue. The definition of commercial life is a bit more technical, but the idea is that a product is born when it is adopted by a certain number of users in the markets over a certain period and death when there is a certain decrease in revenue over a particular period[8].

Polli (1969) proposes a methodology for classifying the stages that the technology is currently in, based on sales data, assuming that the pattern of sales follows a bell shaped, normally distributed curve (Polli 1969, p. 393). Anderson (1984) uses a questionnaire and interview approach to determine the PLC of each product. Similarly, Covin (1990) uses questionnaires, but this time in an attempt to examine the ILC stages. Both these approaches suffer from the typical problems related to interviewing, i.e. subjectivity, and bias.

[8]The actual figures of this classification can be found in Cox (1967, p.376).

Thietart and Vivas (1984) use quantitative and qualitative approaches. The qualitative approach is based on interviews conducted by the PIMS (Profit Impact of Market Strategies) programme, while the quantitative approach is based on actual market growth, defined as the average growth rate of the market served by the business, corrected for inflation, over a four-year period. A business with real market growth exceeding 4.5% is located in the growth area. Within the range 0% and 4.5% the business is considered to be in the maturity stage. Finally, products with negative real market growth are classed as in the decline phase (Thietart, & Vivas 1984, p. 1408). No justification is given for the use of these criteria and they suggest that if there is a disagreement between qualitative and quantitative indicators, the observation is dropped.

Mullor-Sebastian (1983) suggests that products can be ranked according to their maturity since this is reflected by their production growth rate compared to the average for other products with similar industrial classification, over an eight-year period. Her aim is to find evidence to justify Vernon's (1966) theory of international production, and to examine signs and strengths of the correlations between the PLC and a country's trade patterns. Nonetheless, this approach does not help in providing a conceptual classification of what production growth rate is necessary to move the industry from growth to maturity.

There is no clear conceptual or empirical method to distinguish between the stages of the PLC, and most work is based on examining sales as the criterion for separating the stages. Thus, the various stages of the life cycle are defined and distinguished by their different patterns of sales growth (Vernon, 1966; Hirsch & Bijaoui, 1985). To deal in part with this problem, we use the concept of dominant design (Abernathy & Utterback; 1978). The idea is that in the early phases of the PLC there are various technologies and eventually one emerges and dominates the market. This is known as the dominant design. All market participants then begin to adopt this technology and we enter the mass market period. Therefore, we can argue that prior to the emergence of a dominant design, the product is in the introduction phase. Any factors that increase the probability of adoption prior to the dominant design are described as the determinants of adoption in the introduction stage. After its emergence, it could be argued that the product has entered the growth stage and, therefore, any factors that influence the probability of adoption at this time are determinants of diffusion in the growth stage.

The main problem of this approach is the absence of a clear methodological approach that allows for an exact dating of the emergence of the dominant design. Rather, identification is made based on expert opinion. To analyse the diffusion of wind, the dominant design is perceived as the three-blade turbine, and is believed to have emerged at the end of 1990s (some point between 1996 and 2000), as illustrated in the technological review of the history of wind in Chapter 1.

Lastly, in this context of wind technologies, we use the threshold of 1MW in order to avoid a situation in which a country has only experimental installations of wind, from a country which has begun to adopt the technology. This approach involves a trade off: on the one hand, there is a loss of accuracy since a country might have adopted wind before the date we set; on the other hand, there is greater accuracy since we reduce the probability of wrongly classifying a country as a successful adopter.

Classification of the stages in the ILC Context

The first attempt to separate the stages of the ILC was made by Gort and Klepper (1982), who initially modelled the industry life-cycle based on visual inspections of net-entry rates. This was followed by a statistical estimation and grouping their observations into stages, through standardization and discriminant analysis. The problem with this approach is that it is driven primarily by the data and not some conceptual framework. Moreover, it focuses on the US economy in order to determine the average net entry and the authors' creation of a general value for each of the stages, independently of the type of industry.

Following Gort's initial attempt, Agarwal and Gort (1996) and Karlsson and Nyström (2003) use the empirical regularities on entry rates proposed in the literature, i.e. that net entry in the early stages of the life-cycle is positive, while negative in later stages, and use different statistical and aggregation techniques to classify the various industries of their dataset along the life-cycle.

In more details, Agarwal and Gort (1996) base their separation into the different product life-cycles on entry rates, and divide the gross annual entry in each phase by the average annual entry for all phases to standardize phases across products. Five phases are identified: "(1) initial low entry, (2) increasing entry, (3) decreasing though still generally high entry, (4) low entry, (5) erratic pattern that typically characterizes the final phase" (Agarwal, & Gort 1996, p. 492). The problem with this method is what constitutes low entry, what high, etc. In other words, there is too much "atheoretical subjectivity" in the methodology; the authors define low, high, etc. based on their own view of the data patterns.

Similarly, Karlsson and Nyström (2003) classifies each industry according to how many years in the dataset there was negative net entry. If net entry appears negative in only one year, then that industry is Group 1; if the number of firms decreases in all years, then it is Group 6. If the industries are in the first three groups, then they are considered to be in the early stages, while Groups 4 to 6 are considered declining industries. There are various problems with this approach, primarily related to the criteria for the classifications, such as the choice of groups, and the length of time. For example, Karlsson does not specify why he chose one year as the determining characteristic for moving from one stage to another. In my view, this is a serious issue, given that different industries have different life-cycle lengths.

Audretsch and Feldman (1996, p. 263) take as starting point Klepper's theoretical arguments on the ILC and create a framework to classify the various industries in his analysis. In more detail, the theory argues that in the early stage of the ILC, innovation activity is high and tends to originate in small entrepreneurial firms. Based on this they suggest that if there is supporting empirical evidence, then the industry is in the introductory phase. Similarly, the theory suggests that if innovation is low, and is conducted by large firms, then the industry is in its maturity stage. If the data support this claim, then the industry is in the maturity phase.

Although, it is an intuitively interesting approach, it does not explicitly set the exact limits for small/large industries and high/low rates of innovation. The authors take the mean of each variable to distinguish between high and low, a process which is clearly driven by the data and thus loses some theoretical validity.

In our work, we propose a simpler yet more intuitively robust approach, which is a variation of Gort and Klepper's (1982) approach on the first stage of industry development. They argue that the first commercial introduction of the product signals the beginning of the first phase of the life-cycle. They emphasize the importance of commercial introduction rather than simple technological innovation since there can be a significant time lag between these two phases. Similarly, we assume that the industry emerges with the first adoption of the technology in question. Therefore, all factors that lead a country to generate electricity from the first turbine would proxy for the determinants of diffusion in the introduction stage. This first adoption has to be significant enough to allow us to assume that it is not just an experimental, but a commercial introduction. In this context of wind, we assume that the industry starts when a country has developed a minimum of 1MW of electricity from wind. In this way, we manage to avoid accounting for random or experimental adoptions, since 1MW of electricity is sufficient to suggest that an industry has started forming.

To capture the determinants of the growth phase of the industry, we look at the factors that explain how fast a country manages to increase its wind turbine capacity from 1MW, since we assume that after the country has established 1MW of capacity, the industry will have moved from the introduction to the growth phase. One limitation of this approach is identifying the maturity stage which requires some kind of event or threshold. However, this is beyond the scope of this thesis, since wind technologies have yet to reach that stage.

2.3.2 Econometric Methodology

The two econometric techniques we use are "Survival Analysis" and "Generalized Method of Moment (GMM)" dynamic panel data analysis. The first is used to identify the determinants of diffusion across the introduction and growth phases of the PLC and in the introductory phase of the ILC model; the latter is used to study the diffusion of wind energy in the growth stage of the ILC model. The remainder of the section discusses these techniques and how they are used in this context, and concludes by describing the dataset.

Survival Analysis

Our first objective in the PLC and the ILC models is to identify the determinants of the introduction phase. Above, we argued that the introduction phase both for in the PLC and the ILC context starts when the first 1MW of electricity is generated. To examine the determinants of this first adoption, we use the method commonly known as survival analysis[9]. The technique originates in medical research, where the aim was to identify the factors that might explain why some patients survive and others do not (Young, G. & Sarzynski, A., 2009). Given the origins of the methods, most of the terminology used is counter-intuitive. For example, failure in this context implies survival, i.e. the patient failed to die. Extending this idea to our diffusion analysis:

- failure is a country that has managed to adopt wind energy;
- survival is the period up to the adoption of wind;

[9]Other names that have been used for this methods include hazard models, duration models, and failure time models.

- the survivor function gives the probability that no event has occurred before time t. In this context, the event is adoption of wind technology;
- the hazard rate is the probability that a country will adopt wind energy in a given period.

The key idea is that this method allows us to investigate a time domain for countries, which can be separated into two mutually-exclusive states at each point in time - absence and presence of wind power. As time passes, countries move from one state to another. The advantage of this technique is that it provides a "convenient way of incorporating time-varying covariates[10]" (Kerr & Newell 2003, p.326). The advantage of using hazard models over simple probit/logit models and OLS techniques is that we are not only interested in the probability of an event occurring, but also in the speed that this event occurs. Moreover, given that we take account of the element of time, there is a high probability that failure will take place outside our period of examination (either before or after). This phenomenon is called censoring, and use of techniques other than hazard models risks losing the information from the censored observations, thereby reducing the efficiency of the model.

Within the survival methods approach, there are three ways to model time to an event: non-parametric, semi-parametric, and parametric. The non- parametric method lets the data to "talk by themselves", i.e. assumes that the variation in survival is entirely due to time. Semi-parametric models leave the baseline hazard unspecified and focus on calculating estimates for the coefficients. This method, proposed by Cox (1972) is also known as the Cox-proportional hazard model. Parametric models are similar to semi-parametric model, with the addition that they assume that the baseline hazard follows a certain distribution (e.g. Weibull, Exponential, and Gompertz-Makeham).

This paper focuses on non-parametric and semi-parametric methods. Non-parametric approaches are useful for survival models in order to get a feel for the data; these are used more as summary statistics. The real choice for the researcher is whether to use parametric or semi-parametric models. We chose semi- parametric models, which have some advantages over parametric models in this context. The key argument is around the baseline hazard rate, which is the probability of failure assuming the values of all the covariates are zero. In the context of wind, this would mean that the diffusion can be explained only by looking at time and no other factor, which is clearly not relevant.

[10] Covariates are the same as independent variables.

One way of accommodating the unspecified baseline hazard is to use the Cox Proportional hazard model. In the Cox model, the baseline hazard remains unspecified, and can take any shape that the data might suggest (Collett, 2002). This presents the analysis with some problems, such as some loss in the efficiency of the estimators, because some information may be left out. However, "this efficiency loss is generally small and can disappear completely in asymptotic results" (Moeller, & Molina, 2003, p.95). At the same time, however, this makes Cox models attractive, since any false attempt to parameterize the baseline hazard rate can create distortions in the model (Larsen and Vaupel, 1993, p.96). From a conceptual point of view, Blossfeld et al. (2012) suggest that social scientists are largely agnostic about the distributional form of the baseline hazard, making semi-parametric models preferable.

As mentioned earlier, these methods originally were used in biomedical science. In economics, hazard models have been used to analyse labour economics issues, such as unemployment spells. In the context of modelling the diffusion process, we find various attempts and numerous papers to review the literature on diffusion models. These include Meade (1984), Mahajan et al. (1990), Baptista (2000), Mahajan et al. (2000) and Meade and Islam (2001; 2006). All these reviews highlight the importance of hazard models to capture diffusion. To apply hazard models for diffusion studies, it is necessary to frame the issue such that the model could try and identify what factors determine the conditional probability of technology adoption in time t, given that the technology has not been adopted by that time. In other words, hazard models can help to answer the following question:

> Given that a country has not adopted wind by time t, what are the chances that it would adopt it during time t?

Hazard models are not widely used in environmental economics, and to our knowledge have not been used to examine RET diffusion. Perhaps the most similar work in this area is Jenner et al. (2012), which uses hazard models to investigate why the EU-27 countries adopt FITs. Similarly, Matisoff (2008) uses survival models to investigate the adoption of renewable portfolio standards (RPS) by states, for the period 1997 to 2005, and Young and Sarzynski (2009) look at the adoption of solar energy financial incentives across states, (1974-2007). These papers belong to a strand in the literature that uses hazard models to examine policy diffusion (Bradford & Branton 2005). Other examples include Stoutenborough and Beverlin (2008) which examines the diffusion of net-metering polices across the states from 1993 to 2006.

The typical formulation of the hazard function using a Cox model is given by equation 2.1.

$$h(t, X, \beta) = h_0(t)e^{X_{it\beta}} \tag{2.1}$$

where $h(t)$ is the rate at which each individual country introduces electricity from wind at time t, given that they have not introduced it by timet_1, h_0 is the baseline hazard, and X_{it} is a vector of all the covariates and their corresponding parameter vector that the model assumes will have an impact on h(t). In our work, the dependent variable is binary, and takes the value 0 if the country has not adopted wind, and 1 otherwise. The values of β are calculated using maximum-likelihood methods and are "interpretable as the effect of a one unit change on the log hazard rate of a unit change in an explanatory variable at time t" (Kerr & Newell 2003, p.327). However, to make the interpretation more intuitive, we normalize the data using the methodology proposed by the OECD (Nardo et al 2005), which uses equation 2.2:

$$X_i = \frac{Y_i - \overline{Y}}{s} \tag{2.2}$$

where $\overline{Y}$ is the mean of the variable Y and s the standard deviation, and $0 \leq X_i \leq 1$. The interpretation of the βs based on the normalised values of the covariates then changes; by subtracting e^{β} from 1, the result gives us a percentage effect on the hazard rate of each covariate.
The baseline hazard (h_0) is assumed to be common across all countries in our analysis, and to vary only with time not with any other variable including the covariates. This can be thought of as similar to the intercept in ordinary least square (OLS) models, because it captures any effects on duration that are not explained by the model. Moreover, "it is based on the assumption that all hazard functions across the different levels of variables in the model are proportional to a baseline hazard function" (Somers, & Birnbaum, 1999, p.280).

Lastly, in order to analyse diffusion in the PLC concept, we need to incorporate in our model the emergence of a dominant design. To achieve this, we assume that our investigation starts in year t, lasts until year $t + n$, and the dominant design emerges in some year $t+k$ (where $k, n > 0$). Then, we assume that the introduction stage occurs between t and $t + k$. Any variables that are significant in this model in this time period are the determinants of diffusion in the introduction stage. Then, we test the same model, but for the period $t+k+1$ until $t+n$, and we identify this as the growth stage. Similarly, any factors that are statistically significant for our model are the determinants of diffusion in the growth stage.

After establishing the conceptual approach, we need to identify the exact date when the dominant design emerges[11]. As already mentioned, there is no clearly specified methodological approach that can help us to identify the exact date when the dominant design emerged. Our review of the technology in Chapter 1 showed that the dominant design for wind emerged at some date at the end of the 1990s. Thus, we take five different dates for dominant design emergence, from 1996 to 2000 inclusive, and repeat our analysis for each time period.

Dynamic Panel Data

To model diffusion in the growth stage of the ILC, we are primarily interested in identifying which factors influence the rate of diffusion, i.e. how fast the industry will grow. In other words, we want to explain why the rate of increase in wind electricity was faster in some countries than others. We cannot use traditional panel data analysis since diffusion is a path-dependent process in which past behaviour determines the future, and also because research on energy sector innovation highlights the importance of lags for determining diffusion. This has been demonstrated in the economics of diffusion, from the early work by Mansfield (1961, p. 763), who argued that "... the probability that a firm will introduce a new technique is an increasing function of the proportion of firms already using it...” Similarly, most of the literature argues that "the probability of adoption by a firm in a given date is positively related to the proportion of those who have already adopted" (Jensen, 1982, p.183). Conceptually, this idea is based upon Schumpeter’s imitation hypothesis (Davies, 1979). This path dependence is illustrated also in the stylized fact of diffusion, the S-curve, which illustrates that the diffusion process follows a certain pattern[12]. This implies that diffusion in time t, is a specific function of diffusion in $t-1$, and therefore this has to be captured by our model.

To capture the issue of path dependency means including a lag of our dependent variable. However, estimation of the above model cannot be performed in the context of a fixed effects model because of serious endogeneity problems caused by including the autoregressive parameter y_{it-1} since it is correlated with the unobserved individual country effects u_{it}. The solution to this problem in this context of first-order dynamic panel data, is to use General Methods of Moments (GMM) (Anderson & Hsiao, 1981; Arellano, 1989; Arellano and Bond, 1991; Arellano and Bover, 1995; Blundell and Bond, 1998). To

[11]A discussion of the covariates that will be incorporated in this model are discussed in detail in the subsequent sections

[12]For more details see Chapter 1

achieve this we use function 2.3.

$$\left.\begin{aligned} Y_{it} = \alpha_1 Y_{i,t-1} + \ldots + \alpha_n Y_{i,t-n} + \beta X'_{it} + u_i + \epsilon_{it} \\ \text{for } i = \{1, \ldots, 63\} \\ \text{and } t = \{1, \ldots, 20\} \end{aligned}\right\} \tag{2.3}$$

where y_{it} denotes the amount of total electricity generated by wind in country i in time t, X_{it} is a vector of our various independent variables, u_{it} are the unobserved individual country effects, and ϵ_{it} it is the error term.

We also apply lags to the independent variables in our model; this aggravates the endogeneity problem and results in upwardly biased coefficients in OLS models and downward biased coefficients in fixed effects models. To correct for this, we use the System GMM (SYS GMM) estimator (Arellano and Bond, 1991; Arellano and Bover, 1995; Blundell and Bond, 1998). This deals with problems of potential endogeneity of some of our regressors, the presence of predetermined variables, the lagged dependent variable, and the presence of fixed effects which may be correlated with the regressors and our finite sample (Belitski & Korosteleva, 2011). This is because SYS GMM makes fewer assumptions about the underlying data-generating process, and uses more complex techniques to isolate useful information; in particular, it allows predetermined and endogenous variables to be appropriately instrumented with lags of their own differences (Roodman 2009).

This approach to dealing with dynamic panel data estimation has become very popular. However, it is still considered new in the field of econometrics, so there is little empirical work. To the best of our knowledge, there are no studies that employ this technique in the context of renewable energy diffusion. The closest study is that by Kok et al. (2011) who use it to investigate the diffusion of energy efficiency in buildings. In diffusion studies more generally, there are a few papers that use this technique[13]. This is most likely because the conceptual approach was developed in the 1990s, but it was not until around 2003 that relevant econometric software was developed[14].

[13] See for example, Yamamura (2008), Denni & Gruber (2007) on broadband diffusion, and Andres et al. (2010) in internet diffusion.

[14] See xtabond2 command in STATA by Roodman (2006)

2.3.3 Variables Used and Descriptive Statistics

We incorporate the two theoretical approaches to diffusion that we use here by identifying the variables that might proxy for each of the main points suggested by the respective theories. This in some way follows the work of Wejnert (2002) who tried to create a framework that integrated multiple variables used in diffusion research. In particular, Wejnert proposes three groups of variables: the first measuring innovation specific characteristics, the second measuring the characteristics of the innovators, and the third measuring the characteristics of the environment within which the diffusion takes place.

We also propose a three-tier classification. In the first tier, we include variables which belong to the neoclassical and DOI framework. In the second group, we have variables that are exclusively sociological, and in the last group we have variables that are particularly relevant to the energy sector. Our selection of variables and their theoretical classification are summarized in Table 2.1. The first column makes the link to the theoretical origins of the indicator; the second column gives the theoretical effect that the indicator captures, the third column translates the theoretical effect into an actual effect, and the fourth column presents the indicators used.

Table 2.1 List of Covariates used in Our Models

Theoretical Origins	Theoretical Effect	Effect	Indicator
Neoclassical/Sociological	Profitability/Relative Advantage	Government Support	Introduction of FITs
		Price of competing products	Price of crude oil (Local Currency and in 2005 PPP)
		Cost of Innovation	Cost for Danish Turbines (€/kw)
		Size of the market	Electricity consumption/capita GDP per Capita Income Group
	Profitability/Compatibility	Availability of the resource (supply)	Weighted average the area of load hours per capita
Sociological	Complexity	Capability	Primary and Secondary education total (average years)
		Level of Development	GDP per Capita Income Group
	Observability	Observability	Distance from Denmark Trade with pioneers Interaction between distance and trade from Denmark Interaction between distance, trade from Denmark, and development
	Nature of the Social System	Political Regime	Polity2
	Change Agent's Promotion Efforts	Environmental awareness and Change Agent	Green party Interaction between green party and polity2 Kyoto protocol dummy EU membership dummy Interaction between Kyoto and EU
Sociological/Energy Specific	Compatibility	Carbon lock-in	% of electricity is produced by fossil fuels Interaction between oil price and electricity from fossil fuels
		Market lock-in	Natural resource rents as % of GDP
		Energy Efficiency	Energy use (kg of oil equivalent) per $1,000 GDP
		Country Pollution levels	CO_2 emissions (metric tons per capita) CO_2 intensity
	Relative Advantage	Energy Dependency	Energy imports, net (% of energy use) Interaction between oil price and energy import dependency Interaction between oil price and energy import dependency and % of electricity produced from fossil fuels

The first theoretical effect we need to capture is the profitability of the innovation, which is the main determinant in neoclassical models, and is captured also in DOI within relative advantage. To measure this effect, we first need to look at the cost of generating electricity from wind. This is a function of the actual cost of setting up and operating a wind turbine across time, and the government support policies. Ideally, we need data for the levelized cost of wind systems in every country in every year. However, such data are impossible to collect for a sample size of 134 countries and a 20 year period. Therefore, we use the cost per kW for Danish turbines, given that Denmark is a major manufacturer of turbines and, over time, has had the most developed knowledge base and most developed wind manufacturing industry. We decided to focus on turbines rather than the whole system, since turbines account for the largest proportion of the cost of a wind system[15].

In relation to support mechanisms, there are various instruments available to government to promote the diffusion of wind. However, the most effective according to the literature is FITs (see, e.g., Butler & Neuhoff, 2008), which in essence is a subsidy paid to producers based on the electricity they generate. It is not feasible to gather data on tariff levels for different types of wind power for different countries across time, so we include a dummy variable for whether a country introduced an FIT policy, rather than including the actual value of the subsidy.

To estimate relative advantage we need an idea of the cost of competing technologies. Again, it is not possible to gather data for all generating technologies for all countries for the whole period. Therefore, the choice of the indicator should be such that it is available for the greatest number of countries in the dataset, and at the same time reflect as much as possible the theoretical phenomenon in question. In this case, we decided to take the price of oil, as this is a fuel that is generally used for electricity generation, and its price is widely recorded. Nonetheless, it could be argued that it does not represent a very accurate representation of the cost of electricity from competing technologies, because it accounts for a very small portion of the total fuel generation, especially in OECD countries where nuclear and hydro are also significant electricity generating technologies. However, it could still be considered a relatively robust indicator to measure the cost of competing technologies, because oil prices are highly correlated with gas prices, and to a lesser extent coal prices; thus, oil prices can be considered a proxy for the prices of fossil fuels, which as a whole constitute a very significant amount of electricity generation. In a way, oil can be viewed as an instrumental variable, whereby it instruments the effects of competing technologies on the probability of adoption.

Other factors identified in the neoclassical literature as important include market size. For this, we use three indicators - electricity consumption per capita as a measure of the country's market size; GDP per capita (which is also a proxy for income levels), and a

[15]For a more detailed breakdown of costs see Chapter 1

categorical variable that distinguishes countries into four different income groups (low, lower-middle, upper-middle, and high)[16] based on the World Bank definition[17].

Another indicator is the availability of the resource in the country, which we capture by looking at the amount of wind in a country. This is not straightforward to measure, as there are many variables that determine "the amount of wind" relevant for wind technologies in a country. To deal with this, a commonly used indicator is called "Full Load Wind Hours". This measures the amount of time a turbine would spend at full load if it always operated at that level. To get this data, we used the database constructed by the US Department of Energy (2008), which gives estimates for all countries around the globe. It includes groups of areas based on full load wind hours and then, for each country, measures the area in km^2 for each load range. We use a weighted average of the area, which we scaled based on the country's population. We use this indicator also to capture the effects of compatibility, i.e. how compatible the technology is with the potential users' values and needs. This is done assuming that the more wind resources the country has, the more likely it will have a favourable attitude to the technology and, thus, the greater the compatibility of the technology with society's perceptions.

To get a deeper understanding of compatibility, we also include some variables that measure the economy's dependence on fossil fuels; the more dependent the economy is on fossil fuels, the less compatible it will be with new renewable resources. The literature refers to this as carbon-lock in, a situation in which the economy can be locked into fossil fuels and be resistant to change if it is earning high rents from the sale of these natural resources. The higher the proportion of these rents in the economy's GDP, the less compatible wind technologies will be with the system. For this reason, we include a variable that measures natural resources rents as a percentage of GDP[18]. On the contrary, if a country has very high emissions and is very energy inefficient, it could be argued that there might be some external factors (e.g. European Union) that would push the country towards becoming more energy efficient and will make the adoption of wind more likely.On the contrary, if the emissions are very high, this might indicate that the established energy inefficient players are well established and thus there is very strong resistance to be expected to the adoption of new technologies. To test which of these

[16]This variable is allowed to vary across time as the classification of some countries might changed with the level of income, however no major variation is observed. We also used this categorical variable instead of the continuous variable for modelling purposes.

[17]For more information see Datahelpdesk.worldbank.org (2015)

[18]This is calculated by dividing the sum of oil rents, natural gas rents, coal rents (hard and soft), mineral rents, and forest rents earned in the country by its GDP.

two situations is valid in our sample, we include some measures for energy efficiency and pollution[19].

In relation to the purely sociological aspects of the DOI, we decided to proxy the complexity of the innovation based on the country's capabilities and level of development. For level of development, although this is an oversimplification of the process, we assume that the more developed the country, the less difficult it will be for it to understand and adopt the technology. Similarly, for capability, we decided to use years of education of the population based on the Barro-Lee database.

A unique element of our framework is the criterion of observability. To capture this, we decided to measure the physical distance from Denmark, which is the most successful country for wind turbines, and one of the leading innovators. We assume that the closer the country is to Denmark (in physical distance and trade volume), the more likely is the country to "observe" the successful adoption of wind turbines and, thus, the stronger will be the observability effects.

A key factor in the model is the change agent, an institution responsible for actively promoting the technology to be diffused. In this context, we tried to find various ways to proxy for this. The first identified was the existence of a green party in the country, modelled by a dummy variable, since data on green party representation and influence were not available in the dataset. Moreover, we recognize that if the country belongs to international institutions that actively promote wind energy, then these could be seen as change agents. In this context, we recognize two such institutions: signing the Kyoto protocol and EU membership, since both institutions have been very active in promoting wind and renewable energy generally.

The change agent operates within a system which influences its strength and effectiveness. This is defined as the social system in the DOI context, and to proxy for it, we use a variable for political freedom, polity2. This indicator is taken from the Polity IV project and is the most popular measure of a country's political regime (Plümper & Neumayer, 2010). We assume that the more open and democratic the country, the greater the strength and effectiveness of the change agent. So, we include in the analysis an interaction term between polity2 and green party.

[19]These measures are primarily CO_2 emissions, and energy imports, but also their interactions. The full list of variables can be found in Table 2.1

Five points need to be underlined. First, the fact that there are no indicators that represent only the neoclassical approach. Rather, the neoclassical indicators can be seen also as falling within the sociological perspective, either in the form of relative advantage or in the form of compatibility. Second, from the sociological framework, the trialability effect is captured only indirectly in the dynamic panel model, by the lags of the dependent variable, as explained in more detail later. Third, some indicators capture more than one effect and, thus, are listed more than once in the table. Fourth, various interactions between the variables were examined, and are discussed in the findings section when they were found to be statistically significant[20]. Five, the only omission from the DOI is the type of the innovation decision, as it is complicated and potentially inefficient to attempt to capture such an effect quantitatively since there is no clear way to identify whether the decision to build was based on a collective, authoritative, or optional process.

Data Considerations

The main databases used in this research are World Bank Development Indicators (WDI) and the IEA Renewables database. The IEA Renewables database provides information on renewable electricity production for 134 countries for the period 1990-2010. The WDI includes a similar number of countries but a wider range of indicators, over a longer time span, but we are limited by our dependent variable which comes from the IEA database. Some of the data, such as the FIT indicator or green party, were collected from a variety of web resources. Another limitation of this analysis is the time span. Ideally, we would have liked to have data from the time of the first commercial turbines were introduced in a country until 2010. However, the IEA database starts from 1990, which means some observations are lost.

Another limitation is related to the dependent variable. Ideally, based on the methodology proposed in the previous section, we would need the number of turbines installed in a country to identify the beginning of the introduction phase. However, there are no available data on number of turbines, only installed capacity in terms of MW, and the amount of electricity produced from wind. However, without a turbine you cannot generate electricity from wind, therefore, both proxies are equivalent to the number of turbines. However, it should be noted that the fact that a turbine is installed does not mean that the turbine is in use; therefore, we use the amount of electricity generated from wind.

[20]For the interested reader, a full list of the variables including the interactions can be found in Appendix B.1

The final limitation is related to choosing electricity generation by wind rather than number of turbines in the ILC framework. The ILC methodology assumes that the factor determining the transition from introduction to growth stage is the first turbine; the first turbine implies the introduction stage, while the second implies the growth stage. Since we do not have data on the number of turbines, we assume that if the country produces electricity from wind in one year this implies it comes from one turbine or one project (which might include multiple turbines)[21]. Thus, the introduction phase of the industry takes place is when the first turbine is established, and then the change in the number of installed MW represents the growth stage of the industry.

Summary Statistics for the Survival and Panel Datasets

Tables 2.2 and 2.3 present summary statistics for the dataset. In relation to the panel dataset, note that the data used for the diffusion model are a subset of the original panel used to model first adoption, but includes only the countries that adopted wind technologies in the time period under examination. Table 2.3 provides summary statistics for the variables used in the econometric model that were significant.

Table 2.2 Summary Statistics for the Survival Dataset

Indicator	Observations	Mean	Standard Deviation	Min	Max
dummy for the imposition of FITs	1892	0.41	2.58	0	20
world price of crude oil	2814	36.14	24.29	12.72	97.26
world price of crude oil in Local currency	1773	6.64E+09	2.8E+11	0	1.18E+13
cost euros/kw for Danish Turbines	2278	876.05	99.38	747	1094
calculated electricity consumption/capita	1814	0.02	0.05	0	0.94
GDP per Capita	1766	87184.74	148640.9	409.86	1390731
Income Group	2814	2.9	1.36	0	5
weighted average the area of load hours per capita	1873	0.02	0.14	0	2.25
weighted average the area of load hours per capita (average in the period)	2793	0	0.01	0	0.12
weighted average the area of load hours	2793	656.83	693.43	219	3285.5
primary and Secondary education total (years)	1878	113.7	68.86	9	280
primary and Secondary education total (years) (average)	2814	11.92	0.62	10.67	13.57
distance from Denmark	2793	5313.1	3708.13	78.08	18247.02
trade with pioneers	1770	5.55E+08	1.28E+09	0	2.37E+10
interaction between distance and trade from Denmark	1750	2.95E+12	9.5E+12	0	2.36E+14
interaction between distance, trade from Denmark, and development	1667	6.31E+16	3.97E+17	0	1.13E+19
polity2	1712	16.46	74.4	-200	200
green party	1892	2.05	4.92	0	20
Interaction between green party and polity2	2585	2.52	4.38	-9	10
Kyoto protocol dummy	1892	2.28	5.25	0	20
EU membership dummy	1892	0.23	1.89	0	20
interaction between Kyoto and EU	1892	0.14	1.55	0	20
% of electricity is produced by fossil fuels	1744	570.45	459.27	3.85	1812.15
interaction between oil price and electricity from fossil fuels	1640	1.87E+11	7.58E+12	0	3.07E+14
natural resource rents as % of GDP	1756	139.2	289.55	0	3097.61
energy use (kg of oil equivalent) per $1,000 GDP	1644	2492.85	2498.55	62.78	21497.19
energy imports, net (% of energy use)	1744	-598.61	2293.84	-19062.7	1800
interaction between oil price and energy import dependency	1640	7.34E+10	2.97E+12	-1.3E+09	1.2E+14
interaction between oil price and energy import dependency and % of electricity produced from fossil fuels	1640	1.92E+12	7.76E+13	-8.3E+10	3.14E+15
CO2 emissions (metric tons per capita)	1629	43.53	87.38	0.01	1037.3
CO2 intensity	1630	17.27	13.84	0.02	87.97

[21] We could correct for this by dividing installed capacity by standard turbine capacity. However, identifying standard turbine capacity for a given year is virtually impossible; also, it assumes that there is a globally accepted standard for each country.

Table 2.3 Summary Statistics for the Panel Dataset

Variables	Mean	Standard Deviation	Min	Max
Proportion of total electricity production produced from wind	0.0053	0.0186	0	0.1904
whether the country has a FIT	0.2188	0.4136	0	1
Crude Oil Spot Prices (USD/bbl)	36.1353	24.2982	12.716	97.256
GDP/capita in 2005 PPP (log)	9.3418	0.9143	7.0037	11.2134
Primary Secondary education total (years)	11.9025	0.7674	10	14
Total natural resource rents (% of GDP)	3.9475	8.0113	0	68.5748
Energy use (kg of oil equivalent) per $1,000 GDP (constant 2005 PPP)	205.8199	128.4205	49.9313	984.498
EU Membership	0.2656	0.4418	0	1
Polity2 score	6.7418	5.1508	-8.0000	10
Existence of Green Party	0.5499	0.4977	0	1
Kyoto Protocol	0.4583	0.4984	0	1

2.4 Findings

We start our findings by looking at the evolution of diffusion determinants across the ILC, then look at the data for the PLC, and compare our findings for the ILC and PLC.

2.4.1 ILC and Diffusion

Determinants of Diffusion in the Introduction stage of the Industry (Survival Models)

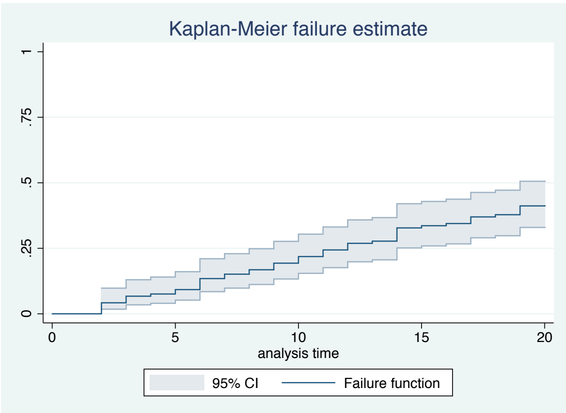


Fig. 2.3 Kaplan - Meier Failure Estimate

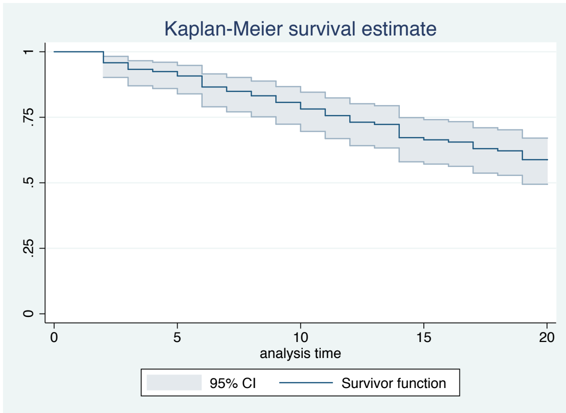


Fig. 2.4 Kaplan - Meier Survival Estimate

Non-Parametric Analysis Figures 2.3 and 2.4 illustrate Kaplan-Meier failure and survival estimates. The Kaplan-Meier failure plot illustrates the probability of a subject failing at time t given that it has survived up to time t. The light shaded areas around the bold line represents the pointwise confidence bands of the Kaplan-Meier function, which is the solid coloured line of the failure and survival estimates respectively. In this case, the probability that a country starts using wind energy in year 10 (i.e. year 2000) is somewhere between 15-25%. Similarly, by looking at the survival estimate, it can be inferred that the probability of not adopting wind by year 10 is somewhere between 75-85%.

However, this analysis implicitly assumes that time is the sole determinant of adoption, an assumption that clearly paints a distorted picture of reality. Time in itself does not determine anything; rather, as time passes other variables change, which in turn have a causal relationship with the probability of adopting of wind. To capture these factors, semi-parametric analysis is used, the results of which are presented in the following section.

Semi-Parametric Analysis After combining the variables and accounting for multicollinearity and various other specification tests[22], a total of 240 models was tested[23]. Of these, roughly 50% were successful, and the results of the significant variables are summarized in Table 2.4. The results reported illustrate the hazard ratios.

The hazard ratio of an independent variable can take values between 0 and $\inf$. The critical value is 1. If the hazard ratio is between 0 and 1, then a positive change in the value of that covariate can be interpreted as having a negative impact on the probability of failure. Conversely, a value greater than 1 indicates that the particular increase in the value of the covariate increases the probability of failure. To be more precise, the impact (as a %) of a one unit change in the covariate on the probability of failure is given by equation 2.4:

$$P(Failure) = 100 \times (HazardRatio - 1) \tag{2.4}$$

[22]These include tests for collinearity, tests for the proportionality assumption, martingale residuals analysis, as well as linktests for model specification

[23]All the results are illustrated in Appendix B.2

Table 2.4 Determinants of the Introduction Phase in the ILC Model

	Model 1	Model 2	Model 2 (standardised)	Model 3	Model 3 (standardised)	Model 4	Model 4 (standardised)	Model 5	Model 5 (standardised)	Model 6	Model 7
Primary and Secondary education total (years) (average)	0.7419	0.7601	0.8462	0.7529	0.8423	0.7859	0.8631	0.7568	0.845	0.7636	0.7678
	-0.2683	-0.2733	-0.1871	-0.2746	-0.189	-0.279	-0.1886	-0.2751	-0.1889	-0.2782	-0.2748
CO2 emissions (metric tons per capita)			1.1334**		1.1451**		1.1341**		1.1333**		
			-0.0594		-0.0604		-0.0593		-0.0607		
calculated electricity consumption (GWh) per capita	1							1	1.0403	1	1
	0							0	-0.0426	0	0
Energy use (kg of oil equivalent) per $1,000 GDP	0.9992**	0.9991**	0.8318**	0.9991**	0.8309**	0.9991**	0.8322**	0.9991**	0.8433**	0.9991**	0.9991**
	-0.0003	-0.0004	-0.062	-0.0004	-0.0615	-0.0004	-0.0614	-0.0004	-0.0591	-0.0004	-0.0004
world price of crude oil in Local currency	1	1	1.15E+82	1	4.74E+84	1	6.44E+78	1	1.68E+85	1	1
	0	0	(.)	0	(.)	0	(.)	0	(.)	0	0
polity2 score	0.9998	1.0005	1.0039	0.9999	1.0002	1.0005	1.0042	0.9997	0.9987	1.001	1.001
	-0.0041	-0.004	-0.0277	-0.004	-0.0274	-0.004	-0.0277	-0.0041	-0.0279	-0.0053	-0.0054
trade as a % of GDP	0.9987*	0.9989	0.943	0.9988	0.9421	0.9989	0.9439	0.9987*	0.9338*	0.9987*	0.9987*
	-0.0007	-0.0007	-0.0359	-0.0007	-0.0363	-0.0007	-0.036	-0.0007	-0.0358	-0.0007	-0.0007
EU membership dummy	0.9191	0.9006	0.899	0.9205	0.9187	0.8996	0.8981	0.8671	0.8693	0.8719	0.8849
	-0.0619	-0.06	-0.0595	-0.0632	-0.0626	-0.0604	-0.0599	-0.1057	-0.106	-0.1066	-0.1066
Dummy for the imposition of FITs	1.1464**	1.1465**	1.1444**	1.1523**	1.1504**	1.1439**	1.1419**	1.1523**	1.1503**	1.1512**	1.1462**
	-0.0692	-0.0658	-0.0653	-0.0692	-0.0686	-0.0657	-0.0651	-0.0695	-0.0691	-0.0693	-0.0701
Dummy for the existence of a Green Party	1.0799*	1.0977**	1.0955**	1.0912**	1.0894**	1.0994**	1.0972**	1.0879**	1.0855**	1.1076*	1.1126*
	-0.043	-0.0466	-0.0462	-0.0451	-0.0448	-0.0478	-0.0473	-0.0453	-0.0449	-0.0665	-0.0677
Dummy for the signature of the Kyoto Protocol	0.9964	1.0031	1.0045	0.9984	0.9999	1.0031	1.0045	0.9859	0.989	0.9875	0.9857
	-0.0435	-0.0427	-0.0427	-0.0434	-0.0434	-0.0428	-0.0427	-0.0462	-0.0461	-0.0465	-0.0462
weighted average the area of load hours per capita (average)		.	13107.12								
		(.)	-87851.9								
weighted average the area of load hours	1.0008**			1.0008**	1.7041**			1.0008**	1.6965**	1.0008**	1.0008***
	-0.0003			-0.0003	-0.361			-0.0003	-0.3611	-0.0003	-0.0003
Energy imports, net (% of energy use)	1.0007***	1.0006**	1.1272**	1.0007**	1.1480**	1.0006**	1.1239**	1.0007***	1.1649***	1.0007**	1.0007**
	-0.0003	-0.0002	-0.058	-0.0003	-0.0617	-0.0002	-0.0576	-0.0003	-0.065	-0.0003	-0.0003
weighted average the area of load hours per capita						3.02E+40	2.5124				
						-2.41E+42	-2.0367				
GDP per capita, PPP (constant 2005 international $)		1	0.984	1	0.9965	1	0.9837				
		0	-0.0438	0	-0.0451	0	-0.0436				
CO2 emissions (kg per 2005 PPP $ of GDP)	1.2951**	1.3080**		1.3375**		1.3095**		1.3086**		1.3192**	1.3010**
	-0.1467	-0.1468		-0.1511		-0.1464		-0.1503		-0.1575	-0.1555
Imports from Denmakr (c.i.f. in USD)	1.0000***	1.0000***	2.9884***	1.0000***	2.5885***	1.0000***	2.9651***	1.0000***	2.3695***	1.0000***	1.0000***
	0	0	-0.5322	0	-0.4593	0	-0.5236	0	-0.4213	0	0
Interaction variable between kyoto and EU								1.0871	1.0785	1.0782	1.0843
								-0.1466	-0.1449	-0.1465	-0.1446
Interaction between polity2 and Green Party Dummy										0.997	0.9973
										-0.0074	-0.0074
Sample Size	1263	1263	1263	1263	1263	1263	1263	1263	1263	1263	1263
Number of Countries	103	103	103	103	103	103	103	103	103	103	103
Number of Failures	40	40	40	40	40	40	40	40	40	40	40
Log Likelihood	-127.66	-130.137	-130.244	-128.065	-128.189	-130.419	-130.524	-127.448	-127.639	-127.364	-126.937
aic	283.3203	288.2741	288.4872	284.1308	284.3772	288.8371	289.0476	284.8964	285.2776	286.7282	286.7282

Dependent Variable: Whether the country has adopted wind
Hazard Ratios reported, with s.errors under the coefficients
* denotes 10% level of significance, ** denotes 5% level of significance, *** denotes 1% level of significance

Starting with country pollution levels, the results suggest that these are positively related to the hazard rate, i.e. the higher the level of pollution, the higher the probability of wind adoption. There are several explanations for this result, but the most probable is that the higher the CO_2 per GPD, the less clean is the country's electricity production, and the greater the pressure from agents on the country to clean its production.

The impact of the agents is captured in the model and in particular by the statistically significant hazard rate of the green party dummy. The existence of a green party in the country increases the probability of adoption of wind by 15.68%. Nevertheless, EU membership or signing the Kyoto protocol have proven statistically insignificant for determining the probability of adoption.

An argument could be made that the change agent per se does not have an impact on the country's decision to adopt wind, unless the country is open and democratic. Therefore, we use the polity2 indicator. The indicator is used in the model in two ways: as a stand-alone indicator, and as an interaction with the dummy variable for green party. In the first case, the aim is to capture the effect of democratic openness on the probability of adoption; the indicator is statistically insignificant, implying that the probability of first adoption of wind does not depend on the level of democracy of the country. In the second formulation, the aim is to moderate the impact of green party; in other words, it was assumed that the impact of green party will vary with the country's freedom. The more open the country, the stronger the impact of green party on society and, thus, the higher the probability of adoption. However, this is not confirmed by the data, which might be explained by the phenomenon being observed. In other words, the model aims to examine the determinants of speed of first adoption rather than the determinants of full diffusion. So, although there may not be an open democratic environment, the mere existence of a green party might reflect some kind of environmental awareness in the country, which could be enough to incentivize the country to adopt at least one wind turbine. To allow for wind technology to spread throughout the country, however, the strength of the change agent (in this case a green party) must be significant and the interaction variable might become statistically significant.

Another important determinant identified in the literature is market size; the larger the market size, the larger the potential for the supplier of the innovation to make a profit and, thus, the more effort the supplier will expend on promoting the technology in the market. In this case, we assume the market is the electricity market, and we proxy this by the amount of electricity consumed per capita. Although we could have used the absolute size of the market, we assumed that the important factor for first diffusion will be the energy richness per citizen rather than the actual size of the market. For example, Russia consumes almost 25 times the electricity consumed in Denmark, and we could expect the supplier of the technology to see that the profit potential in Russia will be 25 times greater than for Denmark. However, if we compare electricity consumption per capita, we see that the two countries are almost identical, which is a more realistic depiction. Consequently, our model confirms that the higher the amount of electricity per capita, the greater the probability of adopting wind.

In relation to profitability, the diffusion literature suggests that the profitability of the buyer of the innovation is equal in importance to the profitability of the supplier of the innovation. In this case, the profitability is captured by three factors: the price of the wind turbine, the level of FITs, and the price of crude oil. The prices of the wind turbine and crude oil are not statistically significant, but the FIT level is. The first finding is perhaps surprising, but may be explained by the quality of the data. The only available data are for Danish wind turbines from 1989 to 2001. We converted these figures into local currencies and assumed that these are the prices each country faces when deciding whether or not to purchase a turbine.

In relation to FITs, wind technologies are significantly more expensive than conventional fossil fuel technologies. Therefore, the adoption and diffusion of wind technologies will require government policy. Although there are various ways that government can intervene and promote wind energy, one of the most effective is based on the use of market instruments and, in particular, FIT. This general finding is confirmed by our analysis, which argues that implementation of FIT in the country increases the probability of adoption of wind by 17%.

Continuing the investigation into the profitability aspects of adoption, the gap between wind and conventional fossil fuel technologies decreases over time, mainly because the wind technology improves, but also because the price of fossil fuel increases. To capture the dynamics of this changing gap, we use the price of wind turbines as previously mentioned[24]. To capture the effect of changing fossil fuel prices, we use the price of crude oil, since the prices of gas and coal are more difficult to capture. Our findings show that the price of oil seems insignificant, which is quite surprising since electricity from oil is a very close substitute to wind. Two potential explanations can be provided. Firstly, electricity from oil might not be as close substitute to wind as it is to coal and gas. Sec-

[24]Ideally, we need also to capture the efficiency of turbines; however, no reliable data are available

ondly, this surprising finding might be related with the fact that the world price was used in local currencies rather than the local price converted into US dollars. We decided to include the world price, since this does not include local taxes which in many cases are a significant part of the final price. At the same time, if we included the world price in US dollars, then there would be no variation across countries, and thus no significant cross-country effect could be identified.

To capture the observability criterion, we tried three different indicators. One was distance from Denmark, arguably the pioneer in wind energy; we expect that the closer the country to the innovator, the higher the probability that it will adopt wind. However, physical distance is not enough; for example, the country might be an immediate neighbour, but they may have not trading relationships. Thus, we also tested the level of trade with Denmark. Neither of these indicators was statistically significant on their own, so we also tested the interaction of the two terms. Distance was moderated by trade intensity, and the results suggest that for two countries at the same distance from Denmark, the one with a higher level of trade has a higher probability of adoption, which confirms Rogers' observability criterion.

A prominent issue in technology diffusion studies is the issue of technological lock-in. The stronger this lock-in, the harder it will be for the economy/sector to move to an alternative technological configuration. In the context of wind adoption, two types of lock-in can be identified, technological lock-in and market lock-in. Technological lock-in refers to how much the economy's electricity sector is based on traditional fossil fuel technologies. This is captured by the indicator of energy use as a percentage of GDP. The more energy inefficient the country, the more we assume it is based on old technologies and the higher will be the resistance of incumbent energy players to change. This negative relationship between energy intensity and probability of adoption is confirmed by our model. Consequently, we reject the alternative hypothesis that high energy intensity might create some pressures to the country to adopt new technologies. This could be understood to imply that technological lock in has a stronger impact on diffusion. However, these results using this indicator should be treated with caution, since there is a very the low correlation between technical efficiency of power generation and energy intensity of GDP.

The other element of resistance to change is market lock-in. An economy or sector is locked-in to a particular technology if it is making an accounting profit by continuing to use that technology. In the case of the energy sector, an economy might find it profitable to use conventional fossil fuel technologies and these may account for a significant amount of its GDP, thus, preventing a shift to alternative renewable technologies such as wind. Nevertheless, energy markets suffer from externalities, and many of the costs of fossil fuel technologies are not captured by the market price.

This phenomenon of market lock-in is captured explicitly by the indicator natural resource rents as a percentage of GDP, which is the sum of oil, natural gas, coal (hard and soft), mineral and forest rents. Ideally, we would like an indicator that focuses solely on oil, natural gas and coal rents, but we expect that a country with good reserves of oil, gas and coal is likely also to have mineral and forest reserves so this indicator should capture similar effects. The coefficient of this indicator is statistically significant and its impact is as expected, i.e. the stronger the country's market lock-in, the lower the probability of wind adoption.

Another issue that is peculiar to the energy sector is energy dependence. Most countries do not have sufficient fossil fuel reserves to cover their energy needs, so their energy supply depends on imports from other countries. This poses considerable risks, which have been widely investigated by a range of social science disciplines from geopolitics and international relations, to energy economics and political economy. Moreover, the importance of this factor is also evident in the extent to which this subject has dominated the agendas of almost all developed energy-importing countries, particularly those in the EU.

One way that a country can decrease its energy dependency is by decreasing its energy needs and/or increasing its domestic energy production. Renewable energy, and wind in particular, contributes to increased domestic production, assuming that the country has adequate wind resources. This argument is supported by the model which finds a positive relationship between energy imports as a percentage of total energy, and the probability of adoption.

Another determinant of diffusion in innovation studies is the economy's absorptive capacity. There is a large and diverse literature on how to measure this, but there are two commonly used indicators which are per capita GDP, and years of schooling. In our case, neither of these was found to be significant, which may be a particularity if the process examined is first adoption rather than full diffusion. Years of schooling were not found significant in this case, and this might have to do with the nature of the indicator, which is more a general proxy for absorptive capacity. Ideally, we would like to use an indicator which would capture wind specific technological capability, but finding such data for this large sample of countries was virtually impossible[25].

Lastly, the amount of wind resources in the country exerts a small, but positive influence on the probability of adoption. This indicator classifies a country's land area into 10 different groups according to full load wind hours. In other words, it measures how many hours a wind turbine could work at full capacity. Clearly, the larger the amount of land in the higher full load wind hour group, the higher the amount of wind. The results suggest that the higher the amount of land area the higher the probability of adoption. This result was expected since the more of the resource available in the country, the more attractive will be the technology based on the assumption that it will be more profitable.

Overall, there seems to be a wide arrange of factors that influence the probability of first adoption. However, this does not necessarily imply that all of these variables have economic relevance. To identify this, we need to look at the magnitude of the effect of each of these variables on the probability of adoption. This is done by looking at the values of the coefficients of the models in which the data are standardized; this allows direct comparison of the variables without having to worry about the units of measurement, and direct comparison of their impact on the hazard ratios. Table 2.5 summarizes the average effect of each variable on the probability of adoption.

Table 2.5 Summary results of the impact of each variable on the probability of adoption

Variable of Interest	Impact on Hazard Rate
CO2 emissions (metric tons per capita)	14%
Energy use (kg of oil equivalent) per $1,000 GDP	-17%
Dummy for the imposition of FITs	15%
Dummy for the existence of a Green Party	9%
weighted average the area of load hours	70%
Energy imports, net (% of energy use)	14%
Imports from Denmark (c.i.f. in USD)	173%

Among the variables found to be significant, imports from Denmark seems to have the largest impact on the probability of adoption, which illustrates the importance of the observability criterion. The second variable with the most important impact was the availability of the resource, which served as a proxy for the innovation's profitability

[25] An alternative indicator was Gross domestic expenditure on R&D (GERD), but it was not available for a significant amount of countries and a long enough time period. Moreover, this indicator does not differentiate between sectors, which reduces its empirical relevance for this work.

and compatibility. Both these variables exert a positive impact on the hazard rate, which means that higher values increase the probability of adoption of wind. Surprisingly, regulation and energy dependency seem to have a very small positive impact on adoption. A final conclusion from these findings on the introductory phase of ILC is that if a country has very close relations with Denmark and ample wind resources, it is highly likely to adopt wind. Thus, in the introductory phase, compatibility, profitability and observability are key factors, with all others secondary. These findings illustrate that first adoption is much more a sociological phenomenon rather that an economic one.

Determinants of Diffusion in the Growth stage of the Industry (GMM)

Table 2.6 presents the results for the different models used to model diffusion of wind energy in the growth stage. Table 2.6 presents only the variables that were found significant, although it should be noted that all the variables specified by the vector of covariates were tested[26].

The first column shows the base model that uses the GMM Arellano-Bond estimation, the second column (model 2) is the same model assuming that crude oil spot prices are a not strictly exogenous, but are predetermined variables[27]. This assumption is made on the basis that higher demand for wind in the future might decrease demand for oil, which might cause a decrease in the future price of oil, albeit small given the relative shares in electricity production. The third column summarizes the results of a fixed effects model specification.

[26]The various tests and results can be found in Appendix B.3

[27]A predetermined variable in this context is a variable which is not correlated with the error component in the past and present, but might be correlated with it in the future

Table 2.6 Results from Dynamic Panel

Dependent Variables	Dynamic Panel (Base model)	Dynamic Panel (Model 2)	Fixed Effects
% of total electricity production generated from wind			
L_1	.78747***	.79665***	
L_2.	.23183**	.23389**	
whether the country has a FIT	.002436***	.002349***	-0.000328
GDP/capita in 2005 PPP (log)	-0.008035	-0.008634	-0.016546
L_1	-0.00333	-0.001966	-0.005528
L_2	.007647**	.007428**	.015084**
Crude Oil Spot Prices (USD/bbl)	0.00002	0.000017	0.000017
L_1	.000031**	.000024*	.000309***
Primary and Secondary education total (years)	0.000301	0.000338	0.000998
L_1	.00064**	.000703**	0.001805
Total natural resources rents (% of GDP)	-0.000078	-0.000105	-.000503**
EU Membership	-0.00082	-0.000998	-.005521**
Existence of Green Party	-.00259**	-.002737**	-.006693**
Kyoto Protocol	0.001811	0.001433	.002868*
L_1	-0.000359	-0.000351	.002429***
L_2	.001025**	.000713*	0.001886
Constant			0.034122
F-test/Wald	18784.55	16525.13	1.8
Sargan test	n/a	n/a	
Arellano–Bond test AR(1)	-1.4997	-1.4993	
Arellano–Bond test AR(2)	-0.80714	-0.81663	
Observations	1014	1014	1077

Dependent Variable: % of total electricity production generated from wind
***,**,* imply statistical significance at the 1%, 5% and 10% level, respectively.
L_N is the lag of a variable in period N

The dynamic panel models suggest that both the first and the second lag[28] of our dependent variable are both significant and positive in our model suggesting that the use of a fixed effects (FE) model would not have been appropriate for this analysis, which is confirmed also by the FE low Wald statistic (1.80). This implies that the null hypothesis that this econometric model does not explain any of the variation in the diffusion of wind cannot be rejected at the 5% level of significance. Therefore, a FE specification does not produce statistically robust results in this situation. Also, at a conceptual level, the fact that we need to include lags of the dependent variable to capture the element of path dependence, and fixed models do not allow for such modelling, is another reason why FE are not suitable in this context.

Both the dynamic models have a very high value for the F-test, suggesting that the null hypothesis that these two models cannot explain the diffusion of wind can be rejected at the 5% level of significance. Moreover, both these models successfully pass the Arellano-Bond test for serial correlation in the first-differenced errors at order 1 and 2, which is necessary to ensure the consistency of the Arellano-Bond GMM estimator. The Sargan test for over-identifying restrictions[29] could not be performed since robust standard errors were used to account for heteroscedasticity, therefore, we cannot formally test for the validity of our instruments. Inability to formally test the validity of the instruments when accounting for heteroscedasticity is common in SYS GMM. A convention in the literature is to perform the Sargan test on the model without robust standard errors and draw conclusions about the validity of the instruments. We complied with this convention and our results illustrate that there is not enough evidence to invalidate our instruments.

In relation to the other two models, note first that crude oil is predetermined in model 2 and has virtually no impact on the significance of any of the coefficients; the only difference is in the value of some of the coefficients, but it is very small (8% on average). Therefore, the rest of the discussion focuses on the results for our base model.

The positive and significant coefficient of both the first and second lags of the dependent variable[30] could potentially be an indication of path dependence. To be precise,

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[28]The first lag means the value of Y_t in period Y_{t-1}, while the second lag means the value of Y_t in period Y_{t-2}, where t is measured in years.

[29]This tests whether the instruments that are included in the model are necessary. In general, it is preferable to include in the model a greater number of instruments than is strictly needed, as this contributes to improving the precision of the model's estimates.

[30]Lags of higher order were also tested but were found to be insignificant.

when talking about "technological" path dependence, we need to refer to exactly the same technology, which is not realistic since the wind turbine technology is subject to continuous technological upgrading. To test this hypothesis, it would be necessary to have data on the models of each of the turbines, which is not feasible given the scope of our work. However, if we look at path dependency from the broader perspective of wind energy systems, and focus on the output, which is electricity, then we could argue that the significance of the lags demonstrates path dependence.

Path dependence in this context implies that the amount of wind electricity produced in year t will have a positive impact on the amount of new wind electricity that will be generated in year t+1 and year t+2, although the effect in the second year will be less than in t+1. One potential interpretation of this finding is the reduction in uncertainty surrounding new wind systems which develops when a country increases its electricity from wind. This increases investors' propensity to invest in new turbines and, thus, increases the electricity generated from wind.

The second finding from our model suggests that government intervention is positive and significant for the diffusion of wind energy, a finding that confirms the wider literature on the importance of market-based government intervention for the diffusion of wind power. In this context, the influence of policy is captured by the positive and strongly significant coefficient of the FIT dummy, suggesting that the introduction of a tariff tends to increase the amount of electricity generated by wind by 0.002%. In absolute terms, the impact of policy seems insignificant. However, if we look at the summary statistics of this variable in our sample (Table 2.3), we see that the average proportion of total electricity production produced from wind is 0.0053%. Thus, when look into this relative context the actual impact of policy is quite substantial. Nonetheless, using a dummy variable to measure the impact of policy undermines the complexity of this mechanism, which might explain the low value of the coefficient. To capture the effects of policy more accurately, the indicator should reflect both the level of the tariff and various other details, such as the length of the contract, the pricing structure, etc.

Thirdly, the coefficient of the log of GDP per capita is positive and significant suggesting that a 1% change in GDP per capita leads to a 0.008% increase in the amount of electricity produced by wind. This suggests that the level of per capita GDP has a positive impact of the diffusion on wind, but only after two years. This is likely due to the time lag between the decision to build the turbine and its actual operation. In order to build a turbine, the wind investor/ contractor goes through a lengthy process that varies across states and time, and with the state of the grid, as well as the size of the turbine, and the given technological state of the turbines. For example, Greece has a much more bureaucratic system and, thus, lengthier time span for project completion, compared to Denmark. Moreover, the larger the grid's spare capacity, the easier the turbine's integration into the grid and, thus, the shorter the time span for project approval. Similarly, the larger the turbine, the greater the impact on the community and the network and, thus, the lengthier the time lag between initial investment and implementation of the project. It is normal to expect the positive relationship between the economic growth and diffusion of wind not to be immediate, but subject to a time lag, which in this case is two years.

The third factor that our model proves as positive and significant is the price of crude oil. Oil and wind energy are close substitutes in the sense that they both compete for electricity generation. Therefore, their cross-price elasticity is positive, suggesting that as the price of crude oil increases, the amount of electricity generated by wind is expected also to increase. Again, the relationship is not direct in terms of time but rather is subject to a one-year time lag, for reasons similar to those described above for the GDP relation. Nonetheless, the magnitude of the coefficient is very small suggesting that the degree of competition between wind and oil is not strong. A more appropriate indicator might be gas and nuclear power which are more direct competitors in the electricity generation process. However, the data are not widely available.

Another indicator that is shown to be positive and statistically significant for explaining diffusion is total years of primary and secondary education. The rationale for using this indicator is that it captures some of the national absorptive capability and, although not a complete measure of capability, was widely available for the countries in our dataset. The fact that it is positive suggests that the higher the country's absorptive capability, the higher will be the level of innovation diffusion. The fact that only the first lag of this indicator was significant sheds some doubt on the validity of this indicator for explaining wind diffusion. This indicator probably captures to a greater extent the country's general absorptive capacity rather than its technological capability.

The Kyoto Protocol and EU membership are both considered to be enforcing mechanisms and are perceived as change agents, which is the reason for their inclusion in the model. However, only the signing of the Kyoto Protocol is significant and positive, while the EU dummy and their interaction term is insignificant. In particular, the second lag of the Kyoto Protocol is statistically significant suggesting that its effect on diffusion takes two years to be felt by the economy. Signing the Protocol does not necessarily imply that it is instantly ratified by the particular country governments; moreover, there is a further lag between ratification of the protocol and development of a framework that would allow for the diffusion of wind energy. We used a dummy to capture the ratification date; it is insignificant, indicating that what matters more for diffusion is the country's commitment to international institutions rather than domestic pressure groups, a finding which points to the field of International Relations, and the work on international regimes. International regimes theories suggest that international institutions have an impact on domestic policy[31]. This finding is particularly interesting as it illustrates the complexity of the diffusion process and the fact that it is influenced by developments in a number of different levels, from the adopter to the global level.

This weakness of domestic institutions for promoting diffusion is captured also by the results for the green party indicator. The existence of a green party can be seen as a proxy for environmental awareness, and as a domestic change agent, since its role in general is to promote sustainable growth and development in an environmentally consistent way. The coefficient is significant and negative, which contrasts with our expectations since the presence of a green party is supposed to stimulate the diffusion of renewable technologies, rather than the reverse. However, the results suggest that countries with a green party, i.e. a domestic change agent, on average have 0.003% less wind generated electricity. In absolute terms the effect might seem trivial, but once we consider the average value of wind electricity (0.005%), the effect of green party becomes both statistically and economically significant.

There are various reasons that might potentially explain this result. First, green parties do not necessarily promote wind technologies. For example, there are various pressure groups that try to prevent the spread of onshore wind, because of the aesthetics and/or the ecosystem surrounding turbines. Thus, the green party although supporting renewable energy and sustainable developments in general, might not support wind technologies and promote alternative sources of renewable energy. Second, from a more technical perspective, the green party indicator might suffer from endogeneity problems; the existence of a green party might influence diffusion of wind, but diffusion of wind might influence the foundation of a green party, by providing grounding for a new constituency. Third, there are problems with the quality of the indicator; there is no unique and reliable database that includes all green parties and their respective foundation dates. The ideal indicator also should include some proxy for party power, such as number of seats or the party's voting rights in parliament. It was not possible to gather detailed

[31] See for example the work by Ruggie (1982), Keohane (1982), and Haggard and Simmons (1987)

information at this level for such a large sample. Moreover, the data covers long periods in which green parties were more focused on nuclear rather than RETs, as they were not so developed. To capture some of these effects an interaction term between polity2 and green party was used under the assumption that the more open and democratic the political system the greater the power of the green party. However, this variable was insignificant.

2.4.2 PLC and Diffusion

Table 2.7 summarizes the results of the survival model used to analyse the determinants of diffusion in the introduction and growth phases, based on the PLC model. The aim is to understand whether the determinants of diffusion vary as the technology matures. To achieve this, we look how the determinants of first adoption vary across time. Instead of looking time as a continuum, we decided to separate it into two periods, according to the PLC theories. The first period is that of the introduction of the technology, and the second period is that of technology growth.

The distinction between the two periods is the establishment of the dominant design. As previously discussed, there is no agreement on the exact year when the dominant design for wind emerged. The literature suggests that it was towards the end of 1990s. For completeness, in this work, we look at the factors that influence adoption under five different time-based scenarios of dominant design emergence and, thus, have five empirical models. The dependent variable is first adoption, i.e. whether the country adopted wind before period t.

A closer examination of the results suggests that there is a consistency in the factors that determine adoption in the introduction phase. In more detail, FIT and the income group to which the country belongs (the richer the country the higher the probability of adoption of wind)[32] have a consistent positive and significant impact on the probability of adoption. In addition, the country's wind resources have a positive impact on the probability of first adoption - the hazard ratio is higher than 1. Lastly, polity2, EU membership and the green party tend to have a positive impact on wind adoption although this result is not consistent across all five models.

The results are more puzzling for the growth phase models. The only result that is con-

[32] Note that the Income Group Variable takes values from 1 to 5, where 1 is the highest income group and 5 the lowest

Table 2.7 Determinants of First Adoption and Diffusion across the PLC

Variables	Dominant Design (1996)		Dominant Design (1997)		Dominant Design (1998)		Dominant Design (1999)		Dominant Design (2000)	
	Introduction	Growth	Introduction	Growth	Introduction	Growth	Introduction	Growth	Introduction	Growth
whether the country has a FIT	1.953***	1.243**	2.073***	1.283*	1.840***	1.289*	1.874***	1.303**	1.711***	1.425**
Existence of Green Party	1.212	1.044	1.134	1.048	0.002	0.956	1.194**	1.183*	1.128	1.179
Income Group	0.294**	0.989	0.280***	1.006	0.373***	0.658	0.463***		0.632*	0.255***
EU Membership	1.418	0.701**	1.493*	0.671**	1.461	0.78	1.487*	0.929	1.47	1.022
Polity2	1.052	0.999	1.029*	1	1.011	0.994	1.009	0.989	1	0.978
Market size	1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.000*
Wind Resources	1.001**	1.001	1.001***	1	1.001***		1.001***		1.001**	
Kyoto Protocol		1.016		1.033		1.292**		1.287***		1.376***
Crude Oil Spot Prices (USD/bbl)		1		1		1	1	1		1
Natural Resource Rents as a % of GDP		0.982		0.976		0.972		0.993		0.99
Distance from Denmark		1		1						
Imports from Denmark		1.002***		1.002***		1.001**			1.000**	
Interaction (Distance-Denmark Imports)		1		1						1
Energy imports, net (% of energy use)		1		1		1				
CO2 emissions (kg per 2005 PPP $ of GDP)		1.157		1.253			1.061		0.952	
Energy use (kg of oil equivalent) per $1,000 GDP		1		1						
Fossil fuel energy consumption (% of total)		1.010**		1.010*		1.009*	0.999		1.002	
Average Years of Schooling						0.424*		0.474		0.213**
Number of Subjects	109	87	107	85	103	85	104	79	103	71
Number of Failures	16	24	17	23	19	22	22	23	25	20
Total Observations	596	776	645	693	690	681	767	566	856	473
Time (origin)	1990	1997	1990	1998	1990	1999	1990	2000	1990	2001
Time (end)	1996	2010	1997	2010	1998	2010	1999	2010	2000	2010

***,**,* imply statistical significance at the 1%, 5% and 10% level, respectively.
Dependent Variable: Whether the country generates electricity from wind.

sistently positive and significant is the FIT dummy. The significance of all other factors tends to vary across the models. The most consistent factors are the Kyoto Protocol and imports from Denmark dummies, and the proxy for carbon lock-in; all have a positive impact on the hazard ratio in three of the five specifications. The findings for years of schooling, EU membership, and income group are less robust and are significant in only two and one of the models respectively.

The lack of consistency in the findings for the growth stage may illustrate the weakness of econometric methods to identify the determinants of diffusion in this phase. The reason might lie within the complexity involved in the growth stage, which involves more agents and, thus, more complicated dynamics, something that cannot be efficiently captured by purely quantitative methods.

2.4.3 Comparing PLC and ILC findings for Diffusion Determinants

Tables 2.8 and 2.9 summarize the findings for the determinants of diffusion across the PLC and the ILC respectively. The PLC model is used in order to identify how the determinants of diffusion vary as the technology progresses along its life-cycle, while the ILC model is in essence trying to capture how do the drivers of diffusion vary as the industry evolves. In this way, we manage to identify what are the different incentives for first adoption and diffusion across the different stages of the PLC and ILC frameworks.

Table 2.8 Results from PLC Modeling

PLC Model	
Introduction Stage	**Growth Stage**
Government Support	Government Support
Size of the market	
Change Agent	
Availability of the resource	
	Observability
	Carbon Lock-in
Political Regime	

Table 2.9 Results from ILC Modeling

ILC Model	
Introduction stage	**Growth Stage**
Government Support	Government Support
Size of the market	Size of the market
Change Agent	Change Agent
Availability of the resource	
Observability	Observability/Learning
Carbon Lock-in	
	Capability
	Price of competing products
Market lock-in	
Country Pollution levels	
Energy Dependence	

The evidence provides some support for our initial hypothesis that the determinants of diffusion vary across the life-cycle, and holds for both the ILC and the PLC models. There are some factors that are common to both the introduction and growth phases, but there are also some determinants of diffusion that are unique to its life-cycle stage.

Closer examination of the empirical evidence shows that the only determinant that remains significant across both models and stages is government support. This, to an extent, was expected since the significance of policy for renewable energy adoption has been well documented. However, the analysis in this chapter shows that its importance for diffusion decreases across time; the results for the PLC show a decreasing hazard ratio as we move from the introduction to the growth phase[33].

Another observation based on the above tables is that there is an apparent similarity among the determinants of the introduction phase, in both models. The existence of government support, market size, availability of resources, and a strong change agent are necessary for the introduction of the new technology and, also, for the emergence of the wind industry. This would suggest that policy, on its own, is not enough for the introduction of wind; rather, it must be complemented by the existence of a large potential market, and adequate resource availability. This rationale largely confirms the neoclassical approach to first adoption and diffusion, which emphasizes the importance of profitability for both the adopter and the supplier of the innovation. Therefore, it could be argued that, in the introduction phase, what is necessary is a clear set of economic incentives to persuade investors to adopt the new technology.

The change agent seems to be significant in both models in the introduction phase. The impact of the change agent is overlooked by the neoclassical approach, and this result illustrates the complementarity of Rogers' framework which highlights the impact of the change agent. However, the impact of the change agent is not consistently significant, a finding that points perhaps to the difficulties of quantifying this phenomenon. In addition, the change agent sometimes is a promoter of wind energy, and sometimes constitutes a barrier. This counterintuitive role of a barrier is illustrated in the ILC model in the growth phase, where a green party seems to have a negative impact on growth of wind energy. This might be specific to wind energy, but not all RETs, since the wind industry suffers from a strong NIMBY effect.

[33] A similar conclusion might apply to the ILC model since the econometric results for the two models are not directly comparable.

In contrast to our expectations, we found no consistent evidence across the four models of the importance of relative advantage, which is captured by the price competitiveness of the innovation. In particular, we found that the oil price seems to be a determinant of diffusion only in the industry's growth phase. This implies that price competitiveness matters only when the diffusion is taking place, at a later stage in the life-cycle. This is additional evidence that the emphasis on profitability in neoclassical economics works is excessive.

When comparing the determinants of diffusion in the introduction phase of both the PLC and the ILC, some interesting finding can be identified. The emergence of an industry seems to be influenced by economic factors and the change agent and, also, institutional factors such as the extent of carbon lock-in and the country's energy dependence, albeit the significance of the later can be questioned. However, with the exception of some weak evidence related to the importance of the political regime, institutional factors seem not to be significant for the first adoption of wind technology when the product is still in its infancy. Rather in the PLC model, the economic incentives are the key determinants. This observation might be related to the higher levels of complexity surrounding the development of an industry, compared to the introduction of a product innovation.

Lastly, a comparison of the determinants in the growth stages of the models is not ideal, since there seems to be a lack of clarity and consistency in the PLC model results, stemming potentially from the decreased sample size. However, what we can observe is that government support remains significant even in the growth stage of the product and the industry.

2.5 Conclusions

This chapter aimed to provide a better understanding of the wind diffusion process. To achieve this, we used two distinct theories and also the support of two theoretical frameworks. Our results illustrated that no theory or framework can by itself explain the diffusion process. Rather we need multiple theories that would provide complementary and congruent explanations of how the diffusion process takes place. Our hypothesis, which was confirmed, was that the determinants of diffusion are not constant but change as the technology improves.

If we focus on the chapter in more details, in terms of the literature, we drew on the DOI and the neoclassical approach to diffusion. The neoclassical model was applied because this literature has dominated policy makers' and regulators' attempts to increase acceptance of RETs. This approach stresses the importance of profitability and focuses on the double externality problem, which has led to a focus on regulation as key to diffusion. However, the excessive focus in this literature on regulation has been at the expense of examination of other characteristics of RETs which might influence its diffusion, such as change agents (political pressures and lobbying). To deal with this, we decided to use the DOI theory, which is the most frequent framework in diffusion studies. Its main advantages is that it provides us a way to incorporate into the analysis some of the particularities of RETs, such as the complicated infrastructures. Therefore,we argued that these two theories are a good complement to each other. Combining these two theories constitutes one of the contributions of this chapter to the literature on diffusion.

However, they both adopt a very static view on diffusion, and ignore the fact that the determinants of diffusion might vary over time, as the technology and the industry evolve. To account for this issue, we decided to examine how the determinants suggested by these theories can vary across time. To provide a theoretical basis to the different points in time, we decided to use life-cycle models, in particular the PLC and the ILC. These frameworks suggest different phases in the evolution of a product and industry, but generally argue that the diffusion of a product and the evolution of an industry follows a bell-shaped distribution when plotted against time. The idea is that initially the number of users and adopters of the product is small, but then the market starts expanding at at an increasing rate, until it stabilises and then declines.

Life-cycle models suffer from various methodological problems, one of which is related to the criteria that define the beginning and end of each stage, which is the one we address in this work. We proposed a conceptual methodological approach to identify the start of the first two stages, and some econometric methods that can be used to pinpoint the determinants in each stage. The econometric techniques combined with the large N dataset only allowed us to study neoclassical and DOI diffusion theories.

The findings in this chapter partly confirm our hypothesis that the determinants of diffusion vary across the PLC and ILC models. The evidence shows some similarities and some differences among the determinants of diffusion across stages. The econometric results show the importance of policy, which is widely supported by work on the diffusion of RETs. However, this chapter also shows the decreasing importance of policy across time, and that policy is not the sole determinant of diffusion of wind. Rather, for the industry to enter the introduction stage, the amount of wind resources (supply potential), the strength of the change agent (linking potential supply and demand), and the size of the market (potential demand), are all important variables. Lastly, our research shows that there is a time-lag between diffusion in the growth stage and the various determinants of wider diffusion. In particular, we found that a country's economic development becomes important for diffusion only after two years, while the price of substitutes (e.g. oil) has an influence on the diffusion of wind only after one year. Our findings with respect to time lags are probably indicative of the particularity of RETs with respect to time, and that their development takes a significant length of time.

Our results also illustrate some of the weakness of purely econometric methods for dealing with complicated phenomena involving multiple stakeholders, particularly in relation to diffusion in the growth stage. Therefore, one of the next steps will be to compare the findings in this chapter with the findings from a more holistic theoretical framework, such as the technology systems approach. Also, we could apply a more qualitative methodology or a mix of qualitative and quantitative techniques such as proposed by Qualitative Comparative Analysis (QCA). This would involve a smaller sample size (fewer countries), but would allow a deeper analysis. Both of these steps are taken in the next chapter.

Chapter 3

Investigating the Technology Innovation System

3.1 Introduction

A technological innovation has value only if it used by the users, in other words, if it diffuses in the system. The fields of renewable energy in general, and solar PV in particular, have been dominated by debate on new materials, new techniques and generally continuous innovations, focused primarily on increasing capacity (i.e. the efficiency of the renewable systems) and enabling storage solutions. At the same time, the innovation literature has been focused on how these improvements come about, which indisputably is fundamental to a transition to a more sustainable future. However, equally important is how users come to adopt these technologies, an element which was largely absent in early work (Grubb 1994). This realisation has brought about growth in the field of diffusion of renewable energy technologies, and with it a significant conceptual and empirical developments.

Early work viewed lack of diffusion of RETs as the result of market failure, a concept that became known as "the double externality problem". In particular, researchers argued in favour of government intervention and policy as a means of correcting the market's inability to to internalize the effects of positive knowledge externalities and negative environmental externalities (see e.g. the work by Jaffe & Stavins, 1994, and Jaffe et al., 2002). The positive externalities are the result of the spillover effects that an the environmental innovation can have on other firms and the rest of the economy, as the RET innovations can lead to further technological improvements and act as a foundation for the generation of new technologies. These spillovers might not be fully captured by the innovator, and thus he/she might under-produce it. The negative environmental externalities might lead to an over-production of non-RETs since the price does not reflect the negative environmental impact these might have on the environment.

As the double externality problem dominated the debate in the field of diffusion of RETs, early researchers concluded that policy is the fundamental determinant of the diffusion of renewables[1]. As a result of this key proposition, the focus of academic research and debate has revolved around what would be the most effective policy[2]. Some try to find the optimal policy mix, while others try to establish the different effectiveness for diffusion of market-based[3] versus quota-based[4] policies (Rader & Wiser, 1999; Helm 2002; Menanteau et al., 2003; Dinica, 2006; Mitchell et al., 2006; Butler & Neuhoff, 2008). In all of these literatures, it is clear that the choice of policy instrument is fundamental for the analysis; however there is no consensus on the optimal policy mix, since the same policy instrument can have different implications for diffusion in different environments.

In addition to work on the relationship between policy and diffusion of RETs, there has been some research on other elements of the process. For example, some studies try to understand how regulation influences the adoption decisions of the various entrepreneurs (Menanteau et al., 2003; Newell et al., 2004; Gillingham et al., 2009) or, more generally, the preferences of the various actors involved in the process (Masini and Menichetti 2010). Others look at how factor costs in energy generation explain diffusion (Fisher-Vanden et al., 2006) and price, and try to identify the appropriate levels for price regulation to achieve maximum diffusion rates (Neij 1997; Nakicenovic, 2002; Rehfeld et al., 2007). Yet others investigate the general institutional environment (Lovely and Popp 2008).

With the advent of evolutionary economics, a re-conceptualization of the process of innovation and diffusion took place, which emphasised its systemic nature. Consequently, instead of explaining the lack of diffusion as simply the failure of the market, these new theorists suggest that there are various other failures in the system that can prevent

[1] The importance of policy for diffusion of new technologies is not something new. Rather, this perspective has it roots in the pioneering work of Stoneman and Diederen (1994) who were the first to provide a systematic synthesis of and research the impact of policy on technology diffusion. Their paper draws heavily on the perspectives of neoclassical economists who view policy as a way to correct market failure.

[2] See e.g. Wüstenhagen and Bilharz (2006) and Gan et al. (2007)

[3] Examples of such instruments are Feed-in Tariffs, which included premium payments to producers of electricity for RETs.

[4] Examples of such instruments are the Renewable Obligations, which make it mandatory for electricity suppliers to buy a certain percentage of their supplies from renewable generators

the development and diffusion of an innovation. This literature came to be known as systems of innovations literature, as it emphasised the systemic and interrelated nature of the process. Within this literature, there are various categories of systems (national, sectoral, technology, etc.).

From all the aforementioned approaches to diffusion, we believe that the approach best suited to understanding the process of diffusion of RETs is that of systems, and in particular technology innovation systems (TIS). The systems approach is selected because the diffusion process is by-itself a complex phenomenon, which is something we illustrated in Chapter 2, while the energy sector is characterised by strong resistance to change[5] and of such crucial importance, which makes the study of diffusion even more complicated. Also, we select the TIS approach because we are interested in identifying how a technology (e.g. solar PV) rather than a particular product (e.g. monocrystalline PV panels) diffuses in the system.

To apply the TIS in RETs, we decided to focus only on solar and wind technologies, and to investigate it by applying Qualitative Comparative Analysis (QCA). To achieve this, we start by presenting the theoretical backbone of the systems perspective approach to the diffusion of innovation, and discuss the technology innovation system (TIS) approach in more details (Section 2). Section 3 presents the methodology and the data used. Section 4 presents the findings from the analysis of solar and wind and Section 5 concludes the chapter.

[5]See for example the literature on carbon lock-in (Unruh, 2000)

3.2 The Theoretical Perspective and Analytical Approach

3.2.1 The Technology Innovation System (TIS)

The TIS is best perceived as 'a social network which revolves around a particular technology" (Suurs & Hekkert, 2009, p.1003). Perhaps the most widely used definition of this concept is that proposed by Carlsson and Stankiewicz (1991, p. 94), who define TIS as "a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of technology" (p.94).

The literature recognizes that the system is comprised of three main structural components (actors, networks and institutions) which come together to complete the system's function. The outcome of their interaction brings about the development of the system and the diffusion of the technology. These structural components can be broken down into the three self-explanatory categories: the actors in the supply chain, the networks, and the institutions. These structural components represent the static aspect of a TIS; their evolution is gradual rather than radical and (clearly) visible from a historical (more than a year) perspective (Suurs et al., 2010, p.420).

In turn, the functions are "the intermediate variables between structure and system performance" (Jacobsson, & Bergek, 2011, p.46). In other words, a function[6] is the contribution made by a structural component or a set of structural components to the performance of a system. Performance is considered in terms of the rate of development, diffusion and implementation of a new technology (Negro et al., 2008, p.60). In turn, the success or failure of each function is analysed and assessed based on the performance of each of its structural components.

Figure 3.1 shows that various functions have been proposed in the literature. However, six major functions are widely applied in empirical research on the emergence of technology systems.

1. Knowledge Development and Diffusion (KD)

[6]The use of the word function has attracted a lot of attention. However, critiques are driven more by semantics than substance. A nice illustration of this is provided by Hekkert et al. (2007), who defend the use of this term as long as the emphasis is on its heuristic rather than its positivistic value. Thus, the functional approach can be used to identify, understand and compare the "crucial activities in technology specific innovation systems and it creates insight in the dynamics and possible patterns of technological change and related innovation processes" (Hekkert et al., 2007, p.429). To avoid unnecessary debate, we use the words activities and functions interchangeably in this thesis.

Hekkert et al. (2007)	Bergek et al. (2005)	Chaminade and Edquist (2005)
Entrepreneurial activities	Entrepreneurial experimentation	Creating and changing organizations
Knowledge development Knowledge diffusion	Knowledge development and diffusion	Provision of R&D Provision of education and training
Guidance of the search Market formation	Influence on the direction of search Market formation	Articulation of quality requirements from the demand side Formation of new product markets
Resources mobilization	Resource mobilization	Incubating activities Financing of innovation processes Provision of consultancy services
Creation of legitimacy	Legitimation Development of positive externalities	Creation/change of institutions Networking and interactive learning

Fig. 3.1 The main functions as summarised in the literature

Source: Markard & Truffer, 2008, p.603

This lies at the core of the technology system, and aims to capture the current knowledge base of the system, and how it evolves across time. The greater the depth of the knowledge base, the faster and more efficient its evolution. It should be noted that some researchers divide this function into two separate functions: knowledge development (learning) and knowledge diffusion [7].

2. Entrepreneurial Experimentation (EE)
   The second function relates to the actions of entrepreneurs, whose aim is to commercialize the various technologies. By creating market niches, and testing the market for the technologies, they decrease the uncertainty related to the knowledge base. This argument comes directly from the literature on the diffusion of innovations which stipulates that uncertainty can be a major obstacle to the potential adoption of a new technology. The fundamental way to reduce uncertainty is continuous experimentation, primarily by market participants, that is, the entrepreneurs.

3. Guidance of Search (GS)
   For entrepreneurial experimentation to take place, the agents need to perceive the various opportunities provided by the emergence of a new TIS .The traditional literature suggests that opportunities are reflected by the market (e.g. when incumbents make supernormal profits they attract new entrants); however, this is based on the assumption of perfect information. In reality, opportunities are rarely clear to every actor and some mechanisms are required to facilitate the dissemination of the relevant information.

[7]See, e.g. the literature on event history especially Negro et al., 2007.

4. Resource Mobilization (RM)
   Alongside the evolution of a new technological system, the allocation of resources also evolves. Although the allocation of resources changes, there are two resources that are worthy of closer attention: human capital and financial capital. Actors (e.g. universities) may fail to develop the appropriate skills and, thus, reduce the amount of human capital that is available; other actors (e.g. banks or government) might fail to provide adequate financial resources for the development of new projects. In the absence of sufficient resources, the TIS cannot emerge and none of the other functions can be performed.

5. Market Formation (MF)
   This function can be seen as key to the evolution of the system, since without a market component (buyers and sellers), no diffusion can take place. Within this function, the authors incorporate all the "market elements" of the technology, such as price-performance, number of buyers and sellers, intensity of competition, etc. TIS scholars, clearly influenced by the product- life-cycle (PLC) (Klepper, 1996) and diffusion of innovation literatures (Rogers, 2010), suggest that market formation can be seen as consisting of three phases: nursing, bridging, and mass market. This implies that the market phase might determine and explain the diffusion process. For example, whether it is a nursing market, a bridging market or a mass market will influence the evolution of the system. To understand this process, actual market development and its drivers need to be assessed.

6. Legitimation (LE)
   Change is always faced by resistance; the more radical the change, the greater will be the resistance from incumbents which find it more difficult to change routines. Therefore, a key function of a new TIS is legitimation, understood as "social acceptance and compliance with relevant institutions" (Bergek et al., 2008). This function is not important on its own, but rather acts as a reinforcing mechanism in combination with other functions and particularly resource mobilization and direction of search.

7. Other Functions
   Some other functions have been proposed in the literature, but have not been adopted on a large scale. These include development of positive externalities and

materialization. The idea of positive externalities is based on the principle of the spillover effects from a new technology when it penetrates the system. This reinforces the process of diffusion by strengthening some of the other functions in the system. For example, the entry of new users leads to a decrease in the level of uncertainty, which, in turn, reinforces the market formation and direction of research functions. Building on the economics of co-location literature, (Bergek et al., 2008, p.418) point out that the main impacts/areas where these externalities can be observed are the "resolution of uncertainties, political power, legitimacy, combinatorial opportunities, pooled labor markets, specialized intermediates, as well as information and knowledge flows". However, these positive externalities are outcomes of other functions such as direction of learning, market formation, and firm experimentation (Jacobsson & Bergek, 2011, p.52). The fact that these are outcomes and not standalone functions is the main reason that they are not used by most of the literature. The materialization function can be defined as the "the development of (and investment in) artefacts such as products, production plants and physical infrastructure" (Bergek et al., 2008). However, this function is mostly overlooked in the literature perhaps because of its potential overlap with other functions (e.g. investments can be seen as part of the resource mobilisation function) or lack of clarity in its definition.

An excellent illustration of how these functions interrelate within the system is given in Negro et al. (2008, pp.59-60). The authors argue that initially the system is dominated by actors (mainly merely scientists and engineers) whose role is to create new knowledge and further improve the existing technologies. As the technology improves, it attracts the attention of the entrepreneurs and government, which causes an initial reallocation of resources due primarily to government support. As the entrepreneurs start testing the technology and develop niche markets, a dominant design begins to emerge. In turn, the technology achieves wider acceptance and displaces the incumbents through a process of creative destruction, and the system reaches full maturity.

Figure 3.3 is a representation of the main idea of the functions of approach , Figure 3.5 depicts an example of its application to system emergence.

Applying TIS to analyse the generation and innovation of a technology provides a theoretical basis for defining the borders of the system being considered. Also, examining the evolution of the functions makes it possible to understand the complex way in which a certain institutional set up shapes the generation, diffusion and utilization of the new technology. (Jacobsson et al., 2004, p.7) Lastly, the functional approach allows us to

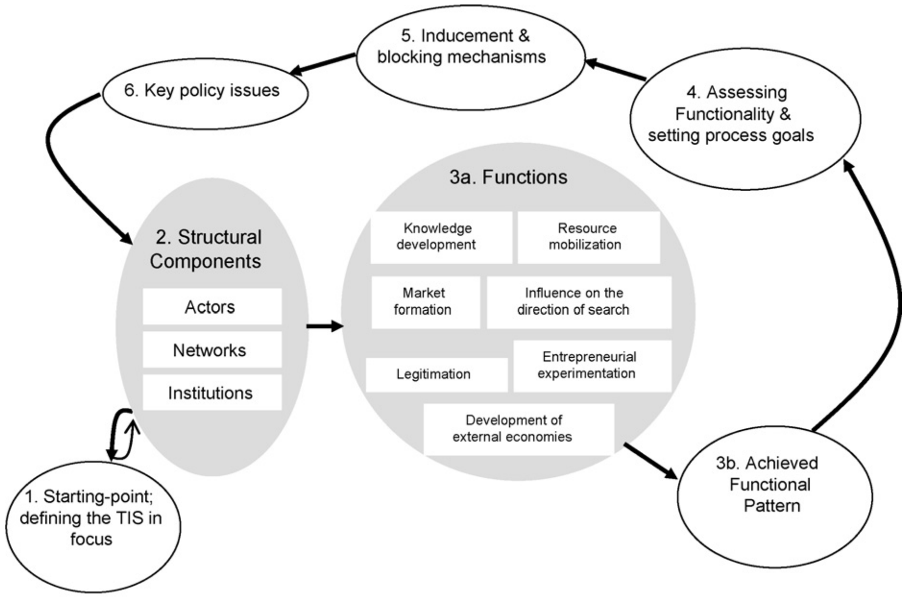


Fig. 3.3 Technology Systems Analytical Framework

Source: Bergek et al., 2008, p.421

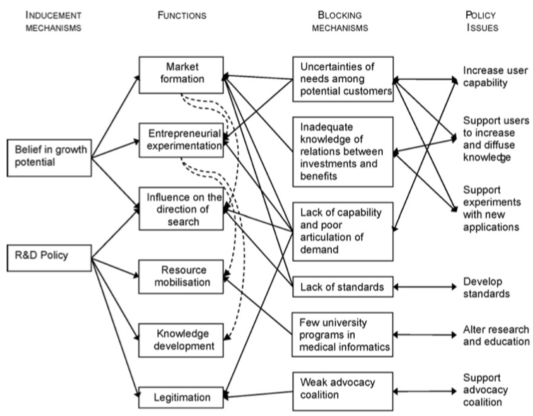


Fig. 3.5 An example of using the Technology Systems Analytical Framework

Source: Bergek et al., 2008, p.422

identify the inducing and blocking mechanisms in the development, diffusion and implementation of the technology, which, in essence, are the issues that government needs to address to facilitate its diffusion (Bergek, 2002).

Weaknesses with the technology systems literature

Like all theoretical frameworks, we can identify various shortcomings in the proposed framework. First the semantics; there is no agreement on either the names or the numbers of functions. Second, there is similarly no agreement on the importance of each function; for example, some argue that functions related to knowledge are the most important, while others argue for the primacy of entrepreneurs. Third, the TIS literature could be accused of mixing outcomes with processes; for example, entrepreneurship as an outcome of the system rather than a process within the system.

Further problems emerge from the empirical literature on TIS. Many indicators are used to measure the performance of different functions. The theoretical openness of each of the functions, and their different interpretations, has resulted in a range of indicators applied by various authors. After thorough investigation of the empirical literature and the indicators used, we found major overlaps among the indicators used to measure the various functions. The Venn diagram in Figure 3.7 provides visualization.

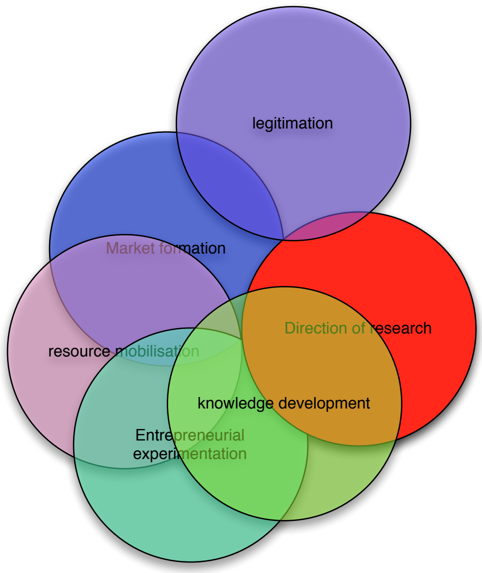


Fig. 3.7 Overlap of the indicators used to measure the TIS Functions

This diagram should be interpreted as follows. The circles represent a particular function and the indicators used to measure this function. An overlapping of the circles implies that different authors have used the same indicator to measure more than one function. In many instances, more than two functions overlap, which means that the same indicator has been used to assess the performance of more than two functions. Examples of such indicators can be seen in Table 3.1.

Table 3.1 Examples of Indicators that have been used to capture the effects of different function in the TIS

Indicator	KD	LE	EE	GS	RM	MF
Subsidies			x	x	x	x
Environmental Standards			x			x
Uncertainties of project developers			x			x
FDI	x				x	
Regulations by the government				x		x
Clarity of demand from leading users				x		x
Research outcomes	x			x		
Government funding for R&D				x	x	
Positive market regulations		x		x		x
Demonstration and pilot projects	x		x	x	x	
Number of new entrants			x			x

At a more theoretical level, some critics, especially adherents to other systems of innovation perspectives, are sceptical about the validity of TIS and argue that innovation is rooted in different systems (e.g. sectoral, regional, etc.). However, the latest work from Jacobsson and Bergek (2011) suggests implicitly that the TIS is a complementary rather than a competing framework, and illustrates that a joint analysis can be used to trace failures in the market formation function, based on the National Innovation System (NIS) and Sectoral Innovation System (SIS) frameworks. Similarly, there seems to be a disagreement in the literature about the geographical boundaries of TIS. For example, Hekkert et al. (2007) argue that because of the international nature of technology, the TIS can be seen as being part of various NIS and SIS. However, in a later study, Bergek et al. (2008) apply TIS within national boundaries; in other words, TIS is continued a subset of the NIS. In our view, although the technology is global, it is primarily formed within a NIS, therefore the operationalization of the TIS framework needs to be within national boundaries.

Another issue with the TIS literature is the concept of time, which has been recognized by the literature as a key element in the evolution of a system (Carlsson& Jacobsson, 1996; Carlsson et al., 2002), but is not explicitly considered; rather most of the work on innovation systems in general, and TIS in particular, is static. This approach has been challenged by several scholars such as Hekkert et al. (2007) and Jacobsson & Bergek (2011). These authors recognize that the importance of functions for the emergence and evolution of the TIS varies across time. For example, they argue that the 7th function, of positive externalities, becomes more important after all the other functions are well established. Hekkert et al. (2007) emphasizes the dynamic nature of the functions, and the fact that some might be more important than others in different time periods; they prove their point by mapping events and processes for each function. In this dissertation, we deal explicitly with the concept of time by combining it with the PLC approach. In particular, we hypothesize that the performance of each function will vary across time according to the phase of the technology. We follow the typical PLC literature[8], which proposes four phases in a product's life cycle, on which basis we assign different values to the performance of the functions. Nevertheless, this distinction is implicit since it influences only the data collection process[9].

An implicit assumption in the TIS approach is that the technology in question has been generated by the system in which it later diffuses. This assumption overlooks the fact that some countries may not be technology developers but technology adopters. Systems that simply adopt a technology should have different configurations from those that also develop the technology; this fact is neither investigated nor accounted for by the theory. This implicit assumption restricts TIS only to countries which operate at the technology frontier. This makes the framework's application on emerging markets problematic (Gosens et al., 2015), as these countries are usually far behind the technological frontier.

Another point of critique for the TIS is its limited emphasis on the geographical and transnational dimensions of the system into consideration (Binz et al., 2014, 2012; Coenen et al., 2012; Gosens et al., 2015). Despite the fact that the theory stresses the international dimension of the technology and this is one of the ways it distinguishes itself from NIS, most of the work has been focused on TIS emergence within national boundaries (Binz et al., 2014). In particular, recent papers suggest that the TIS is weak in explaining the diffusion process in emerging markets, where transnational dimensions seem to be of major importance. This is because emerging economies are usually latecomers in the diffusion process, and are thus very likely to be influenced by developments of the technology that have taken place at the international level. By incorporating the international dimension on the TIS, the dynamics and factors that influence the various functions change[10].

[8]For more details see Chapter 1

[9]A further formalization of this approach is provided in Chapter 4

[10]For a detailed discussion of how the functions change in an emerging market environment see Gosens et al. (2015, p.381)

A final critique of this approach is the inability of the framework to account explicitly for technological specificities, i.e. factors which are external to the system, but still influence it and are at the same time different for each technology. For example, for the diffusion of RETs, a key factor that influence the diffusion should be the availability of the resource (e.g. for solar PV installations the solar irradiation in the country). However, this should be treated with caution, as in some technologies, the availability of the resource might not be significant. For example, if we think about the diffusion of personal computers and the TIS around them, then the amount of silicon available in a country does not seem to be of a great importance.

Having discussed the TIS, the next step is to discuss how we are going to apply it in the context of RETs diffusion. The aim of the next section is to operationalise the framework, so as to enable us to use it with QCA. Moreover, we will present the data and their particularities, and also justify our selection of countries, time period and technologies.

3.3 Data and Methods

This section presents some of the main methods used in the TIS literature and their drawbacks. It then proposes an alternative methodology which is applied in this work, discussing its advantages and its relevance in the TIS context. The section concludes by presenting the data used and some issues surrounding them.

3.3.1 Methodological Considerations in TIS

A thorough investigation of the TIS literature shows that there are two main methodological approaches[11] to conducting empirical research in this field: a purely qualitative case study approach, and event-history analysis (EHA). The main authors, grouped under their methodologies, are presented in Table 3.2.

Table 3.2 Classification of Research Methods used in TIS Literature

Case Studies	Event History
Bergek et al., 2008	Alphen et al. 2009
Dewald & Truffer, 2011	Harborne & Hendry, 2012
Dewald, & Truffer, 2012,	Negro et al., 2007
Guo et al., 2009	Negro et al. 2008
Hawkey, 2012	Suurs & Hekkert, 2009
Jacobsson & Lauber, 2006	Suurs et al., 2009,
Jacobsson et al., 2004	Suurs et al. 2010
Kohler et al" 2012	Vasseur et al., 2013
Lai et al, 2012	
Marinova & Balaguer, 2009	
Musiolik, & Markard., 2011	
Praetorius et al., 2010	
van Alphen et al., 2009,	
van Alphen et al., 2010a	
Musiolik et al., 2012	
van Alphen et al. 2010b	

The first TIS studies use a broadly-defined qualitative approach which focused primarily on the results of interviews and expert opinion. The data are synthesized within the TIS framework of functions and then analysed. This approach was justified on the basis that the emphasis was more on theory development than empirical validation of the

[11]Some other approaches include variation analysis (Markard et al., 2009), and network analysis (van Alphen, et al. 2010; Musiolik et al., 2012; Klitkou & Coenen, 2013).

theory and lent itself to a more exploratory approach complemented by case-study analysis. However, problems arise when one wants to increase the sample size, especially because most work is based on interviews. Although interviews are good for providing depth, they sometimes omit events, and it can be difficult to generalize their findings. There is also a misconception that case studies do not constitute a scientific way to test hypotheses, primarily due to the absence of comprehensible mathematical and statistical methods. Other difficulties are related to observing the evolution of functions across time, since interviews track only some key events (Negro et al., 2007, p.928).

To try to deal with some of these problems, TIS scholars applied the EHA method, proposed by Negro et al. (2007) in their investigation of the Dutch Biomass Sector. This technique works by measuring instances of events based on various credible sources. The authors then allocate these events to different functions, allowing them to assess the performance of each function in the system. Negro et al. (2007) argue that the main advantage of EHA is that it allows one to track the evolution of functions across time enabling a better understanding of TIS performance. The more recent empirical literature tends to follow this approach; this is undoubtedly a valuable contribution to the field, its only downside being the huge effort required to collect sufficient data for each case which makes it difficult to expand the analysis to a large n. In addition, it cannot assess how functions interact with one another, and lacks a proxy for the strength of the complementarities among functions.

3.3.2 Qualitative Comparative Analysis (QCA)

To deal with some of these issues related to the TIS methodology, we decided to use the relatively new methodological technique QCA, pioneered by Ragin (2000, 2014). This methodology is designed to bridge the qualitative-quantitative gap. In simple terms, QCA helps to convert features of case studies into numbers, which then can be analysed using Boolean Algebra, without sacrificing too much of the depth provided by case studies. The aim is to identify different combinations of factors which lead or are associated to a given outcome, while having a small enough number of cases which do not allow sufficiently robust quantitative analysis.

There are several important and relevant advantages of QCA which apply particularly to the type of investigation in the present work. QCA is underpinned by the concept of equifinality, which means that different paths can lead to the same outcome. In other words, ..."a system can reach the same final state from different initial conditions and by a variety of different paths" (Katz & Kahn, 1978, p.30)

To apply QCA in this study, we need to consider the following. In the TIS literature, there is the implicit assumption that for the system to work efficiently and for diffusion to take place, all the functions have to be operational. This idea comes from the principle of systems, which states that each component in the system is interdependent and intertwined with the others (Hughes, 1983); thus, weaknesses in just one component can prevent the system from operating (Carlsson & Jacobsson, 1997; Edquist, 1999; Malerba, 1996) and lead to "system failure" (Smith, 2000).

We are interested in looking at how the system operates in the absence of some of the functions, and to test whether all of the functions are continuously necessary for diffusion. This is enabled by QCA since it allows for "several combinations of factors to lead to the same result" (Marx, 2010, p.256) by introducing the concept of conjunctural causation. This implies that single conditions cannot be examined independently to trace their impact in the final outcome. The impact on the outcome of each condition will be different if looked at in combination with the other conditions. This departs from the traditional approach to causality which assumes additivity, that is, that each condition has its own unique and independent impact on the outcome. Moreover, a given causal condition might have a different impact on the outcome, according to which other conditions are included in the particular configuration. For example, function F_1 if present with F_2 might have a positive impact on the system, but if present with F_3 it might have a negative impact.

Finally, another advantage of using QCA is its ability to deal with small n-analyses. Given the context of the TIS framework, a very detailed and in-depth analysis is required to assess the performance of this function. This makes the very large body of data required for quantitative analysis impractical. Moreover, in cases such as the one in our analysis which includes a small number of countries adopting solar and wind, gathering a large enough sample for quantitative analysis is almost impossible.

Types of QCA

QCA includes two distinct types: crisp-set and fuzzy-set. In Crisp-Set (csQCA), each country in the sample can be either a success or a failure. In our case, this would imply that the TIS of a particular country is either successful or unsuccessful in terms of diffusion. Fuzzy-Set (fsQCA) implies that it is not clear whether the country belongs or not to a particular set. In other words, in our case, we might say that the TIS in a country was successful, unsuccessful, or partially successful in the diffusion of the innovation.

At first glance, the choice of fsQCA might seem more rational since we are interested in measuring the degree of diffusion. However, we decided that this extra level of complexity would add nothing to our analysis, for the following reasons. The key to fsQCA is determining the degree of success, that is, the degree of diffusion, for each case. This means we would need to find a way to set a threshold level for perfect diffusion and a threshold for absence of diffusion. We would also need some way to make an extra assessment of the value of 0.5, which is the point of maximum ambiguity, indicating the country is neither successful nor unsuccessful. Therefore, it seems that using fsQCA would not help to deal with any of the problems involved in csQCA, and would only increase the level of complexity in our analysis, which, given that we are striving for parsimony, is not desirable.

How does QCA work?

This method is used to analyse the relationships between complex social phenomena based on the idea of sets, and particularly the idea of Boolean algebra, introduced in the 19th century by George Boole (1847; 1854). The key idea is that data are converted into binary variables, and QCA is applied to identify patterns using logical associations within sets and subsets of data. In Boolean algebra, the most important element is the concept of Boolean minimization whereby a solution is found with the minimum number of conditions necessary to achieve a certain outcome.

Causal relationships are modelled in terms of conditions, which can be either necessary or sufficient, an approach which contrasts with the quantitative method of correlations and the qualitative idea of comparisons. The relations between conditions and an outcome may be necessity. This means that when a particular outcome occurs, the condition is always present. For example, if the outcome can only be successful if $F_1 = 1$, then $F_1 = 1$ is a necessary condition. Another type of relation is that of sufficiency: "A condition (or combination of conditions) is sufficient to produce an outcome if the outcome always occurs when the condition (or combination of conditions) is present" (Devers et al., 2013, p.25). For example, if $F_1 = 1$ is sufficient for a successful outcome (O), then whenever $F_1 = 1$, then $O = 1$. But if $F_1 \neq 1$, this does not necessarily imply that $O \neq 1$.

QCA has its own notation based on Boolean Algebra, so the following points need to be considered:

1. $\bullet$ indicates that all factors have to be present; for example, $A \bullet B = 1$ means that if both A **AND** B are included, then the outcome is equal to 1;

2. $+$ indicates that either of the factors needs to be present; for example, $A + B = 1$ means that if A **OR** B is included, then the outcome is equal to 1;

3. $\sim$A means that the condition A is false;

4. $\leq$ means that "is sufficient for";

for example, if we have relation 3.1:

$$A \bullet B + A \bullet \sim D \leq Y \tag{3.1}$$

then, this implies that for outcome Y to occur, either conditions A and B need to be satisfied, or condition A and not condition D.

Methodology Steps for QCA

The research steps proposed in the QCA literature are the following (Marx, 2010; Rihoux & De Meur, 2009):
1. Development of an explanatory model with the relevant significant variables;
2. Creation of a dichotomous data table;
3. Construction of a truth table (table of configurations)[12];
4. Resolution of contradictory configurations;
5. Generation of parsimonious explanations for the outcomes[13];
6. Interpretation of the explanatory models and discussion of the results[14].

Step 1 - Developing a Model

In this context, we are testing an already developed theoretical framework, which suggests that a technology can diffuse through a system if six functions are present. In our context, the set of explanatory variables, known as conditions in QCA jargon, are the six functions of the system, which then are used to explain the outcome variable, which is a proxy for the success of the system in diffusing the particular technology.

Step 2 - Creating of a data table

The data table in essence is our dataset, constructed based on the conditions and the

[12]This is achieved using QCA software.
[13]This is achieved using QCA software.
[14]This is discussed in the next section

outcome variables. The two main elements in this step are conversion of the continuous quantitative data into binary variables, and construction of the outcome variable.

To deal with the first element, we created some guidelines based on the theory, to aid our understanding and classification of the performance of each system in each function. These are presented in Tables C.27 and C.30 which can be found in the Appendix C.8.

To qualify countries based on these criteria, we need indicators and other qualitative evidence to allow us to assign scores for the performance of each function. To achieve this, we examined a wide range of indicators drawn from the TIS literature to identify which pieces of information are used for each function, the sources used by the authors, and the availability of these indicators for time periods and countries. This task was far from straightforward for various reasons. Starting with case studies, given their descriptive nature, it is quite difficult to find a specific set of indicators that have been used consistently across all the cases. Firstly, the indicators are not explicitly stated, neither is their source or time period. The authors just give narratives and examples, which they then use to illustrate the performance of a function. Despite these difficulties, an attempt was made to identify what indicators were used when the researchers were making their claims, and a list of these can be found in Appendix C.9.

The event history papers are geared more towards testing the theory and less on theory building. For this reason, they have a methodological advantage in the sense that they make explicit reference to the indicators they use to measure the performance of each function. For this work, we have focused on the main works on TIS using event history methods, and we have identified the list of these indicators used. These can be found in Appendix C.9. As it is evident from the tables in the appendix, event history modelling requires a very large number of indicators. This is one of its limitations, as this makes it very difficult to apply it for a large sample size.

To impose order in this seeming "chaos", we subdivided each function into various subactivities and, based on these activities, identified relevant indicators. After making a list of these indicators, the next step was to filter them, by identifying for which of these it would be possible to find reliable and adequate data so that we can construct a large-n dataset[15]. This process led us to produce table C.18[16].

[15]In this context, large n implies anything more than 10, since the vast majority of TIS work has focused only on one to five cases.

[16]The full version of this Table can be found in Table 3.3 in Appendix C.9.

Table 3.3 Activities and Sub-Activities

Activity	**Sub-Activity**
Development of Knowledge	Downstream Upstream
Resource Mobilisation	Quality and Availability of Financal Capital Quality and Availability of Human Capital
Legitimation	Social Lobbying Political Geopolitical
Direction of Research	Market Growth Expectation Technological Expectations Government Expectations
Market formation	Demand Supply Institutionalisation Of The Market
Enterpreneurial Experimentation	Entrants And Incumbents Available Technologies

Then, for each function we recorded events and indicators that were relevant using the NVIVO software and a conventional spreadsheet tool. NVIVO was useful as a tool for recording events, documents and other evidence which we could use to support the activities of a function. Then, based on the criteria above, we could assign values for the performance of the functions and record them on a spreadsheet. Indicators that were already in quantitative form were kept in a spreadsheet format and then united with the results from NVIVO to construct the final dataset that would be used for the analysis.

After constructing the final dataset, we created a composite indicator for each function. A typical composite index is constructed using equation 3.3.2 (Freudenberg, 2003, p.7):

$$I_i = \sum_{i=1}^{n} w_i X_i \tag{3.2}$$

where I_i is the composite indicator, X_i is the normalised value of component variable, w_i is is the weight of each observation, and $0 \leq w_i \leq 1$.

Clearly, these are all expressed in different values, so we need to normalise them before being able to construct the composite indicator. To calculate the normalized variables, we use the methodology proposed by the OECD (Nardo et al., 2005), which uses equation

3.3.2:

$$X_i = \frac{Y_i - \overline{Y}}{s} \tag{3.3}$$

where $\overline{Y}$ is the mean of the variable Y and s the standard deviation, and $0 \leq X_i \leq 1$.

The next issue to deal with was the element of time. Throughout our analysis we assume that the performance of each function varies across time, thus creating four distinct time periods based on the PLC literature[17]. The data and assessments are made across these four periods to create a panel dataset. However, QCA cannot be used to analyse panel data and account for time-varying indicators. Thus, we take an average for the performance of each function across all periods using formula 3.4.

$$\bar{F}_i = \frac{F_{i1} + F_{i2} + \cdots + F_{in}}{n} \tag{3.4}$$

where $\bar{F}_i$ is the average score of Function i over n periods.

Finally, we need to convert all the values of the functions $\bar{F}_i$ into binary values. The literature suggests that the best way to achieve this is to apply some theoretical threshold level. If the performance in the condition is greater than this level, then the condition is a success and takes the value 1, and if it is below this threshold it is a failure and takes the value 0. However, in our context it is almost impossible to find theoretical threshold levels. For this reason, we follow the approach suggested by Devers et al (2013 p.13), who argue that either the mean or the median of each value can be taken as the threshold level. For completeness, we decided to use both mean and median to code our data[18].

After coding the conditions, the next step is to create an outcome variable, which specifies whether each case is a success or a failure. Measuring system performance is still considered one of the most troublesome elements of TIS. Carlsson et al. (2002) and Rickne (2002) propose some theoretical elements that should be considered. Their arguments support the view that there is no single indicator that is sufficient to capture system performance. Rather, they suggest that at least three groups of indicators are necessary, with the first group capturing the system's ability to generate knowledge, the second measuring the actual diffusion of knowledge, and the third the economic use

[17]Explicit identification of the four phases for each technology is done in Chapter 1

[18]No differences were found in classifying success and failure, irrespective of whether the mean or the media were used.

of this knowledge.

In this work, a successful system is one that has been successful for diffusing the technology, since we are interested not only in systems that produce knowledge but also in those which adopt it and make an economic use of it. In an ideal world, a successful TIS is one where the technology has penetrated 100% of the market; in our context, this would mean that a country would have to produce 100% of its electricity from solar or wind. This is infeasible, for reasons related to the maturity of the technology and also because of issues such as energy independence. At another extreme, it might be argued that success is whether a country has produced any electricity from solar/wind and failure if the country has produced no electricity from these sources. Moreover, making such a distinction leads to further complications in the analysis. Firstly, the production of any electricity from RET might be considered a random event. Secondly, if we assume that no electricity from any of these sources is failure, then we need to include all of the countries in the world which do not generate electricity from such sources; this would imply an unnecessary large sample, which would complicate the analysis even further. For all the aforementioned reasons, we concluded that a successful TIS is the one that has shown significant progress in diffusion of a particular technology.

To define significant progress, there are numerous indicators that could be used. Firstly, there are various ways to measure diffusion of the resources including generation capacity and the actual consumption. Since diffusion implies some measure of utilization, it is more rational to look at consumption patterns. Consumption is usually measured in MWh. However, using these data means accounting for the size of the economy, which suggests it would be better to measure MWh per capita. Another way to account for size is to consider electricity from solar or wind as a percentage of total or total renewable electricity. However, all of these issues are scaled using indicators which are not directly related to the technological system being considered. We are interested not in finding a measure for diffusion per se, but rather a measure for system performance.

In order to deal with these issues, we took the decision to look at average growth rate of renewable electricity (from either wind or solar) and, based on these levels, classify whether the system works successfully or not. However, we recognize that the degree of diffusion is an important success criterion and needs to be incorporated in the analysis. That is why we decided to complement the analysis by using some more indicators that focus on the absolute amount of diffusion, and they were mentioned in the previous paragraph. For simplicity, we decided that it would be better to create a composite indicator rather than use all of them separately in the analysis, which was using Equation . For this work, we have a total of four variables measuring performance, and we assume that the values of all the weights for all the variables are the same, since there is no reason to believe that either of the indicators is more important than any other in this context[19]. The components used are:

1. Growth rate of electricity output from SolarPV/Wind (%)
2. Electricity output from SolarPV/Wind (GWh)
3. Electricity from SolarPV/Wind per capita (GWh/capita)
4. Electricity from SolarPV/Wind per size of the country (GWh/square Kilometer)
5. Electricity from SolarPV/Wind as a percentage of total renewable electricity (%)

Clearly, these are all expressed in different values, so we need to normalise them before being able to construct the composite indicator. This is done following Equation that was presented above.

After creating the composite indicator which captures the performance of the system, the next step is to find a threshold level that would separate the successful from the unsuccessful TIS. We did this in four different ways: using the mean and the median of the composite indicator, by visual inspection of the composite indicator[20], and by visual inspection of the growth rate [21]. Tables 3.4 and 3.5 present the most successful countries using different measures for each technology[22].

[19]To be more accurate, we theorised that the Growth rate of electricity output of the RET should be more important. For this reason, we tried allocating a greater weight on this indicator compared to the others, but it made virtually no difference on the final outcome variable.

[20]These graphs can be found in Figures C.1 and C.2 in the Appendix

[21]These graphs can be found in Figures C.3 and C.4 in the Appendix

[22]A more detailed discussion and justification of the data and the countries in our dataset are presented in the end of the section.

Table 3.4 Successful TIS systems for Solar PV

Composite Indicator (mean)	Composite Indicator (median)	Composite Indicator (visual)	Growth (Visual)
	Austria		
Belgium	**Belgium**	**Belgium**	**Belgium**
	Czech Republic		Czech Republic
	Denmark		
	France		France
Germany	**Germany**	**Germany**	**Germany**
	Greece		
Italy	**Italy**	**Italy**	**Italy**
Luxembourg	Luxembourg	Luxembourg	
	Netherlands		
Portugal	Portugal		
Spain	**Spain**	**Spain**	**Spain**

Table 3.5 Successful TIS systems for Wind

Composite Indicator (mean)	Composite Indicator (median)	Composite Indicator (visual)	Growth (Visual)
	Austria		
	Belgium		
Denmark	**Denmark**	**Denmark**	**Denmark**
	France		
Germany	**Germany**	**Germany**	**Germany**
	Greece		
	Italy		
	Luxembourg		
Netherlands	Netherlands	Netherlands	
Portugal	**Portugal**	**Portugal**	**Portugal**
Spain	**Spain**	**Spain**	**Spain**
	Sweden		
UK	**UK**	**UK**	**UK**

For the solar TIS systems, we can conclude that the successful countries are Germany, Italy, Belgium and Spain, and potentially Luxembourg, since these systems are categorized as successful under all four classifications. The success of all other systems is relatively less robust. In the case of wind, Denmark, Germany, the UK and Spain are clearly successful since they are categorized as such for all five measures. Portugal and the Netherlands show potential for success, but the remaining countries show little evidence of successful systems.

With these caveats in mind, and for the sake of robustness, we use all four proxies for success, and add an extra category, which includes only those countries that are successful across all five previous proxies. In this way, we can be confident that we have created a category which is restrictive enough to include the most successful TIS. Table 3.6 presents the successful countries based on this new category, for both technologies.

Table 3.6 New Classification of Successful Solar and Wind TIS

Successful Solar TIS	**Successful Wind TIS**
Belgium	Denmark
Germany	Germany
Italy	Portugal
Luxembourg	Spain
Spain	UK

In terms of coding, we use the implicit convention in the literature and assume that the [0] outcome value stands for failure of the system to diffuse the technology, and a [1] outcome value as denoting success of the system in diffusing the technology.

Step 3 - Construction of a truth table (table of configurations).
The truth table is the key tool in QCA. Its aim is to identify which set of conditions lead to a positive and which lead to a negative outcome. A distinction needs to be made between the truth table and the data table. The truth table reports all the possible combinations of the given conditions that might lead to a successful outcome, and the number of cases in our dataset for each configuration. The data table is a simple matrix in which each row describes a particular case, including its performance in the conditions as well as the outcome. Each row in the table represents a country, its performance in each of the functions, and whether it is a successful case for diffusion of energy. Examples of the data and truth tables are provided in Tables 3.7 and 3.8.

Table 3.7 Example of a Data Table (Solar)

Country	Knowledge Development	Legitimation	Guidance of Search	Enterpren Experimentation	Resource Mobilisation	Market Formation	Diffusion Outcome
Austria	1	0	0	1	0	0	0
Belgium	1	0	1	0	1	0	1
Bulgaria	0	0	0	0	0	0	0
Czech Republic	0	1	0	1	0	1	1
Denmark	0	0	0	0	0	0	0
Estonia	0	0	0	0	0	0	0
Finland	1	0	0	0	0	0	0
France	1	1	1	1	1	1	1
Germany	1	1	1	1	1	1	1
Greece	1	1	1	1	1	1	1
Italy	1	1	1	1	1	1	1
Latvia	0	0	0	0	0	0	0
Lithuania	0	0	0	0	0	0	0
Luxembourg	0	1	1	0	1	1	0
Netherlands	1	0	0	1	1	0	0
Portugal	0	0	0	0	0	1	1
Slovakia	0	0	0	0	0	0	0
Spain	1	1	1	1	1	1	1
Sweden	1	0	1	0	0	1	0
UK	1	1	1	0	1	1	0

Table 3.8 Example of a Truth Table (Solar)

Knowledge Development	Legitimation	Guidance of Search	Enterpr. Experiment.	Resource Mobilisation	Market Formation	Number of Countries	Diffusion Outcome
1	0	1	0	1	0	1	1
1	1	1	1	1	1	5	1
0	0	0	0	0	1	1	1
0	1	0	1	0	1	1	1
0	0	0	0	0	0	6	0
1	0	0	0	0	0	1	0
1	0	0	1	0	0	1	0
1	0	0	1	1	0	1	0
1	0	1	0	0	1	1	0
0	1	1	0	1	1	1	0
1	1	1	0	1	1	1	0

The first row in Table 3.7 shows the performance of Austria. Based on the coding, Austria has been unsuccessful in the diffusion of solar energy, and the only functions that were active in the system are Knowledge Development and Entrepreneurial Experimentation. The first row in Table 3.8 shows the configuration of a successful system in which only three functions operate. In our dataset, only one country follows this configuration (since it has 1 in the category "Number of Countries"), and has a successful TIS (since it has 1 in the category "Diffusion Outcome").

4. Resolution of contradictory configurations
Contradictory configurations are those with the same conditions, but different outcomes. In our data there are no contradictory configurations so we proceed to the next step, which is the generation of parsimonious solutions through Boolean minimization, and explanation of the findings. However, there are some points that should be highlighted related to the interpretation of our results.

A Guide to understanding the findings

After creating the truth tables, the data are inputed to the fsQCA software, which produces three distinct tables. The first table presents the results of the successful configurations for a Complex Solution, the second represents the Intermediate Solution, and the third the Parsimonious Solution. The main difference between the three tables is the use of the counterfactuals. Counterfactuals or logical remainders are theoretical configurations which have no empirical observations in the dataset[23]. This is expected in the context of social sciences research, since "naturally occurring social phenomena are profoundly limited in their diversity" (Ragin, 2008, p.147). This means that it is difficult to find empirical evidence for all potential configurations, that is, for all possible combinations of causal conditions.

In QCA, there are three potential ways to deal with counterfactuals. The first solution is to ignore them, and to produce something known as the Complex Solution. This would cause a smaller number of cases in our dataset, since we would only use the ones for which we have actual empirical observations. Thus, the solution produced will be complex in the sense that it will be difficult to find a logically simpler solution, given the very smaller number of cases. The second is to be indifferent about the existence or not of these counterfactuals and to incorporate them all in the analysis. This produces the Parsimonious Solution. This is the simplest possible configuration since it includes the

[23]For example, imagine a case for which all functions would be equal to 0, and the diffusion will be 1, and for this case we had no empirical observation.

largest number of configurations in the dataset, and can thus find the logically simplest solution. However, this solution might be unrealistically simple, due to the incorporation of counterfactuals that are highly unlikely to be found in the real world. To deal with this, the third option of the Intermediate Solution, allows an informed selection of the counterfactuals to be included in the analysis. Under this condition, a counterfactual will only be included in the analysis if it is an "easy counterfactual". This means that it helps to make the complex solution simpler, but also this configuration has potential theoretical justification (Rihoux & Ragin, 2009, p.110-111). In our case, for example, if a counterfactual has all functions zero and an outcome of 1, although it might help simplify the solution, it will not be used because it makes no theoretical sense.

After establishing how to interpret the findings, the next step is to provide some measures for significance and validity, with which to assess the findings. In QCA jargon, we need to develop some statistical measures that show the extent to which each proxy is necessary or sufficient for the analysis, and also the extent to which the proposed configuration covers our empirical observations. For these purposes we use the two indicators of consistency and coverage[24].

Consistency is "a measure of the degree to which a dataset supports the claim that a set relationship exists between a condition (or combination of conditions) and an outcome" (Devers et al., 2013, p.28). In other words, "consistency gauges the degree to which the cases sharing a given combination of conditions agree in displaying the outcome in question"(Ragin, 2009). For example, if the dataset consists of three cases which satisfy the relationship $A \bullet B \leq Y$, then the consistency of this solution is 1. If only two out of the three cases satisfies this configuration, then the consistency would be $\frac{2}{3}$. Clearly, the greater the consistency the greater the significance of our result.

Coverage is the same as strength and accounts for the extent to which a condition (or combinations of conditions) explains the outcome. It allows us to "identify which conditions (or combinations of conditions) have more empirical importance than others" (Devers et al., 2013, p.28). Our findings include three measures of coverage. Firstly, raw coverage measures "the proportion of memberships in the outcome explained by each term of the solution" (Ragin et al., 2006, p.85). In other words, it shows how much of the total membership is covered by this configuration. Secondly, unique coverage, which "measures the proportion of memberships in the outcome explained solely by each indi-

[24]A detailed presentation of our results with all these statistical measures can be found in Appendix C.12 and C.12

vidual solution term (memberships that are not covered by other solution terms)" (Ragin et al., 2006, p.85). This allows us to see how much of the total coverage can be attributed to a specific configuration. Finally, solution coverage", which measures the proportion of memberships in the outcome that is explained by the complete solution" (Ragin et al., 2006, p.86). In other words, it shows how much of all the cases is covered by all the configurations in the table. The reason why this figure is less than the sum of the raw coverage is because of the overlap among the paths offered by the configurations. If we think in terms of parallels with regression, solution coverage can be perceived as R^2 and unique coverage as the corollary of the partial regression coefficients.

To get a better understanding of these measures, we can look at Table 3.9, which shows the results of one of the QCA models.

Table 3.9 An illustration of QCA Results and Diagnostics

List of Configurations	raw coverage	unique coverage	consistency
∼f1*∼f2*∼f3*∼f4*∼f5*f6	0.125	0.125	1.000
f1*∼f2*f3*∼f4*f5*∼f6	0.125	0.125	1.000
∼f1*f2*∼f3*f4*∼f5*f6	0.125	0.125	1.000
f1*f2*f3*f4*f5*f6	0.625	0.625	1.000
Diagnostics			
solution coverage:	1.000		
solution consistency:	1.000		

This table presents the solution of the QCA analysis for a given dataset in our sample. This dataset has the six functions, and models the successful TIS for a given RETs[25]. The solution consists of four configurations. Looking at the first configuration, we see that the only successful function is f6. Moreover, the raw coverage of this configuration is 0.125. This means that this configuration covers 12.5% of the successful TIS in our sample. Unique coverage is also 0.125, which means that 12.5% of the successful TIS can only be explained by this configuration. Solution coverage is 1.000, which means that these four configurations can explain 100% the successful TIS of our sample. The consistency of the first configuration is 1.000, which means that all cases with this configuration had the same outcome.

[25] We do not want to go on to details about the conceptual interpretations of these particular results, as this is only for illustration purposes of the statistical measures we discussed. A fuller conceptual interpretation of the results takes place in the next section.

3.3.3 Dealing with the Data

For this analysis, we decided to collect data on solar and wind; we believe that although the systems have different actors and institutions, there is a lot of overlap between the two. For example, companies that deal with wind installations often also sell solar installations, since most of them are renewable energy solutions firms rather than specialists in one or the other technology. Moreover, the perception of many policy makers is that these two technologies belong to the same category of "new renewables" and they frequently formulate policies that affect both simultaneously. For example, when a country launches a FIT system, it very rarely applies to one of the two technologies. To be clear, in this work we do not analyse both technologies together as if they belonged to a single system; we perform QCA analysis on each separately and then compare the performance of the systems and, potentially, generalize for the TIS , given the overlaps between these systems.

In an ideal world, where all data were readily available, a database that would trace the evolution of a technological system would consist of a (n x m) matrix, where n would be the number of countries/cases under consideration and m the number of indicators capturing elements of the various functions[26]. The maximum number of countries obtained would be around 190, the maximum time would vary across technologies (e.g. 20 years for solar PV), and there would be a total of at least m indicators.

Under these conditions, an econometric/statistical analysis could be conducted, similar to what we demonstrated in Chapter 2. However, in this context, such an analysis is not realistic for the following reasons. Firstly, the TIS approach is developed with a more qualitative perspective in mind, which implies difficulties in terms of indicators. However, we partially solve this problem by splitting the functions into subfunctions and assigning various indicators to these subfunctions. The problem is that these indicators are not easy to collect and, as the number of countries and time periods increases, the difficulty increases exponentially. Secondly, there are very strong correlations among many of these indicators and, as a result, most conventional regression methods cannot operate. Even if we where to decide to create a composite indicator for each function, the correlations between functions would not allow for a robust econometric analysis[27].

As a result of the above, we decided to focus on a limited number of countries, for

[26]On average, the number of indicators in empirical papers varies between 20 to 50

[27]To be precise, we already tested various binary dependent models, with outcome as the dependent variable, and the functions as the independent variables, but none were successful.

which we have sufficient data across time for most of the indicators, and which have also adopted at least some wind and solar. To be consistent, we use the IEA Renewable Energy Database to decide whether a country produces electricity from wind or solar. In this database, if a country produces less than 1MWh of electricity from either of these resources, the value will be zero and thus we can conclude that no diffusion has taken place. This is a realistic assumption, because if a country has production of less than 1MWh, then it cannot be considered to have achieved diffusion, since this amount is so small[28]. The time period considered is 1990 to 2010, which are dates for which IEA Renewables Information provides complete data[29]. After identifying the countries with a successful TIS in this time period, the next criterion is completeness of the data for the indicators. If a country has less than 80% of the data on sub-functions it is excluded from the dataset on the grounds of insufficient information to assess its performance. The countries included in our final sample are presented in Table 3.10.

To conduct QCA, the literature suggests that the number of cases selected depends on the number of conditions used in the model. Clearly, there is a trade-off between the number of conditions chosen and the number of cases. Ideally, we need to minimize the number of conditions and maximize the number of cases because, as the number of conditions increases, the number of potential combinations that might explain the potential outcome increases exponentially. To be precise, the number of theoretically potential combinations, C, is a function of conditions, k, based on the following formula: $C = 2^k$. Ideally, we need to have one empirical case for each theoretical combination, so that we have a complete dataset. In this study, each function is one condition, which leads to a total of six conditions, which implies that the number of theoretical combinations C is 64. The literature suggests that for csQCA with six conditions, the database should include approximately 20-24 cases (Marx, 2010; Thygeson et al., 2013). In our database, we have a total of 18 countries for wind, and 22 countries for solar which is just about enough to conduct QCA.

[28]Note that this does not imply that all countries with more than 1MWh are successful in developing a TIS. A discussion of the success criterion is made in the previous section.

[29]The exception was some countries from Central and Eastern Europe which were also included in the dataset for reasons related to the author's special interest.

Table 3.10 Countries in the Dataset

	Date of Wind Adoption	Date of Solar Adoption
Austria	1994	1993
Belgium	1990	2004
Bulgaria	2003	2008
Cyprus	n/a	2006
Czech Republic	2002	2006
Denmark	1990	1999
Estonia	n/a	2011
Finland	1992	1991
France	1993	1994
Germany	1990	1990
Greece	1990	2001
Italy	1990	1990
Latvia	n/a	2011
Lithuania	n/a	2012
Luxembourg	1997	2003
Netherlands	1990	1992
Portugal	1990	1990
Romania	n/a	2010
Slovakia	2002	2009
Spain	1990	1990
Sweden	1990	1993
UK	1990	1999

3.4 Findings

3.4.1 Bivariate Analysis

The aim of this section is to present the results of our analysis. Given the bias in social sciences towards conventional statistical methods, we could not resist the temptation to conduct elementary bivariate analysis before proceeding with the discussion of the results from the QCA. In this context, we have a set of six binary independent variables (the six functions), which could potentially explain the binary outcome variable (success of the TIS). Given that all the data are binary, we calculated the Phi (ϕ) coefficients[30], which are similar to the Pearson-correlation coefficient ρ, in terms of both properties and interpretation. In more detail, ϕ can be negative or positive, indicating positive or negative associations. Moreover, the higher its values the stronger the association between the two variables of interest.

Also, for each technology, we have two datasets (having used both the mean and the median to code them), and six outcome variables. This in turn creates two 6×6 correlation matrices between the functions and the outcome variables for Solar PV and two 6×6 correlation matrices for wind (see Appendices C.10 and C.11). For simplicity, we take the average correlations from these tables and summarize the key findings in Table 3.11.

Table 3.11 Table of ϕ Coefficients between Outcome and Functions for Wind and Solar

	Outcome Solar	Outcome Wind
Knowledge Development	0.00	0.19
Legitimation	0.52	0.43
Guidance of Search	0.45	0.42
Enterpreneurial Experimentation	0.32	0.10
Resource Mobilisation	0.42	0.32
Market Formation	0.10	0.46

As expected, all the coefficients are positive, which implies that, even from a statistical perspective, there is a positive impact of each function on the performance of the TIS. The results for solar show the rather surprising finding that knowledge development and market formation are virtually insignificant for the development TIS since the correla-

[30] These are also known as the "mean square contingency coefficients" (Cramer 1946).

tion values are very close to 0. Similarly, the ϕ for entrepreneurial experimentation is quite low, which implies that this function is not hugely significant. The only functions with a relatively significant impact on the solar TIS are guidance-resources-legitimation. For wind, we see that knowledge development, entrepreneurial experimentation and resource mobilization have almost no correlation with system success. The successful TIS tends to be closely related to legitimation, guidance, and market formation.

However, these results should be treated with some scepticism as the dataset construction was not intended towards such a quantitative bivariate analysis. The remaining of this section presents and discusses the results of the QCA analysis for both wind and solar, and represents the main body of our work.

3.4.2 QCA

For reasons of space and reader-friendliness, the only results presented here are those for high levels of consistency and coverage[31]. Although all three types of solutions (complex, intermediate, parsimonious) are presented, the emphasis is on interpreting the intermediate solution, since this is considered superior to the other two. This superiority is because this solution both incorporates the researcher's theoretical knowledge and exploits QCA's ability to create parsimony (Rihoux & Ragin, 2009, p.111).

Solar

Table 3.12 shows the results from our analysis on solar.

[31]For a full list of results from all types of coding, the reader can look in Appendices C.12 and C.13

Table 3.12 Results from QCA on Solar PV

Solar TIS Configurations		
Model	1	2
Outcome Variable	Subjectively Based	Composite Indicator (Median)
Conversion Factor	Mean	Mean
Complex Solutions	$(f1 \bullet f2 \bullet f3 \bullet f4 \bullet f5 \bullet f6)^{*}$	$(f1 \bullet f2 \bullet f3 \bullet f4 \bullet f5 \bullet f6)$
Parsimonious Solutions	$(f2 \bullet f4)^{**}$	$f4^{*}$
Intermediate Solutions	$(f6 \bullet f4 \bullet f2)^{**}$	$(f4 \bullet f1)$
Model	3	4
Outcome Variable	Subjectively Based	Composite Indicator (Median)
Conversion Factor	Median	Median
Complex Solutions	$(f1 \bullet f2 \bullet f3 \bullet f4 \bullet f5)^{**}$	$(f1 \bullet f2 \bullet f3 \bullet f4 \bullet f5)$
Parsimonious Solutions	$(f2 \bullet f4)^{***}$	$(f4 \bullet f5)^{*}$
Intermediate Solutions	$(f6 \bullet f4 \bullet f2)^{**}$	$(f5 \bullet f4 \bullet f1)^{*}$
Notes	**f1**: Knowledge Development **f2**: Legitimation **f3**: Guidance of Search	**f4**: Enterpreneurial Experimentation **f5**: Resource Mobilisation **f6**: Market Formation
	* denotes raw coverage >60%, ** denotes raw coverage >70%, *** denotes raw coverage >90%	

Focusing only on the **Intermediate Solutions**, we can formulate equation 3.5:

$$\left.\begin{matrix} f6 \bullet f4 \bullet f2 \\ f5 \bullet f4 \bullet f1 \end{matrix}\right\} \quad \leq \text{Diffusion} \tag{3.5}$$

The success configurations, together with their respective countries, are illustrated in table 3.13. This implies that for a TIS to be successful in diffusion of solar power, it needs to have legitimation, entrepreneurial experimentation, and market formation or knowledge development, entrepreneurial experimentation, and resource mobilization.

Table 3.13 Solar TIS countries for each Configuration

	Configurations	**Successful TIS systems** [32]
(1)	$f6 \bullet f4 \bullet f2$	FR, DE, GR, IT, ES, CZ, PT
(2)	$f5 \bullet f4 \bullet f1$	FR, DE, GR, IT, ES, NL, AU, BE

The first striking result from this analysis is the guidance of search for explaining the success of the system; in other words, contrary to the initial expectations, explicit guidance from the government towards the entrepreneurs is not necessary for the diffusion of solar PV. A possible explanation for the lack of guidance of search from our results might have to do with the way this function influences the system. The results from the QCA show only the factors which are absolutely necessary for diffusion; in other words, it can only measure the "direct effects" of a function on the system. What our results therefore suggest is that the guidance of search does not have any direct effects on the success of the TIS. But this does not preclude the possibility that guidance might have indirect effects on the TIS. Unfortunately, QCA cannot differentiate between direct and indirect effects, so we cannot argue about their existence[33]. Therefore, we can only hypothesise that guidance influences all other functions in these configurations, which, in turn, influences the performance of the system and has an impact on the diffusion process.

There is always an overlap between guidance of search and policy, as in many instances these are treated as synonymous, as this function is primarily captured by using policy indicators. However, as we illustrated above this finding should not be confused to

[33] Another technique which can measure such effects is Structural Equation Modelling, but this is not possible with a relatively small sample. For this technique to work, the sample has to consist of at least 100 observations.

imply that policy is not necessary for diffusion. Rather policy influences a variety of functions, such as resource mobilisation and market formation; our finding here simply implies that policy as a means to guide entrepreneurs is not necessary.

The second interesting finding from this analysis is the importance of entrepreneurial experimentation. Both configurations show that the common function between the two of them is f4. In essence, this implies that in the absence of entrepreneurs the TIS system cannot operate. This points to a "Kirznerian" argument about the importance of entrepreneurs who can be viewed as carriers of technology and as agents that can reduce technological uncertainty (Kirzner, 1973). The importance of entrepreneurial experimentation can also be traced to Schumpeter and his notion of creative destruction, in which he shows that entrepreneurs are the agents of innovation (Schumpeter, 1942).

The third interesting finding comes from the specific configurations. In the first, we see entrepreneurial experimentation paired with legitimation and market formation, while in the second configuration, it is paired with knowledge development and resource mobilization. These configurations can be seen as reflecting the country's distance from the technological frontier, since the former system can be viewed as facilitating technology adoption, while the other as facilitating technological development. The former group of countries is the one that is not on the technology frontier, and is catching up. What these countries need are institutionalized markets and public acceptance. The latter configuration includes those countries that are on the technology frontier, and are those who are developing the technologies. We can assume that these countries have already solved the issues related with market development and legitimation, otherwise it would be very unlikely for them to invest their resources into technologies for which there are no markets or not accepted by the society. Rather, what the system of a technology adopter seem to be in need of is a strong enough knowledge base and enough resources to continue expanding the technological frontier.

With these observations in mind, we next look at the countries to which these configurations apply. We can identify two main groups of countries: robust and weak. The robust groups consist of five countries (FR, DE, GR, IT, ES), all of which are apparent in both configurations. These countries have been successful in achieving diffusion and are at the technological frontier, which leaves little more to be said about them since all the functions are active[34]. This highlights one of the weaknesses of QCA, which is

[34]Not much new can be said about these countries since, given their robust profile, they have been the focus of much research, including some of the pioneering work on TIS (see e.g. Neij, 1997; Jacobsson et

not sufficiently developed to allow panel data set ups, something that would allow us to trace the evolution of functions and understand how these five countries reached a fully functioning TIS[35].

The weak countries are more interesting and show two configurations. We can identify CZ and PT as belonging to configuration (1), which we label followers, and countries NL, AU, BE belonging to configuration (2), which we call pioneers. Among the followers, we see a clear absence of technological innovation. Rather these countries are pulled by the technological developments taking place in other systems, and are focused on making the penetration/adoption of new technologies as straightforward as possible. For example, in Portugal in 2008 a huge solar farm – the biggest in the world – was constructed near the town of Moura, based on imported panels and technology. It was enabled by the removal of any administrative barriers that might cause delays, and by decisive government action. Similarly, in the Czech Republic, solar installations increased from 0MW of electricity to over 2000MW in a three year period. This was achieved primarily by government legitimation of the solar PV technologies, through a very generous policy and institutionalization of the market, and removal of administrative barriers, which stimulated the entry of numerous entrepreneurs and diffusion of the technology.

Among the pioneers, we see that their level of economic development is higher than that of the followers. Moreover, they are pushed to develop and innovate. For example, if we look at the case of the Netherlands we can see that there is a continuous push towards innovation in the solar field, to become the global leader in solar technologies. For example, it has established one of the world's most prominent knowledge institutes, Energieonderzoek Centrum Nederland, and one of the world's largest the Photovoltaic Solar Energy Conference and Exhibition (PV SEC) centres. In addition, it has a vibrant industry cluster of solar companies (including OTB Solar, Tempress Systems, Smit Ovens, Scheuten Solar, Rimas, Solland Solar, DHV), and multiple promising start-ups (Solarmagazine, 2010).

Similarly, Austria has a highly diversified solar PV industry, producing mainly PV modules, converters and tracking systems, involving 50 firms which are heavily research driven, and multiple specialized institutions and universities engaged in international PV R&D. The Austrian government is a big supporter of the industry and provides gen-

al., 2004; Šúri et a., 2007; Dewald & Truffer, 2011;).

[35]We try to deal with this weakness in Chapter 4, by conducting in-depth case analysis of 4 countries and developing a dynamic model of the TIS.

erous subsidies to the research institutes, to a total of more than 10 million euros per annum (Bernsen et al., 2011). In Belgium also, both Flanders and Wallonia have very vibrant research communities with many innovations being produced in the field of solar PV. Greece has been one of the earliest adopters of solar PV, and has continuously tried to develop a solid research base on the field. This is evident from the establishment of the Centre for Renewable Energy Sources (CRES) in 1987, an institute which aimed at promoting research in the field of renewables, particularly solar PV. Lastly, in Italy, research on solar energy was conducted since 1953 in the University of Bari, where there was a special centre devoted to solar distillation of sea water, and the use of solar as a source of energy (Nebbia, 2005). The history of solar PV research on Italy is so old that a special centre for the History of Solar Energy has been established (GSES).

Wind

Table 3.14 illustrates the successful configurations for the wind TIS.

Table 3.14 Add caption

Wind TIS Configurations			
Model	1	2	3
Outcome Variable	Strong Cases	Composite (median)	Subjectively Based
Conversion Factor	Mean	Mean	Mean
Complex Solutions	$(f1 \bullet f2 \bullet f3 \bullet f4 \bullet f5 \bullet f6)^{**}$		
Parsimonious Solutions	$(f2 \bullet f5 \bullet f6)^{**}$	$f3^{**}$ $f5^{*}$	$f3^{**}$
Intermediate Solutions	$(f6 \bullet f5 \bullet f3 \bullet f2 \bullet f1)^{**}$	$f5 \bullet f4 \bullet f1$	
Model	4	5	
Outcome Variable	Subjectively Based	Composite (Median)	
Conversion Factor	Median	Median	
Complex Solutions	$f1 \bullet f2 \bullet f3 \bullet f4 \bullet f6$	$f1 \bullet f2 \bullet f3 \bullet f4 \bullet f6$	
Parsimonious Solutions	$f3^{**}$	$f1^{**}$ $f2^{***}$	
Intermediate Solutions	$(f6 \bullet f5 \bullet f3 \bullet f2)^{**}$	$(f4 \bullet f2)^{*}$ $(f4 \bullet f1)^{*}$ $(f6 \bullet f5 \bullet f3 \bullet f2)^{*}$	
Notes	**f1**: Knowledge Development **f2**: Legitimation **f3**: Guidance of Search	**f4**: Enterpreneurial Experimentation **f5**: Resource Mobilisation **f6**: Market Formation	
	* denotes raw coverage >60%, ** denotes raw coverage >70%, *** denotes raw coverage >90%		

Focusing only on the **Intermediate Solutions**, we can produce formula 3.6:

$$\left.\begin{aligned} f6 \bullet f5 \bullet f3 \bullet f2 \bullet f1 \\ f6 \bullet f5 \bullet f3 \bullet f2 \\ f4 \bullet f2 \\ f4 \bullet f1 \end{aligned}\right\} \leq \text{Diffusion} \tag{3.6}$$

To facilitate our analysis, Table 3.15 presents the countries with successful systems. Surprisingly, there are no outliers for any of the four configurations. Note that configuration (1) is not of great interest since the number of successes is limited and the configuration is very complex and points to a successful TIS with all functions, except entrepreneurial experimentation present.

Table 3.15 Wind TIS countries for each Configuration

	Configurations	**Successful TIS systems**
(1)	$f6 \bullet f5 \bullet f3 \bullet f2 \bullet f1$	DE, DK, ES
(2)	$f6 \bullet f5 \bullet f3 \bullet f2$	DE, DK, ES, GR, IT, SE, LU, PT, UK
(3)	$f4 \bullet f2$	DE, DK, ES, GR, IT, SE, FR, NL, AU
(4)	$f4 \bullet f1$	DE, DK, ES, GR, IT, SE, FR, NL, BE

Configuration (2) points to the necessity for four out of six functions, while configurations (3) and (4) suggest that diffusion can take place with only two functions. From these four configurations, we see that entrepreneurial experimentation is a function that requires either knowledge development or legitimation to allow efficient functioning of the system. In the absence of entrepreneurial experimentation (i.e. configurations 1 and 2), we see that at least three more functions need to operate for the TIS to work efficiently. This finding suggests that functions 3-5-6 are a substitute for function 4. This points again to the necessary role of entrepreneurs to promote the diffusion of a new technology. Also, it can be inferred that in the presence of entrepreneurs, guidance of search becomes secondary, but in the absence of entrepreneurs, guidance of search alone is not enough for the functioning of the system or for compensating missing functions. This finding indirectly shows the importance of complementarities among functions.

Legitimation seems a rather important function for wind, probably because of NIMBY effects, something which can be observed by the presence of legitimation in three out of four configurations. In the presence of legitimation, the effective functioning of the system happens either because of the very strong approval and acceptance by the public or its combination with very strong entrepreneurial experimentation.

As in the case of solar, we can identify three countries DE, DK, and ES, which are consistently successful in all configurations. These countries already have fully developed TIS, reflected by our findings here, since they appear in all four configurations associated with a developed TIS. Unfortunately, this type of analysis does not allow us to identify which functions have contributed the most to the evolution of the respective TIS. In other words, there are no coefficients for each function as it would be the case in traditional regression analysis.

A similar argument can be made about the second group of countries GR, IT and SE, all of which have fully active functions, and are consequently successful in system performance. The reason why they are not also present in configuration (1) is due to how the data were coded; for configuration (1), the mean was used as the a threshold level, while for configurations (2)-(3)-(4), the median was used. Nonetheless, we see that these three countries are relatively less successful than DE-DK-ES, since not all functions are consistently positive in both datasets, but they still remain largely successful cases with fully developed systems. Greece, for example, has been deploying wind turbines since 1983, primarily as a way of covering the needs of remote islands, but it was not until the late 1990s that diffusion really took off, primarily due to liberalization of the electricity market and reduction in the administrative barriers. Similarly, Italy shows the highest expenditure for supporting wind which has been the major contributor to the system's development. This huge mobilization of resources has attracted investors, and allowed the formation of markets, the development of knowledge and the successful operation of the TIS. Getting accurate figures for this expenditure is difficult given the complex system involved, an EU report suggests that just in 2009 "2,637.52 million euros was spent on incentives for RES" in Italy (Cortinovis et al., 2011, p.6).

Looking at Belgium, it can be argued that is unique in being the only country that belongs exclusively to configuration (4). For the system to work in Belgium, only knowledge development and entrepreneurial experimentation are necessary. This can be explained by the fact that Belgium has very limited potential for diffusion in traditional renewable energy resources (hydro, geothermal). At the same time, it is facing intense pressures from the EU to increase its production of electricity from renewables. The only renewable sources with some potential in Belgium are wind and biomass (IEA, 2009). Thus, Belgium aims to become a pioneer in wind, so that it can satisfy the general renewable energy requirements imposed on it, and for pioneers it becomes evident that knowledge development needs to be accompanied by some entrepreneurial experimentation so that the innovation can be tested and commercialised. Therefore, it could be argued that BE is a necessity-driven system, which is forced to become a pioneer by the pressures from the EU.

A similar configuration is found in Austria, which is unique in that the function complementing entrepreneurial experimentation is legitimation rather than knowledge development. In contrast to Belgium, Austria has a very well diversified balance of renewable energy, and is well developed in hydro and biomass. This implies that a market for renewables, knowledge, and resources already exists due to the diffusion of the other RETs. For such a country, what is necessary is a social push from one of the other functions to promote wind. So, in contrast to Belgium where there are almost no natural resources, in Austria almost all resources are available, and the key driver for system growth is the function of legitimation, which could potentially come by increased social pressures in favour of wind rather than other technologies.

Luxembourg, Portugal, and Great Britain represent a unique configuration. So far, there has been an implicit assumption that for a system to be successful, it needs to develop the technology and allow it to diffuse through the market, which is the main justification for including knowledge development and entrepreneurial experimentation functions. However, this configuration suggests that even if a country is not an innovator in the technology, it can still achieve diffusion and a successful TIS. For this to happen, the local technology needs to enjoy public acceptance, which leads to the establishment of supportive policy and mobilizes enough resources and helps develop markets. This suggests an alternative configuration for countries that are followers and not pioneers. So, this configuration is more downstream oriented and is driven by the use or adoption of foreign technologies which thus does not require local entrepreneurial experimentation for the new technology. Also, as we point out below, the entrepreneurial experimentation in wind is less intensive due to nature of wind technology systems.

Such a series of events can be observed in the UK and Portugal. Despite the fact that the first electricity generating wind turbine was invented in the UK in 1887, the country failed to become a pioneer in the industry, and did not achieve sustainable development in this field until the mid 2000s. Part of the delay was due to the absence of guidance, which prevented markets from forming, and lack of research funds. At the same time, public opinion was mixed, with strong support groups on the one side, but very strong local opposition. Recent polls suggest that, since the mid-2000s, public opinion has shifted strongly in favour of wind turbines, and recognitions of their importance for the UK's transition to a sustainable energy future. Looking more closely at the case of Portugal, we see a similar situation to the UK. However, the characterization of technology adopter better matches Portugal than the UK, since the UK historically has been a knowledge hub and mother to a plethora of innovations. In Portugal, diffusion started relatively early, but underdeveloped markets, lack of clear policy and complete absence of knowledge hubs and investment clusters meant the technology did not take off until the introduction of FIT in 2005, which pushed the market formation and thus led to a development of the Portugese TIS.

3.4.3 Discussion

The first observation we can make with respect to comparing the results of the bivariate analysis and the QCA is that they are almost opposite to each other. This divergence in findings can have multiple explanations. Firstly, this might be because of the linear way that statistical analysis perceives associations among the variables. This would imply that all functions of the TIS should be independently correlated with the outcome. In other words, the systemic nature of the functions and their interactions cannot be modelled in this context. A second reason is more technical and it is related to the research design. The way the dataset was compiled was not intended towards a quantitative bivariate analysis, but rather for QCA, which in turn would imply that the results produced from this correlation matrix should be viewed with some scepticism.

Turning now our attention entirely to the results of the QCA, when we examine the results of both TIS systems from a comparative perspective, the most striking difference between the two seems to be the role of entrepreneurial experimentation, which is omnipresent in the successful solar configuration, but of secondary importance in the field of wind. A potential explanation for this paradox is related to the nature of the entrepreneurial activity. We argue that the entrepreneur differs in the case of solar and wind. In the case of solar, the entrepreneur can be any individual firm with some basic engineering background. However, for wind, the capital expenditure required to set up a business, the know-how involved, and other institutional complexities (e.g. geographical issues), the entrepreneur must be either an institutional investor, a well established firm (usually a multinational), or a state-owned corporation (perhaps a public utility). Therefore, it is not that entrepreneurial experimentation as a function is not necessary, but rather that the nature of the function is different, and the way we have attempted to measure it in this work does not account for it very clearly.

Similarly, in both technologies we see different systems for pioneering countries and for followers. In the case of wind TIS, the configuration for followers is $f2 \bullet f3 \bullet f5 \bullet f6$, while for solar is relatively more simple with one less function, i.e. $f2 \bullet f4 \bullet f6$. In terms of the similarities between the two configurations, we can see that for both systems legitimation and market formation are necessary, while for wind there is also a need for resources and guidance of search. In both cases, the TIS are more downstream oriented than in the pioneers, as none of them has developed knowledge development.

The difference in the configurations for adopters is related to the costs involved. Wind systems are much more costly than solar systems, so resources are more crucial. In terms of guidance, the difference might refer to the fact that wind systems are usually first to be implemented in a country, probably because wind was developed earlier on, and was more cost competitive to conventional energy sources than solar. Some evidence in favour of this hypothesis can be seen in Table 3.10 and Figure3.8 that show that in the majority of countries, wind adoption preceded solar. Earlier adoption of wind meant that the whole set of institutions around the adoption of RETs would have to be designed from scratch when the first wind installations were made. Later, when a TIS around solar would develop, some institutions necessary for RETs would already be in place, making thus the evolution of the solar TIS a bit easier. An example of such an institution would be access to distribution networks; in many countries, before the introduction of wind, there would be no way to connect an external power source to the national grid. In other words, any electricity one would produce from a wind turbine could only be used to cover his own energy needs. As the wind TIS evolves, this situation would change, and the regulatory framework allowing integration to wind would change. Thus, when the solar TIS would start developing some years later, it would already be easier to grow since this issue would have already been resolved. Lastly, another reason for which guidance and policy agreement is more important for wind rather than solar could be related to NIMBY, which is more apparent in wind rather than solar.

Also, as discussed in Chapter 1, there is a lot of overlap between the two technologies in terms of the infrastructure necessary to integrate them into the grid. Therefore, if a country has already established a wind system, it will be easier from a technological perspective to integrate solar, thus, making guidance a less important function for solar systems.

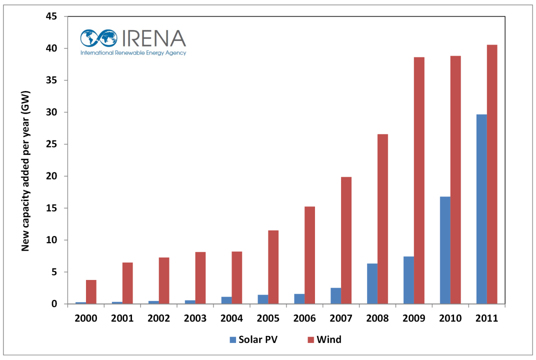


Fig. 3.8 Global Capacity of Wind and Solar PV

Source:IRENA

Lastly, legitimation seems an important function for wind, since it is present in three out of four configurations, but less so for solar. This is probably the result of the NIMBY effect related to wind, which is a barrier to the system's development, a phenomenon virtually non-existent in the case of solar. This points to technological specificities which can influence the development of the TIS, and are transfused through the importance of individual functions, something not explicitly accounted for in the current literature.

3.5 Conclusions

The aim of this Chapter was to apply the technology systems approach and identify the factors that can explain the diffusion of renewable energy, in particular, solar and wind. Having used a conventional econometric approach in previous chapters (see Chapter 2), and realizing its many shortcomings for capturing the dynamics of the diffusion process, in this chapter we adopted a more systemic approach to diffusion. In particular, we looked at the literature on innovation and argued that the diffusion of innovations is best captured by the technology system proponents.

The TIS approach to diffusion has numerous advantages since it provides us with a much clearer understanding of the dynamics and interconnectedness of the various elements of diffusion. Moreover, one of the major innovations of this framework is that it helps us to bring together all the elements that might influence the diffusion process, within six main functions. The performance of the system then is determined by the performance of these six functions.

This advantage of the framework is also the source of many of its weaknesses. There is an implicit assumption in the framework that for diffusion to take place, all functions in the system need to be fully functional. Also, the framework does not differentiate between adopter and innovator countries, as it was originally developed for new sectors, and consequently pioneering countries. There is also no consensus on the names, numbers and properties of the functions, and no clear way to measure them. Although the dynamic nature of the TIS has long been recognized, this crucial characteristic has not been formally incorporated into analysis. In turn, this lack of clarity has influenced the way the performance of each function has been assessed; in particular, no clear set of indicators has been proposed by literature. This has been exacerbated by different authors using similar indicators to measure different functions, and in some cases, the same author using the same indicators to assess the performance of different functions. Clearly, this confusion has contributed to the absence of a clear methodology, and lack of a comprehensive study on the technology.

To deal with some of the methodological problems in this approach, we proposed use of Qualitative Comparative Analysis, a methodology which combines the depth of qualitative analysis, with the clarity and replicability of quantitative analysis, and has never been used in this context. We first divided each of the functions of the system into sub-functions, and then assigned various indicators to each of the functions. We next coded these indicators and assessed the performance of each function and the system. In terms of data, we decided to investigate both the diffusion of wind and solar PV in Europe. Since both of these technologies belong to the informal group of new renewable energy, we decided to look at them in conjunction since their systems might have some complementarities.

Our analysis provided very interesting findings in the form of configurations of successful diffusion countries. In particular, we found that for a TIS to work not all functions are necessary, but rather different configurations of functions can help a system achieve diffusion of solar and wind. Starting with the results on Solar, firstly, we found that guidance of search is not a function necessary for diffusion. In other words, our findings do not suggest that guidance is absent from successful configurations, but that it has only indirect effects on the system. This is similar to the findings from Radosevic and Yoruk (2014), which show that institutional opportunities do not directly affect entrepreneurship but indirectly via technological and market opportunities. Secondly, entrepreneurial experimentation is key for the effective functioning of the TIS. Lastly, the results of our work on solar point to two distinct configurations with respect to countries which are adopters of a technology, and those that are developers of the technology, with legitimation and market formation being important for the former, while resources and knowledge development on the latter.

Looking at the findings from wind, firstly, legitimation is a crucial function for the wind TIS development, probably because of the significant NIMBY effects. Also, we discovered that even if a country is not producing the technology itself, it can still be successful in adopting it and creating a successful TIS system. Lastly, looking at individual wind TIS systems, we found that increasing pressures from elements outside the system can push a country to such an extent that it becomes not only successful in the diffusion of a technology, but also a pioneer (see for example Belgium), showing the importance of the transnationalisation of the TIS.

When looking at the systems of wind and solar in parallel, we found that entrepreneurial experimentation is more important for solar than wind. We assume this finding is related to the different nature of entrepreneurship that exists in solar compared to the wind. Another interesting finding has to do with the existence of countries which develop and adopt the technology (pioneers) and those that simply adopt the technology (adopters), configurations which exist in both the wind and solar TIS. The difference between the two systems is the role of resource mobilization, which seems more important for wind than solar (for reasons probably associated with wind's higher costs). In terms of individual functions, we see that legitimation is also more important for wind, probably due to NIMBY effects.

However, this work has some limitations, which are mostly attributable to the weaknesses of QCA. A problem with this approach in relation to configurations is that it assumes that a given combination of functions is necessary for the successful functioning of the system, irrespective of the stage of the technology. Clearly, this is counter-intuitive and hides some of the complexity of the system since it would be normal for market formation to be important in the later phases of the product life cycle compared to the earlier ones.

Another problem with using QCA is that we cannot account for variability in the performance of functions. For example, in system A, f1-f2-f3 might be operational, and the same might apply to system B. However, there is no way to identify whether the functions are operating in the same way. For example, in system A, f1 might be working more than in system B, and in system B f2 might be more active.

Lastly, an interesting point that needs to be examined further is related to the impact of each function on another, especially across time. For example, how would the system with a strong legitimation function in the niche market phase, influence the guidance of search in the next period. Unfortunately, QCA as a method is not sufficiently developed to take account of the dynamic nature of a system's evolution.

Chapter 4

Diffusion as evolution of technology systems

4.1 Introduction

Based on a number of recent studies (e.g. Hekkert et al.,2007; Bergek et al., 2008; Suurs, 2009), the diffusion of renewable energy technologies in advanced economies can be viewed as the process of establishment of Technology Innovation Systems (TIS). The idea is that diffusion is an outcome of socio-economic activities which, by mutually reinforcing each other, generate a technology system focused around the new technology. The diffusion process is thus driven by the factors of the neoclassical and the DOI approach, but the innovation of the TIS approach is that it emphasises the interrelations between these factors, and emphasis on the dynamics of the process. The TIS approach has become a standard framework to conceptualize the process of diffusion of a new technology as well as its determinants, and has been especially popular in the field of renewable energy technologies (RET).

However, there are various theoretical and practical weaknesses with this framework, which were discussed extensively in Chapter 3. The key problems include the treatment of time, which has been recognized by the literature as a key element in the evolution of a system (Carlsson& Jacobsson, 1996; Carlsson et al., 2002), but is not explicitly considered. Another issue with the TIS approach is related to the empirical and conceptual overlap between functions, and the lack of consensus on the exact number, and properties. For example, some authors argue that a system has seven main functions (Hekkert et al., 2007), while others argue for the existence of six (Bergek et al., 2005). Also, if we look at the indicators, a subsidy might be seen as part of guidance of search, but also as part of market formation. Pilot projects can be perceived as an indicator for knowledge development, entrepreneurial experimentation, guidance of search, and resource mobilisation. Lastly, although the issue of complementaries between the functions , and its importance, are acknowledged in the literature (Bergek, 2002; Jacobsson & Bergek, 2004; Edquist, 2005; Hekkert et al.,2007) there are no studies that formalize these relationships or provide an in-depth investigation of this issue.

The aim in this work is to address some of these aforementioned problems. In particular, we examine in depth how the system and its functions evolve across time, by identifying key points in time using the life-cycle models. We argue that this is a key omission of the original literature; the nature of the functions, the way the interact with each other, as well as the complementarities between them varies according to the stage of the technology in question. Examples of such functions are entrepreneurial experimentation and guidance of search, both of which operate differently as the technology matures. At the early stages of the life-cycle, the aim of the entrepreneurs is to test different designs, and for the government to guide them towards the most appropriate technology. As the technology matures, the entrepreneurs become suppliers and producers of the technology, and their role becomes more diffusing the technology rather than experimenting with them. Similarly, the government does not have to guide entrepreneurs, but it is to maintain the proper functioning of the market. Lastly, in this work we address the issue of complementarities between the functions and try to identify how different functional configurations operate at different points in time and how they influence system performance.

The main theoretical contribution of this chapter is that it deals with the evolutions of the functions of the system across times. This deals with one of the most important, in our opinion, shortcomings of the TIS framework. In particular, the concept of time and how it influences the TIS has been recognised by the literature (Carlsson& Jacobsson, 1996; Carlsson et al., 2002). However, the main TIS literature does not introduce a dynamic TIS, but rather it approaches it as a static framework. To achieve this, we use four case studies of countries which adopted Solar PV; these are Germany, UK, Czech Republic, and Greece. We selected these four countries as they represent good extremes of time to adoption, and extent of adoption. In particular, both Germany and the UK were some of the first countries to adopt Solar PV, with former being considered a success and the later a failure. Similarly, Greece and the Czech Republic were both late to adopt; however, the latter was considered a "miracle" adopter, while the former relatively unsuccessful.

To achieve our aim, Section 2 starts by examining how the literature has treated the element of time, and how our research differs and contributes to the literature. Moreover, we provide a clearer definition to the concept of legitimation, as we consider it to be a vital initial condition for a successful TIS development. Then, in Section 3 we discuss the rationale behind the use of the case study methodology and how the cases were selected, while in Section 4 we proceed by analysing the evolution of the Solar PV TIS and its functions across four countries; Section 5 summarises the key findings from our work, and in Section 6 we conclude.

4.2 A Dynamic Model of TIS Evolution

The absence of the time element from the TIS has been already identified and challenged by several scholars, such as Hekkert et al. (2007), Jacobsson and Bergek (2004; 2011), and Dewald and Truffer (2011). These authors recognize that the importance of functions for the emergence and evolution of the TIS varies across time, especially given the dynamic nature of technology, and in their work they attempt to investigate how these vary. The dynamic element of TIS adds another layer of complexity into the analysis, and make the dynamics of the innovation process difficult to map and identify. This is arguably the main reason why this type of analysis has not been widely used in most of the TIS literature, but rather it is focused on the static analysis of the system, a problem also commonly found in national innovation systems work (Hekkert et al., 2007). One of the problems with dynamic analysis is that there are too many elements in the system changing continuously, and becomes impossible to model all of them. This means excluding some elements, running the risk of missing vital information.

Looking more closely at the literature, we can start with Jacobsson and Bergek (2004; 2011), who in their earlier work suggest that the TIS evolves across two stages, the formative phase and the market expansion phase, without however making an explicit discussion of how each of the functions will vary across the phases. Rather they only focus on what events take place in each period, and try to identify different blocking mechanisms for different period that might influence the system's performance. In their later work, they make some explicit references to some functions, especially the 7th function, of positive externalities and how it becomes more important after all the other functions are well established. Nonetheless, they make little systematic attempt to see how the TIS evolves across time.

Hekkert et al. (2007) emphasize the dynamic nature of the functions, and the fact that some might be more important than others in different time periods; they illustrate this by mapping events and processes for each function across time. However, they do not deal with time adequately. In particular, their paper is more on methodology, rather than tracing how the system changes across time. Moreover, they do not explicitly examine the evolution of a particular system and technology, but rather use examples from various TIS in every function. For example, for legitimation they use the German biofuel, for market formation the German and Dutch biofuel systems, and for guidance of search policy for RETs in California. Lastly, they fail to identify how the functions evolve overtime, and also if and how the complementarities between the functions of the system change across time.

Lastly, Dewald and Truffer (2011) hypothesize that the mechanisms behind the market formation function are different in mature markets. In particular, in their work they conceptualise the development of market structures in the TIS context, and examine how the interactions between the market segments that constitute the market formation function vary according to the maturity of the technology. They apply their conceptual framework to solar PV markets, and find that the market formation process does not follow a linear model, as this is the case in other areas (Geroski, 2000; Baskerville and Pries-Heje, 2003). The weakness of this paper is that it focuses only on one function of the TIS and not the whole system.

Differently to the previous work on the dynamic TIS, in this chapter we will explore how *all* of the functions of the TIS will evolve across time, and we will do this in conjunction with the product life cycle theory. Life-cycle models gives us theoretically justified points in time that we should expect the behavior of the functions of the system to defer. In particular, we separate the development of a product into four distinct phases, and then investigate which TIS functions are active, how they interact with each other, and how these then influence the functioning of the TIS. To achieve this, we plan on using four case studies, a method which is discussed in details in the next section.

4.2.1 Legitimation: a vital condition for the successful TIS

As we argue throughout this Ph.D., the importance of the diffusion determinants, as well as the role of the functions of the TIS, vary as the technology evolves. A function which the literature considers vital for the evolution of the TIS from its early development is that of legitimation (e.g. Aldrich & Fiol 1994; Van de Ven, 1993; Rao 2004; Bergek, Jacobsson and Sanden, 2008). In this work, we support the literature's claim, and therefore will briefly discuss the idea of legitimation, how it operates, and how to measure it.

In broad terms, the legitimation function captures those elements of the TIS that contribute towards technology's social and political acceptance. In the earliest stage of the TIS evolution, legitimation can be perceived as all the events that could potentially lead to a change in the perceptions of the actors of the TIS on the technology. In particular, the legitimation function tries to instill in the other players in the system the idea that the new technology can become a viable alternative to established technologies and that it is acceptable for the existing institutions. This change in perceptions would then be able to improve the political and regulatory environment, which will allow the development of institutions conducive to the new technology and thus enable the evolution of a successful TIS.

Various indicators can be used to measure the performance of the legitimation function[1]. Some authors have used official statements in favour of the technology or against competing technologies, the incidence of public protests against a particular system[2], opinion polls and lobbying organisations, as well as demonstration projects suggesting the feasibility of the technology. Another example specific to a TIS in RETs is the establishment of a Green party, an active lobby and support group for the TIS in question.

From the above discussion and the suggested indicators, it becomes evident that there is some overlap between the legitimation function and other functions, especially that of guidance of search. Guidance of search is the function that encompasses all events that could contribute towards the direction of the actors towards the particular technology of the TIS and against established technologies. For example, a policy document demonstrating the commitment of a government in favour of RETs, in general, can be considered both an indication of legitimation and guidance of search. It is an indication of legitimation as it aims to create acceptance for the new technology in the system. However, it is also an attempt by the government to signal its support towards new technology and thus guiding researchers and entrepreneurs towards the new TIS. This problem of one indicator being used to represent activities of more than one functions is a recurring issue in the literature of TIS[3]. It is an inevitable outcome due to the conceptual openness of the functions as categories, as well as their interconnectedness.

Our approach to this issue comes from the selection of method used in this chapter: case studies. Given that they are qualitative in nature, the overlap between functions and indicators is not an issue of great concern, as there is no risk of having multicollinearity or other similar problems. With case studies, we are given the opportunity to present and discuss exactly how each indicator contributes to the performance of each function at each stage, and also understand how this indicator at the same time can influence another function. Therefore, if discussed appropriately, a single indicator can contribute

[1]For a more detailed list of indicators used in the literature to measure the performance of the legitimation function, see Appendix C.9.

[2]An example of such protests can be found in the field of RETs, with environmental protests against fossil fuels being an example which would strengthen the legitimation function of a RETs system.

[3]For a more extensive discussion of this issue, please see the discussion on weaknesses with TIS literature in Chapter 3.

to more than one function.

Another reason this problem is not a major concern in this work has to do with our aims. In particular, we are not trying to establish a direct link of causality between one event and diffusion, but rather to understand the mechanism through which one event can influence the functions, which can then contribute towards the development of the TIS, and eventually the diffusion of the technology. The next section focuses on discussing the case study methodology, and further illustrate its appropriateness for this work.

4.3 Conducting a Case-Study Analysis

Case studies are an excellent analytical method when the aim of the work is to answer the "how" and the "why" questions. The key to case studies is the creation of a narrative. In our work, the aim is to identify how the TIS evolves over time, and why does the evolution takes place; i.e. why the interactions between the functions vary across time. Therefore, our work has an exploratory, descriptive, and explanatory purpose, something which is in line with the aims and objectives of case study research (Yin 2003).

To be more precise, Yin (2003, p.13) suggests that a case study is "an empirical inquiry that investigates a contemporary phenomenon in its real-life context, especially when the boundaries between phenomenon and context are not clearly evident, and multiple sources of evidence are used". In this way, the researcher can maintain the link with reality and avoid unnecessary simplifications and abstractions from the real world cases. The more holistic approach to case studies can thus help identify better causal links between phenomena of interest.

One of the greatest strengths of this method of analysis is its ability to analyse a phenomenon for which there are many more variables of interest than data points available. In this context, to analyse the various functions, multiple indicators could potentially be used (see Appendix C.9) while only a limited number of countries and data sources. To put this into perspective, if we assume that we have six functions, and for each function there are on average fifteen indicators, this gives a total of 90 independent variables. As a rule of thumb, one would need at least ten observations for each independent variable, which makes a total of 900 cases. Clearly, this is not only impractical but also impossible given the number of countries in the world.

Another advantage of using case studies is their ability to combine both quantitative and qualitative data, and explain social phenomena which are too complex for survey or experimental strategies. This issue is particularly valid for our work, as the TIS can be viewed as a complex system with multiple interactions between its elements. So, to capture the performance of these elements, it is necessary to have a wide variety of both quantitative and qualitative data.

As with all methodological approaches, there are some weaknesses in the use of this method. In one extreme, there is the work of Miles (1979) who argues that qualitative data are an attractive nuisance. In particular, it could be argued that case studies can be very time consuming in their data collection process, and even if we collect sufficient data, it might be difficult to generalise from them. We recognise the difficulties with data collection, and for this reason, we decided to focus only on one technology solar PV.

Another issue is related to selection bias or a situation whereby the selection of cases are focused either on one outcome (e.g. only successful adoption of technology) or have a very narrow range of variation (Collier & Mahoney, 1996). To avoid this bias, we decided to pay much attention to our selection of countries, an issue discussed in the subsequent section.

4.3.1 Selection Criteria for Selection of Cases

Our choice of countries was not random; we have tried to choose four extreme cases in terms of the success of diffusion and speed of adoption since both the element of time and the amount of solar electricity produced are crucial for the diffusion. To identify success, we avoid the complexity of the methodology used in the previous chapter and use solely solar PV per capita as an indicator (Figure 4.1). This indicator is commonly used to assess the extent of solar PV diffusion (Denholm & Margolis 2007). Then, to distinguish between successful and unsuccessful countries, we use the mean and median of the values as a cut-off point. This method leads to Tables 4.1 and 4.2.

Another important element in our work is time, and as we identified in the previous chapters, we have the dominant design as a key point in technology's evolution. A crucial point, therefore, is to determine if the country first adopted the technology before the emergence of the dominant design of after. As we discussed in the introduction, the dominant design for solar PV can be argued to have emerged in the early 2000s. So, we will make a binary distinction between early adopters, and late adopters, with the former being those countries which adopted the technology before 2000, and the late those that adopted after 2000 (see Table 4.3).

Combining the above two selection criteria, we produced Table 4.4. To avoid the selection bias and be as representative of the sample as possible, we decided to select one case from each category. In particular, we decided to select Germany, which has achieved the greatest diffusion and is an early adopter. The UK is an early adopter but performed poorly regarding relative diffusion. Greece is an example of a late adopter, but relatively

Table 4.1 Successful vs. Unsuccessful (using mean)

Successful	Unsuccessful
Belgium	Austria
Czech Republic	Bulgaria
Germany	Cyprus
Italy	Denmark
Spain	Estonia
	Finland
	France
	Greece
	Latvia
	Luxembourg
	Netherlands
	Portugal
	Romania
	Sweden
	UK

Table 4.2 Successful vs. Unsuccessful (using mean)

Successful	Unsuccessful
Austria	Cyprus
Belgium	Denmark
Bulgaria	Estonia
Czech Republic	Finland
France	Latvia
Germany	Netherlands
Greece	Portugal
Italy	Romania
Luxembourg	Sweden
Spain	UK
Sweden	

Table 4.3 Early vs. Late Adopters

	Date of Solar Adoption	Status
Austria	1993	Early
Belgium	2004	Late
Bulgaria	2008	Late
Cyprus	2006	Late
Czech Republic	2006	Late
Denmark	1999	Early
Estonia	2011	Late
Finland	1991	Early
France	1994	Early
Germany	1990	Early
Greece	2001	Late
Italy	1990	Early
Latvia	2011	Late
Lithuania	2012	Late
Luxembourg	2003	Late
Netherlands	1992	Early
Portugal	1990	Early
Romania	2010	Late
Slovakia	2009	Late
Spain	1990	Early
Sweden	1993	Early
UK	1999	Early

unsuccessful, since it is only unsuccessful if we use the mean[4]. The Czech Republic was chosen as a representative case of late, but successful adoption. In population terms, Greece is slightly larger than the Czech Republic, and Germany is slightly bigger than the UK. Furthermore, regarding levels of economic development, these pairings are quite comparable.

Table 4.4 Success and Timing

Country	Timing	Success (mean)	Success (median)
Austria	Early	Unsuccessful	Successful
Belgium	Late	Successful	Successful
Bulgaria	Late	Unsuccessful	Successful
Cyprus	Late	Unsuccessful	Unsuccessful
Czech Republic	Late	Successful	Successful
Denmark	Early	Unsuccessful	Unsuccessful
Estonia	Late	Unsuccessful	Unsuccessful
Finland	Early	Unsuccessful	Unsuccessful
France	Early	Unsuccessful	Successful
Germany	Early	Successful	Successful
Greece	Late	Unsuccessful	Successful
Italy	Early	Successful	Successful
Latvia	Late	Unsuccessful	Unsuccessful
Luxembourg	Late	Unsuccessful	Successful
Netherlands	Early	Unsuccessful	Unsuccessful
Portugal	Early	Unsuccessful	Unsuccessful
Romania	Late	Unsuccessful	Unsuccessful
Slovakia	Late	Unsuccessful	Successful
Spain	Early	Successful	Successful
Sweden	Early	Unsuccessful	Unsuccessful
UK	Early	Unsuccessful	Unsuccessful

Our analysis is similar to the work by Jacobsson et al. (2004), which splits TIS analysis into two phases according to the maturity of the solar cell technology. We break it down into four time periods based on the stage of the technology's lifecycle. For three of the cases, the same time periods are used as we wanted to be consistent with the global evolution of the TIS, because the timing in three countries coincides with global evolution of the TIS. The exception is the niche market phase in Germany, which started slightly earlier than in the other countries, probably because Germany was a pioneer in

[4]This country was preferred to ones with very low diffusion levels as these would not have enough data to allow a testing of the TIS evolution

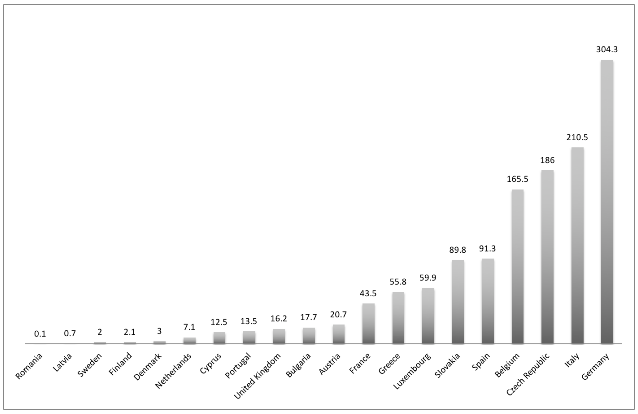


Fig. 4.1 Solar PV per capita (2011) (Wp/inhabitant)

Source: Eurobarometer

solar PV. Moreover, we assume that the dominant design is a universal phenomenon and emerges in all countries at the same time period, which was identified in Chapter 1. Then, for each period, we provide a summary of system performance as well as the key functions operating in this period and then continue by looking at the performance of each function in detail. Also, at the end of every phase of the case studies, we provide a schematic representation of the interactions of the functions for that period, together with conclusions about the system performance in that phase.

4.4 Investigating the Dynamics of the TIS Evolution

4.4.1 Germany: The Early And Successful

We start by analysing Germany, the most successful EU country for diffusion of solar PV, and the most researched. The introduction of solar PV in Germany was in the 1970s, but the technology did not take off until the late 1990s followed by dramatic increases towards the mid 2000s as depicted in Figure 4.2.

Emergence of Technologies (1970s-1990)

The first major push towards renewables came as a result of the oil crises in the 1970s, which created a need for energy independence and a move to non-fossil energy sources. At that time there were two options: nuclear and renewable energy. Given the status of the technologies, the Germans chose nuclear. However, the Chernobyl accident in 1986 turned the public opinion against use of nuclear and the emphasis was directed to

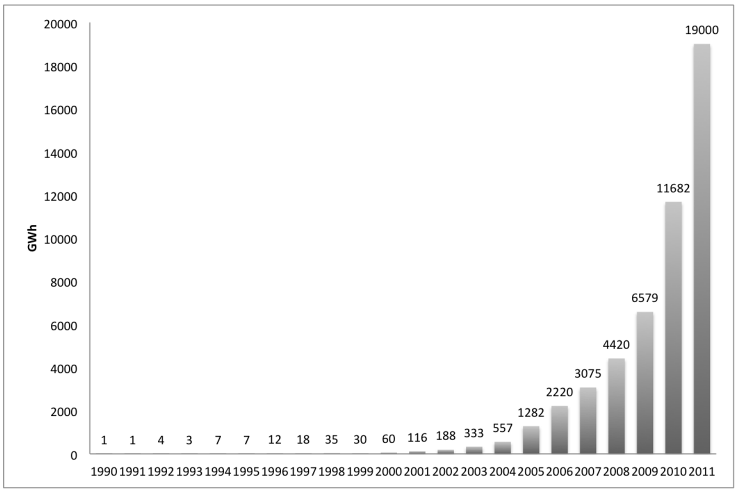


Fig. 4.2 Electricity Output from Solar PV in Germany (1990-2011)

Source: IEA

renewable energy, particularly solar and wind. In terms of the functioning of the TIS, we see that the following functions were very active: legitimation, knowledge development and resource mobilization.

Knowledge Development Numerous industry and academic institutions were established during this phase, and engaged in research on PV. The academic research centres included the Institute for Solar Energy Research Hameln (ISFH) in Hameln established in 1987, the Zentrum für Sonnenenergie in Stuttgart and the Institut für Solare Energieversorgungstechnik (ISET) in Kassel, both founded in 1988. In 1981, the Fraunhofer ISE institute was established in Freiburg as the first non-university affiliated research institute for solar energy systems. Industry players included Wacker Chemie, Siemens, Interatom and AEG-Telefunken who were the forerunners (Räuber, 2005, p.155). In addition, the public energy utilities were also involved in the research in the field. RWE was involved in the construction in 1980s of Germany's first PV power plant on the island of Pellworm. However, no major advances in technology can be observed until the beginning of the 1990s (BINE, 2003, p.4) .

This increased interest among researchers and research institutions is evident in the number of their publications (Figure 4.3), particularly since the late 1980s, and the intense patenting activity in the field of solar technologies (Figure 4.4).

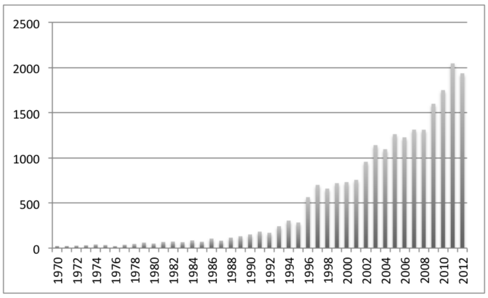


Fig. 4.3 Number of Papers in PV area generated by German Institutions (1970-2012)

Source: Scopus

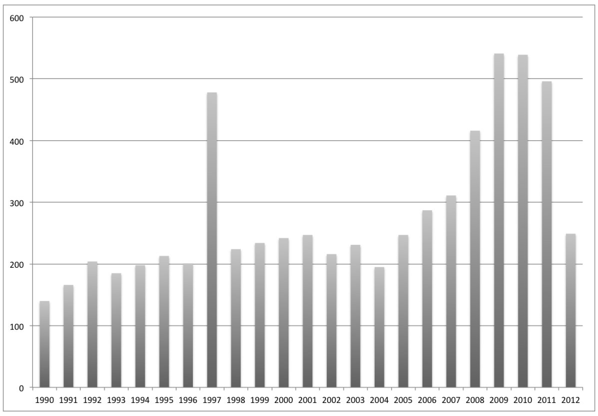


Fig. 4.4 Patents for Solar PV by German Authors (1989-2012)

Source: PATSTAT

Legitimation In this early period many events contributed to strengthening this function, and several institutions supported the development of renewable energy generally, and solar PV in particular. These included solar associations, and industry and academic institutions. The most influential lobbying institutions were the solar associations, which later actively promoted the diffusion of solar energy. Among other things, they were responsible for shaping public opinion to favour solar and later contributing to policies such as the concept of cost-covering compensation[5]. The solar institutions included EUROSOLAR (1988), the German Society for Solar Energy (DGS) (1975), and the German Association for the Promotion of Solar Power (SFV) (1986). The industry associations include the Association of Solar Energy SMEs (Verband mittelstandischer Solarindustrie e.V. – VSI), founded in 1979, which later became the German Solar In-

[5] A forerunner for the Feed-in Tariff, whereby the grid operators and local suppliers will have to reimburse suppliers a certain amount for every kWh fed in the system

dustry Association (Deutscher Fachverband Solarenergiee.V. – DFS) (1986). Academic associations include the Institute of Ecology founded in 1977.

The strength of the legitimation function can also be observed by looking at the environmental protests in this period. As we can see in Figure 4.5, in the late 1980s the number of protests were very high, and they were mostly related to energy (Figure 4.6). This provides further evidence that the legitimation function was very strong in this early period of the TIS evolution.

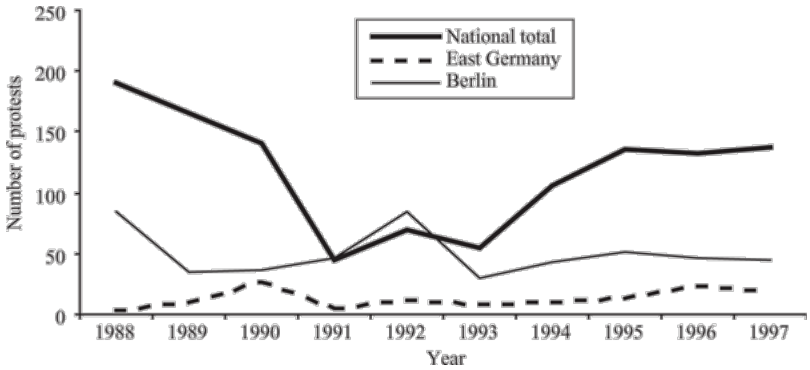


Fig. 4.5 Environmental Protests in Germany

Source: Rootes 2003

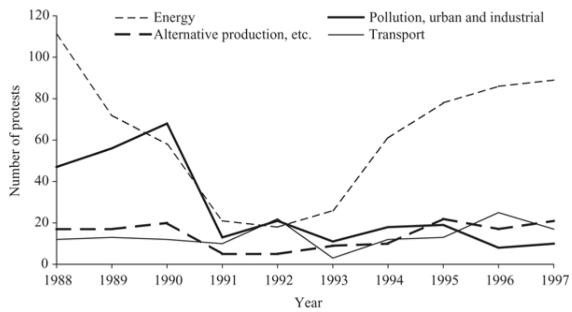


Fig. 4.6 Environmental Issues Raised by the Protests

Source: Rootes 2003

Guidance of Search The government initiated several demonstration projects which were conducted over the period. One was the factory in Pellworm established in 1983; it was a pilot plant, using cells manufactured by AEG. The plant, which was financed entirely by federal research funding (Jacobsson et al. 2004, p.18), was the largest plant in Europe at the time, with an output of 300 kW. In 1985, the Federal Research Ministry launched a demonstration programme that involved the use of PV technologies in various small scale installations such as ocean buoys, street lamps, and street signs ((Brüns et al., 2010, p.171). A similar programme, which also involved the Philippines, was launched in 1982.

In relation to government's expectations, various studies were published during this period that demonstrated the benefits of solar PV over other non-renewable and nuclear resources. For example, the 1983 Federal Ministry of Research and Technology report describing the benefits of renewables over plutonium (New Scientist, 1989), and the 1986 report produced by the German physical society (Bhargava, 2004) and the report from the German Bundestag's Enquete Commission on Preventive Measures to Protect the Earth's Atmosphere (Schmidbauer and Hartenstein, 1991). Attitudes to solar and renewables generally were further strengthened by the foundation in 1988 of the Intergovernmental Panel on Climate Change (IPCC) by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP).

Overall, this period was characterized by strong policy orientation towards RET led by federal research funding , and we can thus conclude that the function was fully active.

Entrepreneurial Experimentation Some initial levels of entrepreneurial experimentation can be observed, albeit in no great extent. Already since the 1960s, Siemens, Wacker Chemie, and AEG-Telefunken began to manufacture silicon cells for the space industry. The first satellite with AEG solar cells was AZUR 1 in 1968 (Räuber, 2005, p.154). However, due to the complex manufacturing process used (Czochralski process), the main customers remained the space industry, and thus the technology failed to commercialise. This lack of major entrepreneurial activities in this period is primarily due to the lack of commercially viable technologies.

Resource Mobilisation An important mobilization of resources towards R&D can be observed in this period, evident in the government decision to fund research in the field of solar technologies by supporting various universities and research institutes (1977 to 1989). This mobilization is evident in the amount of resources devoted to solar energy developments, particularly on the research side (see Figure 4.7). Specifically, spending on solar R&D in absolute terms increased dramatically from 1979 onward and also increased in relative terms - in the early 1970s almost 100% of funding for renewables went to solar.

This spending was channelled mainly through the First Energy Research Programme (1977-1980) of the Federal Research Ministry and a programme focused specifically on solar PV, called "Technologies to Harness Solar Energy". The objective of this programme was to improve PV base materials, mainly for handheld devices rather than household use. The Second Energy Research Programme (1981-1989) was focused on research on thin-film solar cell production, and aimed at reducing the production costs of silicon manufacturing.

At state level, there were some funding initiatives, the most prominent being the programme established in North-Rhine Westphalia. This began in 1987 and is still running, and came to be known as the programme for "Rational Energy Use and Use of Inexhaustible Energy Sources" (REN). Its aim was to promote renewable energy sources in general, but its funding was targeted mainly to solar panels[6]

Thus, the resources mobilized in this period were very significant, which suggests a very strong activity. Interestingly, looking at the number of papers and patents produced we can also see a gradual increase in both these indicators, although the increase was not as dramatic as the increase in spending. This lack of direct correlation could potentially be explained by the cumulative character of technology, whereby increasing spending in one period does not necessarily lead to an increase in the amount of papers and patents in the same period, but as more and more spending gets devoted to the technology eventually patents and paper tend to emerge.

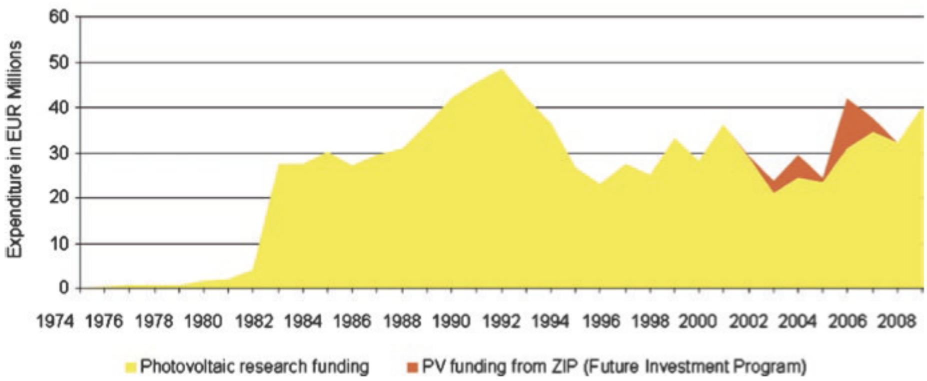


Fig. 4.7 Annual R&D Funding in PV in Germany (1974-2008)

Source: (Brüns et al., 2010, p.165)

[6]Up to 2007, 26,000 solar panel systems with a collector surface of 225,000m^2, and 11,000 photovoltaic systems with an installed capacity of about 65,000 kW photovoltaic systems were installed (Brüns et al., 2010, p.172).

Market Formation There is nothing to be said about this function since there was no commercialization of the technology to a level that would suggest this function was active.

Conclusions from this phase The KD function is very developed with a plethora of research institutes, universities, and even business engaged in solar R&D. Similarly, LE was very active, with institutions specifically targeted towards promoting solar. Some of these institutions were also providing a platform for R&D development, so we can see a very strong complementarity between KD and LE, allowing us to argue that there is a two way relationship and interaction between these two functions.

In combination with KD and LE, we see that the government was also favouring solar, by initiating projects which were specifically targeted to solar PV, but also by participating in research that was geared towards investigating the potential of solar PV over other renewables. Thus, it could be argued that KD and LE are influencing GS, but are also influenced by GS. Stronger GS led to greater resource mobilisation, which in turn promoted knowledge development .

Although there was not a great number of new firms entering the solar PV market, existing firms were experimenting and producing some solar cells, but since the technology was not advanced enough to be commercialised, no major developments in EE and MF can be observed. We can argue that EE was influenced primarily by GS, rather than any other functions. Diagrammatically, the behaviour of the functions can be seen in Figure 4.8.

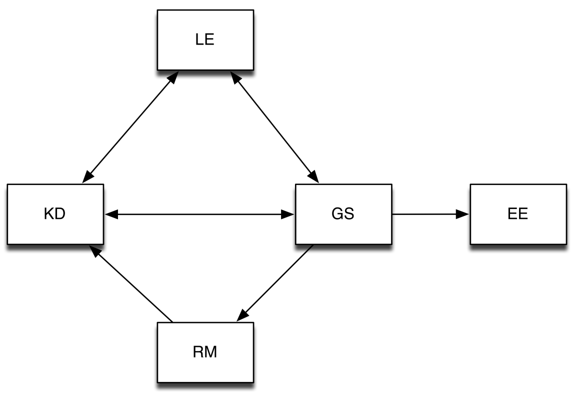


Fig. 4.8 TIS evolution in Germany in Emergence of Technologies

Niche Market (1991-2000)

This period is characterized by the introduction of the Act on Supplying Electricity from Renewables (Stromeinspeisegesetz - StrEG), a decrease in the world oil price, and the 1000 Rooftops programme. Despite these conflicting dynamics, the foundations for the establishment of solar PV market were set in this period, and some attempts were made to commercialize the technology. However, there were still multiple competing designs, an underdeveloped manufacturing base, and a great deal of experimentation, justifying our characterization of this phase as niche market in the field of RETs. All activities were present, although market formation and legitimation were relatively weaker.

Diffusion in this period can be attributed primarily to the 1,000 Rooftops programme. This programme can be judged a success; it achieved significant diffusion of solar PV while simultaneously demonstrating the feasibility of using grid-connected solar systems in small scale installations, despite some initial technical problems with inverters. It also involved private households in the process of solar electricity generation, and stimulated further research, especially in the field of materials development and manufacturing technologies (Brüns et al., 2010, p.183). However, both the installation (around 10,000 to 12,000 euro/kWh) and the electricity generation costs (over 1 euro/kWh) remained high (Brüns et al., 2010, p.181), which prevented further diffusion of the technology.

Knowledge Development The main developments in this period arise from the 1,000 programme, and all the improvements were mostly targeted towards inverter technology (Brüns et al., 2010, p.190). Inverters are key for the integration of solar PV to the grid. By developing this technology, there would be no major hindrances afterwards in the formation of a mass market for solar technology, as this would allow for solar PV to be integrated to the grid. Moreover, we see a gradual increase in the number of patents (Figure 4.4) produced and the number of papers (Figure 4.3). What is particularly interesting is the sudden rise in the level of patent applications in 1997. This can be considered the result of the 1,000 rooftop program which acted from the previous five years, and largely served as a demonstration project. This also include a local content requirement (Eichelbronner and Spitzley, 2012), which meant that only German firms could get involved. The result of this program was an increase in the number of activities around Solar PV, which consequently led to numerous innovations, which the innovators wanted to comercialise and protect. Overall, we can thus conclude that this activity remains strong.

Legitimation There are two main opposing forces in relation to legitimation. On the one hand, we observe a strengthening of the function through loss of momentum among pro-nuclear groups driven primarily by the Social-Democrats' change of attitude, especially after the events in Chernobyl; at the same time, renewable energy was finding support from the Green Party, the Conservative CDU/CSU parties, and the Association of Small Hydro generators. In 1998, the Green Party gained control in the parliament by entering a coalition with the SDP. Also, Germany's signing of the Kyoto Protocol in 1997 further reinforced the country's commitment to green energy and, thus, strengthened the legitimation function.

On the other hand, a weakening of the system is observed through the various adverse reactions from the established electricity players such as the German Association of Electric Utilities (VDEW), Preussen Elektra, RWE, E.ON, Vattenfall Europe, EnBW and the rest of the electric utilities industry. They were unhappy about the promotion and "unfair" subsidization of the renewables industry by the German state. Eventually, this led in 1996 to a formal complaint to the EU Competition Commission against the StrEG, but this met with little success (European Court, 2001).

In this period there was also a fall in oil prices from around 60USD to 20USD (see Figure D.1 in Appendix D.1). Clearly, this decreased the price attractiveness of solar installations and led to a further weakening of the legitimation function. In the meantime, the Solar Energy Research Association (FVS) was founded (1990). This brought together all the research institutes that were not part of the academic system, and aimed to unite their strength and influence and promote the interests of PV. FVS became the focal point for the research, business and politics of PV.

Overall, these opposing forces led to a weaker legitimation function compared to the previous phase, but it still remained significant

Guidance of Search This function was the most active in the German solar TIS in this period. The ultimate example of guidance of search was the 1000 Rooftops Photovoltaic Programme, which imitated the Swiss 333 Solar Programme,[7], which began in 1991 and lasted until 1995. It was equivalent to a large scale demonstration project, which aimed at testing the existing solar PV technologies, and reviewing the potential for solar PV in small grid installations. It worked by subsidizing the installation of Grid connected PV

[7] The project in Switzerland ran from 1989 to 1990 and aimed at the installation of 333 3-kW roof systems, amounting to total installed capacity of 1 MW.

with a capacity between 1-5 kW on Roof Tops, only for Single and Two Family Houses. The subsidy was 70% of the project's total cost, and the responsibility was shared between the Federal (80%) and State (20%) governments. The programme also included a local content requirement, according to which only installations from German producers were supported, although PV modules could be imported. The programme was very successful, and achieved installation of more than 2,000 PV installations with an overall capacity of 4 MW (see Figure 4.9). Its success was so great that it was extended to 2,250 installations on the pretext of including the former East German States (IEA, 1999; Stryi-Hipp, 2005, p.183).

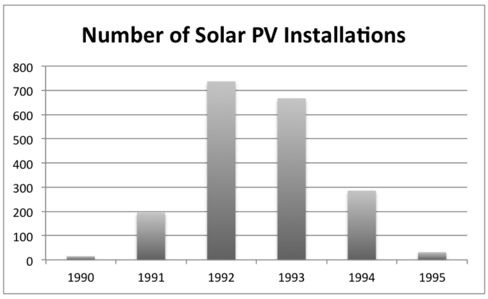


Fig. 4.9 The effectiveness of the 1,000 Rooftops Programme)

Source: (Eichelbronner and Spitzley, 2012)

The popularity of the 1000 Rooftops programme was an incentive for some states, including Baden-Württemberg, Berlin, Hamburg and Hessen and Saarland among others (Staiß, 2003), to launch similar programmes. In addition, the industry launched some initiatives, for example, the energy supply company PreussenElektra financed 450 school rooftop installations with the same capacity, as part of the Solar Energy Online programme (Sonne online) in northern Germany (Brüns et al., 2010, p.190). Furthermore, from 1994 to 1996, as part of the Solar Energy in Schools (Sonne in der Schule) programme, Bayernwerk provided funding for 544 PV installations, with a capacity of 1 kW each (Brüns et al., 2010, p.189).

Apart from the demonstration programme, in 1991 the Act on Supplying Electricity from Renewables (Stromeinspeisegesetz - StrEG) came into force. This proposed the introduction of a subsidy to renewable energy producers - the FITs. These were primarily targeted to wind and hydro producers, and the subsidy for solar PV was too low to make it competitive with the other RETs[8]. In the 1990s, this resulted in payments of less than

[8] In particular, the subsidy for solar electricity was set at at least 90% of the average revenue per kilowatt

10 cents/kWh, while the costs of producing the electricity at that time amounted to 1 euro/kWh" (Brüns et al., 2010, p.181). However, the act also included provisions that guaranteed connection of decentralized electricity systems to the grid, thus establishing an important framework condition for the technology's further development"(Brüns et al., 2010, p.179).

Further guidance towards renewables in general was given by the German Federal Government's climate protection programme and by the UN Conference on Environment and Development held in Rio. The latter proposed The Framework Convention on Climate Change which in 1994 imposed internationally binding commitments to carbon dioxide (CO_2) reduction and signalled a future energy sector using more sustainable energy sources.

Entrepreneurial Experimentation The 1,000 Rooftops programme and its local content requirement gave some scope for entrepreneurs to enter a market that was dominated by the subsidiaries of big companies (e.g. RWE, Siemens, ARCO, DASA) which had launched pilot projects in the previous period. This is depicted in Figure 4.10, where we can see a relative increase in the number of new entrants. However, only two of Germany's major module manufacturers (ASE and Siemens) were still active in 1996, a sign which suggests some consolidation taking place in the industry. Therefore, we can argue that in this period we see the first signs of entrepreneurial activity primarily driven by the 1,000 Rooftops programme.

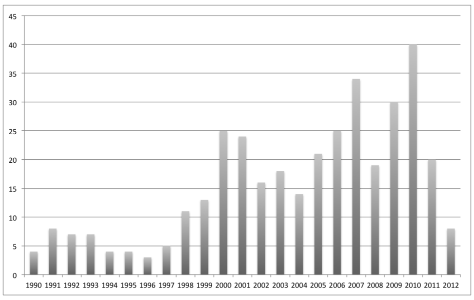


Fig. 4.10 Number of New Entrants in the Solar PV Industry

Source: Amadeus Database

Resource Mobilisation Funding for research into PV was maintained at similar levels (see Figure 4.7) and primarily came from the Federal Government's Third Energy

hour generated from the sale of electricity by utility companies to all final consumers.

Research Programme (1990-1995) and the Federal Ministry of Economics 100-Million Programme, which planned to allocate funding to PV amounting to 10 million euros over a four-year period. However, towards the end of the 1990s, there were plans to discontinue funding for solar research (Brüns et al., 2010, p.181), but various regional initiatives kept the market going. An example is the REN programme in North-Rhine Westphalia.

At the same time, the "New Economy" was growing and giving private investors increased appetite for risk, and motivating investments in high risk high return companies. Solar companies were in this category and were trading on the "Neuer Markt", a special segment of the Frankfurt Stock Exchange. This development greatly facilitated the raising of funds for solar companies, which stimulated new entrants (see Figure 4.10).

In addition, various collectives and associated companies were created in this period, aimed at pooling funds to invest in expensive solar projects. One of the first solar collectives was led by Hans-Josef Fell and established in 1994 (Fell, 2007) and in that year, "the energy and solar agency Energieagentur Regio Freiburg developed the concept of a community PV plant and offered shares in the Regio solar power plant at a price of 10,000 German mark per 500-watt share" (Stryi-Hipp, 2005, p.184). These projects were motivated by the culture, ideals and attitudes of users to sustainable development, rather than from the economic benefits promised by the current state of the technologies (Mautz and Byzio, 2005, p.40).

Last but not least, increased funding resources for solar PV were also provided through the StrEG and it FiT program, as we discussed in the guidance of search section.

From all the above, we can see that see that resources were mobilized through several schemes, including federal subsidies, stock markets and a range of NGOS funding, and we can conclude that this function remained very strong in this period.

Market Formation Cost-covering compensation and similar funding models were introduced in a number of municipalities from 1993. These programmes, instead of financing the construction phase of solar PV installation, allowed for compensation to the producer once the electricity was fed into the public grid. Thus, financiers were pushing the market to develop. Also, the 1000 Rooftops programme demonstrated the feasibility of using grid-connected solar systems in small scale installations, despite some initial technical problems with inverters. Lastly, the FiT although decreased the costs of solar systems and thus increased their attractiveness, it did not make them competitive enough with conventional energy sources.

Some weakness in the supply from local producers can be observed, given that most PV modules were imported mainly from the USA. At the same time, funding dried up after the 1000 Rooftops programme, which did not allow the infant German solar industry to grow (Kreutzmann, 1997, p.3). The key element in the market formation activity was the cost of installations, which remained prohibitively high[9].

Therefore, we can say that this activity had started operating, but was entirely dependent on state subsidies which were aimed at testing the feasibility of PV. Therefore, we can conclude that this function, although active, it was far from fully functioning.

Conclusions from this phase KD was focused on the commercialisation of the technology, and was very effective as we can see from the number of patents and papers produced. This was greatly influenced by GS which promoted the 1000 Rooftops demonstration project. This gave the opportunity to entrepreneurs to experiment with the technology. Therefore, we can see that there is an interaction between these three functions. GS influences KD and EE. At the same time, GS is influenced by KD, since the government is interpreting the findings of the institutes as a sign on whether or not to promote the technology. KD is also influencing EE as there are various patents which are used by entrepreneurs, but are also generated by entrepreneurs.

At the same time, GS also influences MF and RM. This happened since the government introduced FiT, which managed to increase the price competitiveness of solar, but was not enough to stimulate MF. Nonetheless, RM still remained high with funding targeted mostly to the experimentation rather than the creation of a mass market for solar. One reason for this might be attributed to the weakening in the LE function mainly because of the resistance of the traditional energy players, or simply because of the fact the technology was still not mature enough. This evolution can be seen in Figure 4.11.

Dominant Design (2001-2003)

This period is characterized by standardization in the solar PV technology, accompanied by a decrease in the costs of PV, and a transition of the technology from the experimental to the commercial stage. We also observe an almost five-fold increase in solar electricity

[9]The installation was around 10,000 to 12,000 euro/kWh and the electricity generation costs (over 1 euro/kWh)

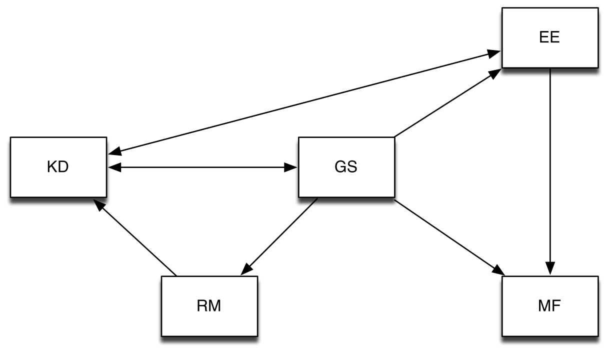


Fig. 4.11 TIS evolution in Germany in Niche Markets

output from 60GWh to 557GWh. In terms of functions, we observe that guidance of search was fully active, as were legitimation and market formation. Knowledge development, resource mobilization and entrepreneurial experimentation, although present, were not the main functions in this period.

Knowledge Development We continue to see an increase in the number of papers produced (Figure 4.3) However, the number of patents have remained relatively constant (Figure 4.4). This might be related to the emergence of the dominant design and how it influences the nature of innovation. In particular, it could be argued that innovation changed from product to process and this can explain the lack of patenting activity, since it is harder to patent a process compared to a product. Most of the innovations were now focused on cost reductions of the manufacturing processes rather than developing new Solar panels. This can be deduced by looking at the government's funding programmefor PV - "Paving the Way for Photovoltaics 2005" (Wegbereitungsprogramm Photovoltaik 2005), which ran from 1996 to 2005 and aimed at cost-reduction innovations. Therefore the performance of this function has remained high.

Legitimation Legitimation became stronger in this phase, mainly due to strengthening and consolidation of the supporting institutions for solar PV. In particular, in 2003 the German Solar Energy Association (BSE) and the German Solar Industry Association (DFS) merged to form the German Solar Sector Association (BSi). This became one of the strongest lobbying organizations representing the whole spectrum of actors in the industry, up until 2006 when it merged with the Solar Industry Trade Association (UVS) to form the German Solar Industry Association (BSW). This led to the flourishing of other support organizations, such as EUROSOLAR and the Federal Solar Industry Association, which further increased pressure on Federal government for more subsidies for solar (Jacobsson et al., 2002, pp.24–25). At the Federal level, the German Energy Agency (Deutsche Energie-Agentur, Dena) was founded in September 2000, as another organization aimed at reducing dependency on energy sources.

There was some opposition to solar PV, perhaps as a reaction to the fact that solar PV was becoming widespread across Germany. The opposition came from associations for the preservation of historic sites and other nature and landscape conservationists, which voiced concerns about the impact of PV installations on the environment (Brüns et al., 2010, p.193). These adverse reactions can be seen more as evidence of the increasing size of the solar market, rather than a weakening of the function.

Guidance of Search There are two major developments that guided research: the EEG and the 100,000 Rooftops programme. The period began with the 2000 Renewable Energy Source Act (Erneuerbare-Energien-Gesetz, EEG)[10], which replaced the StrEG. This law was aimed at doubling the amount of electricity from renewables in 1997, by 2010. To achieve this, it introduced FITs for the whole amount of RES electricity generated, and increased the remuneration for PV electricity from 8.2 cents to 50.62 cents/kWh. At the same time, it forced the grid operators to purchase all electricity produced by renewables for a 20 year period to 2020. It also clarified the responsibilities of the grid operators and the producers vis-a-vis the costs of connection of PV systems. In addition, a special department for the settlement of disputes related to the grid was set up by the Federal Ministry of Economics and Technology (BMWi). The law gave such a huge boost to the industry that the original cap of 350MW was increased to 1,000MW in June 2002. Thee developments can be argued that they boosted the confidence of entrepreneurs that the government was committed to supporting solar PV.

The second development in this period was the 100,000 Rooftops Programme; the aim was to install 300MW of new solar capacity in the 1999-2003 period, by installing 100,000 3kW PV systems. The total cost to government was 510 million euros in the form of long-term soft loans (maximum 500,000 euro per system) with very low fixed interest rates (4.5% below the market level) for a term of 20 years. The grant effectively covered 35% of the investment (Stryi-Hipp, 2005, p.185). In addition, the private sector was expected to invest 1.3 billion euros. Again there was a local content requirement, which would eventually strengthen the position of German solar manufacturers in the international market. The programme was generally successful and 55,000 systems with total capacity of 346 MW received support from loans amounting to 1.7 billion euros, in a total invest-

[10]More information of the act can be found in the work by Krewitt and Nitsch (2003)

ment of 2.3 euro billion (Oppermann, 2004). However, in relative terms, the amount of energy produced by the project amounted to less than 4% of that produced by an equivalent nuclear plant, due to the infancy of the industry.

Lastly, two further developments contributed to strengthening the guidance of search function. Firstly, the EU Directive on the promotion of electricity produced from renewable energy sources, which aimed at achieving 20% of electricity from renewables by 2010 (European Commission - Energy, 2016). This can be interpreted as giving further confidence and guidance to entrepreneurs and boosted diffusion of solar PV. Secondly, in 2002 the Nuclear Face-out Act was ratified, confirming Germany's orientation to renewables. Clearly, all these developments further strengthened this function and facilitated the diffusion of solar.

Entrepreneurial Experimentation The period is characterized by a range of takeovers, an increase in entry rates, and an increase in employment in the solar sector[11]. At the same time, production capacity increased from roughly 6 MW to just under 100 MW (IEA 2011b), a fact that shows that the German entrepreneurs have developed enough knowledge and experience dealing with solar installations. These facts, combined with the emergence of the dominant design, could be used to argue that the experimentation phase has finished and we should expect any developments related to entry and exit from the market to be signs of market formation rather entrepreneurial experimentation. Nonetheless, any entry still remains an experimentation from the perspective of the individual investor/entrepreneur.

Resource Mobilisation The main support came from the Federal Government's Fourth Energy Research Programme (1996-2004) and its subprogramme for PV - "Paving the Way for Photovoltaics 2005" (Wegbereitungsprogramm Photovoltaik 2005), which ran from 1996 to 2005. This programme aimed to provide solutions that would decrease the costs of cells and installations, which was thought that it was the main factor preventing the more widespread use of PV (Brüns et al., 2010, p.200). In terms of R&D, we observe a small decrease in the amount available for research, probably because of the increased amount available for funding (see Figure 4.7). Therefore, we can conclude that this function remains strong.

Market Formation The main recorded event related to this activity is the fall in the prices of modules, which was caused by the institutionalization of both demand and sup-

[11] Employment in the sector rose from 2,500 to 6,500 (Frondel et al., 2008)

ply. In particular, there was a sharp increase in demand, which led to a radical reshaping of the production process and a fall in costs. Rising demand for PV was driven primarily by the 100,000 Rooftops programme, while the cost reductions stemmed from a series of process innovations (mostly related to factory automizations) that began to pay off particularly after 2000.

At the same time, we observe cost reductions related to the manufacturing process, especially inverters, and other installation costs. These were caused by a reduction in the cost of solar modules based on economies of scale in the production of cells (see Figure 4.12). Overall, Oppermann (2004) finds that the specific costs (excluding sales tax) for small solar power installations of up to 4 kW, had fallen from 7,300 euro/kWh in 1999 to around 5,500 euro in 2003, while larger scale projects also decreased significantly),[12] as shown in other studies (see Figure 4.13).

Another development that increased the price attractiveness of solar, although relatively less important, was the Ecological Tax Reform (ETR) (1999-2002), which made conventional fuel sources relatively more expensive by imposing taxes. In particular, it increased the taxes on motor fuels (3.07 euro cents/l), fuel oil (2.05 euro cents/l) and natural gas (0.164 euro cents/kWh) and introduced an electricity tax (1.02 euro cents/kWh).

Therefore, we can conclude that the market has been fully formed and that diffusion became demand not supply policy led, and thus the market formation function was fully active.

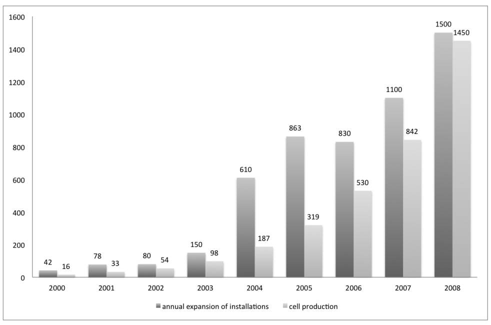


Fig. 4.12 Production of PV Cells in Germany (2000-2008)

Source: (Brüns et al., 2010, p.214)

[12]installations of up to 10 kW, the cost had dropped by about 500 euro/kWh

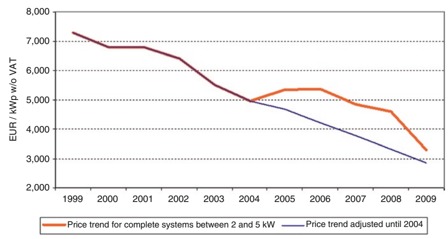


Fig. 4.13 Rooftop PV prices in Germany

Source: (Brüns et al., 2010, p.214)

Conclusions from this phase KD remains active, but the knowledge output in terms of patents seems to be slowing down, something potentially attributed to the changing nature of the innovation process, while LE is stronger and becomes consolidated. But the major impact came from GS, which increased subsidies and increased demand for solar PV through the 100,000 rooftops program. In this way, EE and MF were stimulated. MF formation was given a further boost since the prices of modules decreased significantly in this period, but also recent innovations from KD further reduced the costs of the manufacturing process. This evolution can be seen in Figure 4.14, with the picture looking very similar to the interactions in the previous phase. In other words, KD is influencing GS and EE, and being influenced by RM, EE and GS. Again, the pivotal function in this phase is GS, which seems to influence all the other functions.

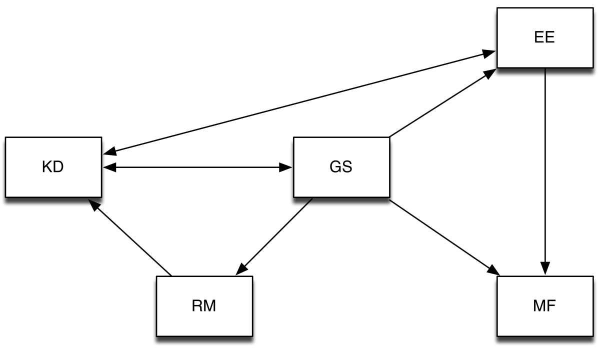


Fig. 4.14 TIS evolution in Germany in Dominant Design

Mass Market (2004-)

After the dominant design emerged, electricity from German solar PV sky-rocketed, and opened the way to the fourth phase of TIS evolution, which we label mass market. Here, knowledge development, market formation and resource mobilization were fully active, while guidance of search and entrepreneurial experimentation were virtually non-existent and legitimation began to turn negative.

Knowledge Development In this period, there was a huge increase in the number of patents generated in Germany (Figure 4.4). However, most advances were targeted at optimizing the manufacturing process; in addition, the efficiency rate of the market-leading inverters, in this phase, achieved 98% and this was accompanied by a steep reduction in inverter failures (Brüns et al., 2010, p.218). Both these developments illustrate that the industry had shifted completely towards process rather than radical innovations, validating the argument that this was the mass market phase.

Another interesting feature related to knowledge development is development of regional clusters, which in essence are areas of cooperation between industry and research institutes, in this case emphasizing rapid commercialization of solar PV technologies. This allowed Germany to maintain and consolidate its position as the leading solar developer, particularly in thin-film PV. Examples of regional clusters include among others the Solar Valley in Thuringia, Saxony, and Saxony- Anhal, the Thin- Film- and Nanotechnology for Photovoltaics (PVcomB) Competence Centre in Berlin, and various technology parks in Eastern Germany, such as the Central German Technology Park (TechnologiePark Mitteldeutschland).

Legitimation In this phase, we see some forces against diffusion, mainly pressure from environmentalists who were uncomfortable with the development of large scale PV, but also the coal sector, supported primarily by the SDP. At the same time, the financial crisis pushed the CDU/CSU coalition government to enforce some price reductions, driven primarily by the adverse reactions of the Liberal FDP party, the miners and chemical industry groups. This shows that in this phase legitimation was still active, but was having a negative impact on the functioning of the system.

Guidance of Search Emergence of the dominant design made this function relatively unimportant at this stage. The factors formerly in this category now fall into the category of market formation[13].

Entrepreneurial Experimentation Like guidance of search, there are few signs of experimentation; rather, most of the action on the supply side was focused on market

[13]This simplification is done only in the case of Germany, which conforms to the pattern of the PLC. In the other three cases, to which the PLC framework does not fully apply, we provide a more complete description of the activities in this function.

formation, since we argue that after the emergence of the dominant design all entry rates are considered to be evidence of market formation rather than enterpreneurial experimentation.

Resource Mobilisation Despite an initial drop after 2002 in the level of funding (Figure 4.7), we observe increasing amounts of resources being channelled towards solar R&D, which probably points to the importance of the solar industry for Germany. In particular, the Fifth Energy Research Programme launched in 2005 was jointly financed, for the first time, by the Federal Research Ministry and the Federal Environment Ministry. The focus in terms of production technology was on automation in factories and streamlining of the manufacturing processes. Some resources came from the Environment and Energy Conservation Programme (EECP) and the Environment Programme (EP), in the form of soft loans, targeted at small and medium sized enterprises (SMEs) - primarily those engaged in producing electricity from wind. Lastly, increased subsidies especially in the beginning of the period, can also be viewed as influencing resource mobilisation, but also market formation. Therefore, we can argue that this function strengthened compared to the previous period.

Market Formation The initial years of this phase were characterized by uncertainty and low levels of market development, following the end of the 100,000 Rooftops programme. The response from the government was the introduction of more subsidies through the Interim Act on Photovoltaic Energy (2003), until the EEG amendment in 2004. This legislation continued the financing of PV at a base rate of 45.7 cents/kWh, and was retained in the EEG amendment. In addition, the amendment recognized the emergence of five different solar PV categories[14], which, in effect, illustrates the plurality and shift towards process rather than product innovation. Prices rose briefly in 2004-2007, but this was the result of steep increases in demand and supply bottlenecks, rather than technological issues. The temporary nature of the increased prices is evident in Figure 4.13, where we can see that from 2004 to 2006 the prices of a complete solar PV system increased from 5,000 EUR/KWp to approximately 5,500 EUR/kWp. Higher prices then resulted in increased production facilities (Figure 4.12), and an almost quadrupling of cell production in Germany.

A steep decrease in solar costs after 2007 led to degressions in subsidies[15], showing that

[14]These categories differentiate between solar PV for rooftops, for façades, and for PV built in free spaces

[15]the degression was 8% for rooftop systems (10% for systems over 100 kW) from 2009 and an across-the-board degression of 9% from 2010. The degression for ground-mounted systems amounted to an initial

solar had become competitive with traditional electricity resources and, if measuring success by cost competitiveness, allowing the conclusion that the system had been successful for diffusion of solar.

A further sign suggesting full institutionalization of the market for solar was the growth of the sector in both size and importance. By 2008, statistics show that it employed around 50,000 people, and achieved revenues of around 7 billion euros (BSW, 2009; O'Sullivan et al., 2009). Therefore, market formation was fully operational, and it could be argued that the diffusion of solar PV in the German market was complete.

Conclusions from this phase KD is now focused on the manufacturing and commercialisation. We can observe however, some negative form of LE. But this does not seem to influence GS, at least in the early period. However, later on GS became less supportive to solar, but still this did not cause any major disruptions in the operation of the German TIS. Therefore, even if LE is negative and there is no guidance, as long as there is a strong established and institutionalised market for solar (i.e. strong MF), the TIS can continue to operate. The two main functions that were seen to be interacting in this phase were KD and MF, and this can be seen in Figure 4.15.

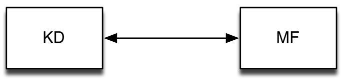


Fig. 4.15 TIS evolution in Germany in Mass Market

10% in 2009 and then also 9% from 2010. A targeted market volume was also agreed upon: if the volume exceeded or fell below the target, the degression rate in the following year would increase or decrease respectively by 1% point. The bonus of 5 cents/kWh for integrating systems into building facades was discontinued" (BMU 2008)

4.4.2 UK: the early and unsuccessful

The UK was one of the first countries worldwide to adopt solar PV and conduct research on it. However, this early start was not accompanied by outstanding success in diffusion, or major further participation in development of the technology. Rather, diffusion took off late, when solar PV was already in the later phase of mass market.

Overview of the UK Solar Evolution

Although the UK had one of the most advanced technological knowledge bases in solar at the beginning of the 1970s, actual diffusion of solar did not begin until 1999. There are two potential reasons for the UK's late start; firstly, UK had ample conventional resources as well as nuclear reactors, making renewables not a topic of great interest for the UK's energy policy. Secondly, in the context of renewables, it is clear that the UK's abundant wind resources attracted most interest in renewables technologies, and overlooked solar technologies.

However, after the emergence of dominant solar design and the introduction of subsidies after 2002, a gradual diffusion of solar can be observed which went hand in hand with introduction of the Renewable Obligation scheme, an alternative to the FiT[16] , which was based on quotas rather than subsidies. This process is depicted in Figures 4.16 and 4.17. Figure 4.16 is based on IEA statistics and shows that the first solar installations took place in 1999 according to the definition that "the PV power system market is defined as the market of all nationally installed (terrestrial) PV applications with a PV capacity of 40MW or more"(IEA, 2008, p.12). Installations not connected to the grid, and capacities of less than 1GW are not included. A more realistic picture of solar PV diffusion in the UK is provided in Figure 4.17, which represents the cumulative capacity of all solar PV in kW. This figure includes non-grid connected (stand alone) solar PV. Thus, it could be argued that the first signs of solar PV deployment started in the UK in 1992, but not to a significant extent.

Emergence of Technologies (1970s-1993)

There are four main functions that show some evidence of development in this early period, namely knowledge development, resource mobilization, legitimation and guidance of search. In particular, this period is characterized by weak legitimation, strong academic research and mobilization of funding resources. Some initial, although not very

[16] The FiT was introduced only in until 2010.

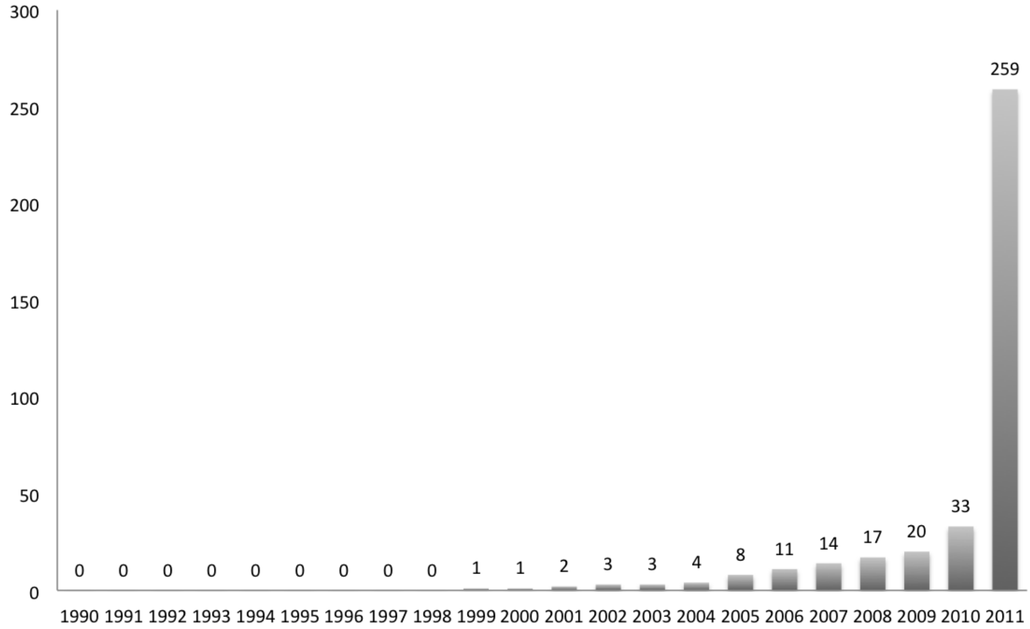


Fig. 4.16 Total Installed PV Power in the UK (GW) (1990-2011)

Source: IEA

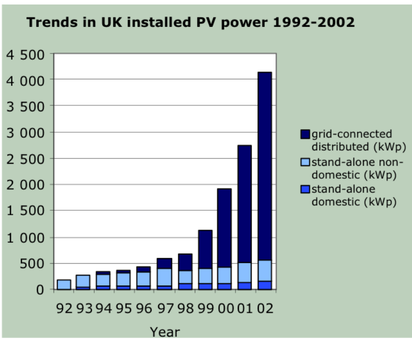


Fig. 4.17 Total Installed PV Power in the UK (kW), including stand-alone systems (1992-2002)

Source: IEA-PVPS

successful steps towards guidance of search can be observed. However, it is surprising that although the UK was responsible for one of the major PV innovations, it was not successful in commercializing it.

Knowledge Development Data on upstream knowledge development begins in 1970 (see Figure 4.18), but there were no major developments until the mid 1980s with the greatest global innovation in the early history of solar PV. In 1985, the University of

South Wales managed to break the 20% efficiency barrier for silicon solar cells, producing the most efficient solar cell for 20 years. This opened the way for major cost reductions in the technology since solar cells are the major cost component of a solar system. However, since then we did not observe any major increase in the rate of growth of paper publications, which one would expect as the result of a technological breakthrough. It is also strange that this major innovation was not accompanied by any major commercializations attempts, or development of a PV market. Because of the lack of continuity after this major innovation, in this period UK's contribution to the solar PV industry was only 2.3% of the world's innovation, as this is measured by the number of patents for solar PV (Dechezleprêtre, A. & Martin, R., 2010).

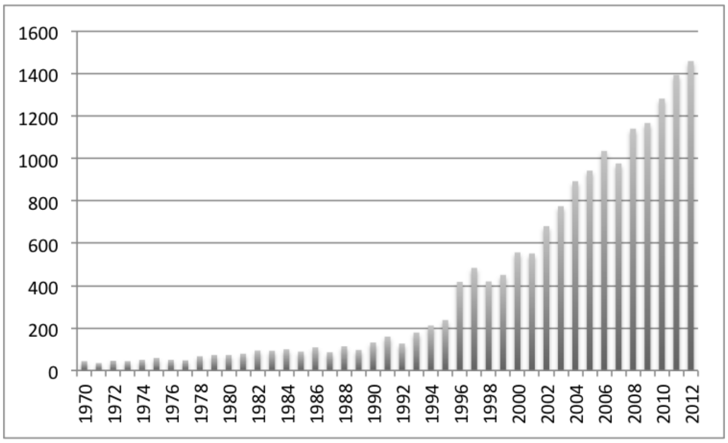


Fig. 4.18 Number of Papers produced by UK Institutions (1970-2012)

Source: Scopus

Legitimation In the UK there has been a well-developed network of environmental protection organizations since the 1960s (Rootes, 2003). The first of these was originally a student movement called "Friends of the Earth" (1970), then in 1977 with the foundation of Greenpeace UK, environmental politics took on a demonstrative form. These organizations were mostly aimed primarily at raising awareness of general environmental issues rather than promoting any particular energy technology. However, an exception was the "UK Solar Energy Society" (UK-ISES), which was established in 1974 to promote solar energy in the UK. The Green movement as a whole in the UK was against nuclear technologies, which could strengthen legitimation for the diffusion of renewable substitute technologies.

However, Figure 4.19 shows no major spikes in environmental protests[17] until 1992-1995 (Rootes, 2003). Moreover, among these protests, only around 10% were for energy related issues (Figure 4.20). In 1992, the UK participated in the 1992 Earth Summit in Rio, which is an indication that environmental awareness existed also at the government levels . This would seem to be confirmed by the establishment in 1993 of "The Energy Saving Trust", a non-profit organization established by the British government to "promote and advance the education of the public in the conservation, protection, and improvement of the physical and natural environment" (Energy Saving Trust, 2012).

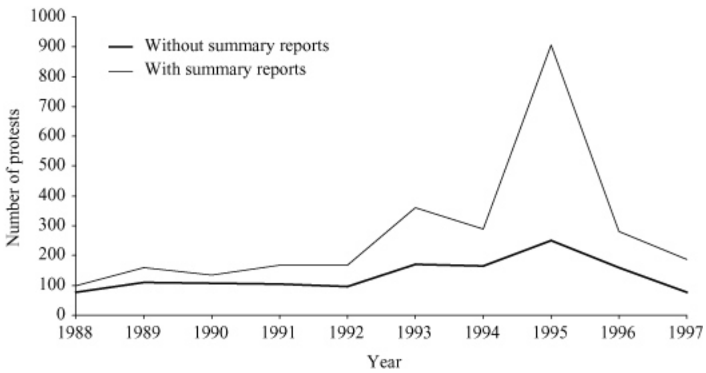


Fig. 4.19 Environmental Protests in Britain

Source: Rootes 2003

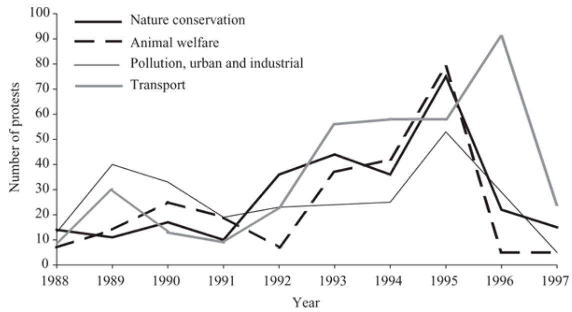


Fig. 4.20 Environmental Issues Raised by the Protests

Source: Rootes 2003

Overall, we can see development and establishment of an environmental community in

[17] The line which includes summary reports has included events which the authors recorded from summary reports from the news. These summary "reports that give minimal information about a large number of (sometimes geographically dispersed) events often (but not invariably) occurring over an extended period of time" (Rootes, 2003, p.26).

the UK and recognition of the importance of the environment by the UK government. However, it could be argued that there were no strong signs of legitimation in favour of solar PV in this period.

Guidance of Search A major regulatory development in this period was the Electricity Act (1989) which essentially privatized the UK electricity sector; in addition, it led to the Non-Fossil Fuel Obligation (NFFO) in 1990, which at that time was seen as a milestone in the development of RETs. The NFFO was a market-based instrument to support renewable technologies through a process of competitive bidding, which obliged public electricity suppliers to secure a specified capacity from renewable energy sources. In turn, the system guaranteed that the electricity would be purchased at fixed prices for long term contract periods (usually around 15 years). At the time, it was hoped that this arrangement would provide incentives to aspiring solar PV and other RET entrepreneurs to enter the market and bring down the cost of RETs over time (IEA 1999).

However, it was not particularly successful, for two main reasons. Firstly, it was indirectly aimed at promoting nuclear energy, and included no specific incentives for solar. Secondly, and most importantly, the whole competitive bidding process was "based on technology tranches predefined by the government, which made the system excessively rigid" (IEA energy policies 2002, p.71 and p.65). In other words, the regulators placed each technology in a particular category based on its competitiveness with conventional electricity generation technologies. Then, the Department of Trade of Industry decided the maximum subsidy it was willing to pay to each group, and the winners in the contract bidding process received the payments (Agnolucci, 2005). This method of segregating technologies masked the price differences among the technologies in each category and, thus, unfairly promoted some at the expense of others. Therefore, we can conclude that although there were some initial movements towards the promotion of RETs, these were not successful for promoting solar PV.

Entrepreneurial Experimentation Without any commercially viable technology and with rudimentary legislation that allowed the integration of renewables into the grid, it is hard to observe any signs of entrepreneurial experimentation in solar. Some small signs of entry emerged in the early 1990s, but the number of firms was too small to be significant (see Figure 4.21).

Resource Mobilisation We observe some resource mobilization in the form of increased spending on solar R&D; however, this spending occurs only in the early 1980s,

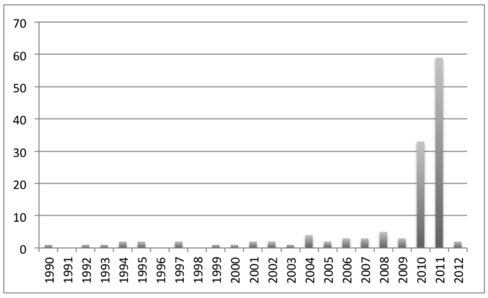


Fig. 4.21 Number of New Entrants in the Solar PV Industry in the UK (1990-2012)

Source: Amadeus Database

and after the radical innovation by the University of South Wales this spending virtually disappeared (see Figures 4.22, and 4.23).

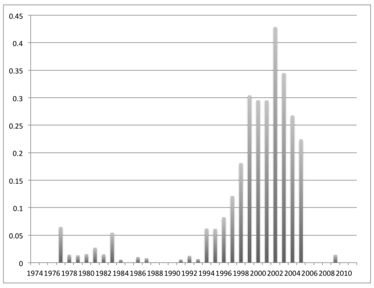


Fig. 4.22 Spending on Solar as a % of total spending on Energy Research in the UK (1970-2012)

Source: IEA

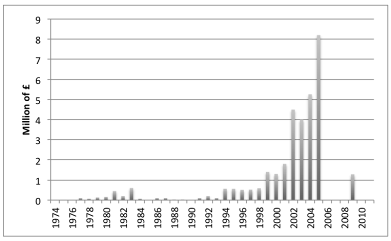


Fig. 4.23 Total Spending in Solar R&D (1970-2012)

Source: IEA

Market Formation The main element that likely led to some initial form of institutionalization of the UK solar market, was the 1990 NFFO, which stipulated that any electricity produced by non-fossil fuel resources must be purchased by the Distribution Network Operators in England and Wales. However, solar markets could not form since there was no grid-connected electricity until 1993 (Figure 4.17).

Conclusions from this phase The general socially favourable climate towards RETs and against nuclear that was captured by the LE function stimulated GS towards promoting RETs. However, the policies proposed were biased against solar. Similarly, although KD was originally stimulated with high R&D funding, and generated a technological breakthrough, but this was not recognised and followed through by the government. In other words, RM was strong, but then disappeared, which suggest that there was no consistency from the government's side in supporting solar KD. UK's indifference towards solar did not encourage entrepreneurs to test any of the solar technologies and together with the novelty and inherent risk of the technology, no EE was achieved. This evolution can be seen in Figure 4.24.

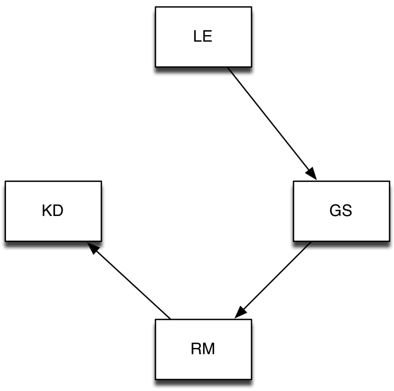


Fig. 4.24 TIS evolution in the UK in Emergence of Technologies

Niche Market (1994-2000)

In this period, Figure 4.17 shows the first introduction of grid connected solar PV systems. The TIS system is marginally operational with knowledge development, legitimation and signs of market formation. However, no major developments are observed in terms of diffusion, an observation which could be explained by the absence of any support policies targeted at solar PV.

Knowledge Development From 1995 there was a steady annual increase in the number of papers in the field of solar (Figure 4.18). This demonstrates progress, which eventually led to the establishment of various knowledge promoting organizations in the field of solar. For example, in 1999 the "PV Net" was established; this is a network of UK research and industry groups working actively in the field of PV. In terms of knowledge output, the number of patents shows a decreasing trend before a recovery towards the end of the period (Figure 4.25).

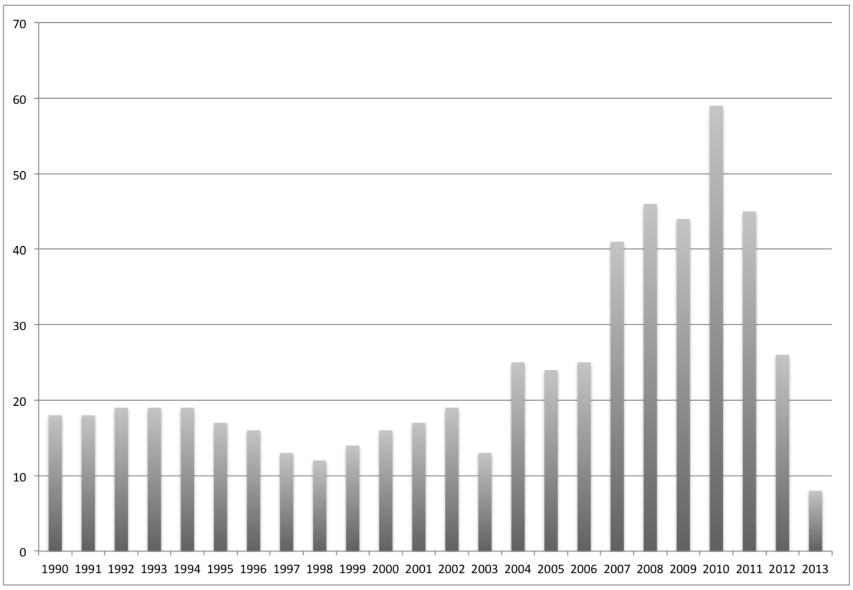


Fig. 4.25 Patents on Solar Technologies from the United Kingdom

Source: PATSTAT

Legitimation The main activity in this period is legitimation. However, this exists primarily in terms of a general green movement, rather than something particular to solar. For example, the greatest number of environmental protests occurred in this period, although the number of protests then decreases substantially (Figure 4.19). In addition, the UK signed the Kyoto Protocol (1997) and the EU's legally binding internal burden-sharing agreement (1998). These agreements commit the UK to reduce its greenhouse gas emissions by 12.5% below their 1990 levels, by 2008-2012.

Lastly, in this period the coal industry was privatized (1994). This abrupt decline in political support for coal gave more space for the development of the Green movement. However, renewables generally were still too expensive compared to other sources (e.g. gas), which has proved a significant obstacle to diffusion of solar.

Overall, we can say that there were signs of legitimation for Solar PV in this period.

Guidance of Search No major actions or policies took place in this period, so there are no signs of this activity being operational.

Entrepreneurial Experimentation There was a very small number of new entrants, perhaps explained by the absence of regulation, market and technologies for solar. Thus, there are no major signs of activity in this period.

Resource Mobilisation Expenditure on solar R&D started to increase in this period (Figure 4.22), but was still relatively insignificant[18].

Market Formation Prices for solar still too high compared to conventional fossil fuels, and most of the projects were demonstration rather than commercial projects. At the same time, we observe the integration of systems in the grid, which points to the existence of an elementary form of market. Thus, we can say that this function is marginally active.

Conclusions from this phase KD made some progress through the establishment of KD institutions, stimulated by some RM, but did manage to influence favourably LE towards supporting solar. Rather, LE continues supporting RETs in general. GS remains non-existent, and given the early stage of the technology, the price remains prohibitively high. Thus, there is no MF and thus very limited EE. Once again we see how important is GS for EE and MF, which implies very strong complementarities. Moreover, we see that there needs to be link between KD and LE, so that GS can then be influenced. This evolution can be seen in Figure 4.26.

Dominant Design (2001-2003)

The emergence of a dominant design (DD) is a universal phenomenon, at least in countries of technological proximity. Therefore, it could be argued that following a small delay, the dominant design emerged in the UK at around the same time as in Germany. Similar to the case of Germany, it took some two years for the design to diffuse through the system, so the dominant design period in the UK is 2001-2003. During this period, most of the functions of the system were operational and no major diffusion can be observed. This might be explained by the fact that most of the events that took place in the functions were not specific to solar, but applied to RETs generally.

[18] It is less than 1million pounds annually, while in the same time period in Germany expenditure was around 50million euros

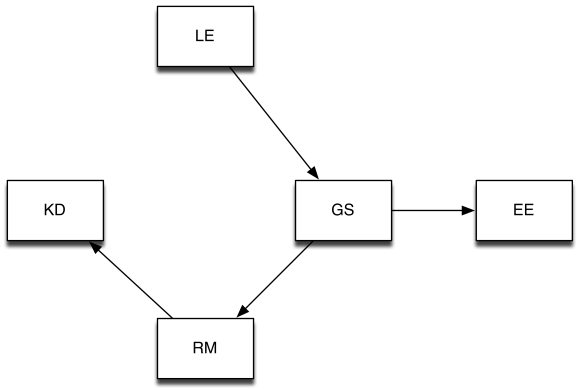


Fig. 4.26 TIS evolution in the UK in Niche Market

Knowledge Development Apart from the annual increase in the number of papers produced, there were some initiatives that indicate knowledge development and diffusion. For example, the establishment of the Energy Efficiency Best Practice Programme, which has become the UK information hub for renewables and cost effective technologies. Also, in 2001 the Carbon Trust was established, aimed at accelerating the diffusion and implementation of low carbon technologies in the business and public sectors, by providing both guidance, resources and research for the renewable industry. However, the number of UK patents remained at very low levels, and contributed only 2.3% to world solar PV innovation, as this is measured by the EPO/OECD World Patent Statistical Database (PATSTAT) (Dechezleprêtre, A. & Martin, R., 2010). Therefore, we can conclude that there was some minor progress in this function.

Legitimation In 2001, the UK government established the Department for the Environment, Food and Rural Affairs (DEFRA), to cover energy efficiency, environmental and sustainability issues. It took over these responsibilities from the Department for Environment, Transport and the Regions (DETR), which point to the importance assigned by government to climate change and energy efficiency issues. In 2003, the government issued its "Climate Change Programme", an action which can be seen as political legitimation of the UK government's commitment to renewable energy. The Energy Efficient Commitment is another piece of legislation that illustrates government's commitment to renewable energy and energy efficiency, which required electricity suppliers to support low income/vulnerable customers by introducing energy saving measures. However, there are no signs of legitimation for solar in particular took place, apart from the fact that it was included as a RET in the Renewable Obligations system.

Guidance of Search The main document produced in this period was the Climate Change Programme (2003). This stipulated that "the UK will reduce emissions by 60% by 2050, and will make significant progress towards that goal by 2020" (Carbon Trust 2005). This development formalized government's interest in the issue of climate change and illustrated its commitment to renewable energy production. However, there is no specific direction for solar PV, which obviously reduced the guiding activities towards PV.

Another development that provided guidance to entrepreneurs in relation to renewable energy in general, was the Climate Change Levy, a tax on energy, introduced in 2001 under the Finance Act 2000. It was imposed on non-domestic users, and aimed at reducing their carbon emissions and motivating them to increase their energy efficiency. Electricity produced from renewables was exempt. It included provisions for a 65% tax reduction for companies that signed a climate change agreement and showed commitment to reducing their emissions[19].

In addition, there was a major PV demonstration programme (PV MDP) with £31 million of capital grants available from 2002 to 2006. The funds were aimed at supporting the cost of equipment and installation of solar PV projects. The aim was to reduce uncertainty, but also to set the basis for market development; the £31 million included construction of huge capacity sufficient to stimulate the market and set some basis for its future development. Therefore, the programme can be seen as contributing to the market formation activity.

Overall, we can see that there were some developments in this function (such as the PV MDP), but no clear support or guidance from government for the diffusion of solar PV.

Entrepreneurial Experimentation Figures 4.21 and 4.27 show that in terms of entrepreneurial experimentation, there was not a significant number of new companies, and also the total number of firms in the industry remain limited.

Resource Mobilisation In terms of financial resources, government promised over £260 million for renewables in 2001-2004; however, only £10 million was allocated to solar PV, and the timeline of the allocations was not clear (IEA, 2006, p.99). However, there was a doubling of R&D expenditure from around £2 million to £4 million (Figure

[19]The benefits were in the form of the Climate Change Agreements between industries and the secretary of state.

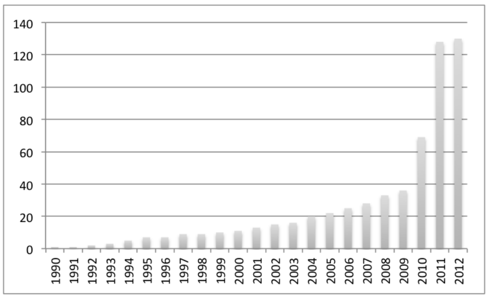


Fig. 4.27 Number of Cumulative New Entrants in the Solar PV Industry in the UK (1990-2012)

Source: Amadeus Database

4.23). This came from various sources including the EDF Green Fund and the EDF Green Tariff, and the Climate Change Levy funds, all of which were established in this period to promote renewable energy projects.

In relation to technical know how, we need to examine its quality in relation to solar PV. Although hard to measure precisely, we would suggest that the quality in the UK is significantly lower than in Germany, based on absence of a solar manufacturing industry in the UK. In particular, there is a very small number of PV manufacturers in the UK, none of which is sufficiently large scale to be a globally recognized player.

Thus, we can conclude that, even in this dominant design period, resources for solar were not sufficiently mobilized, at either a financial or human capital level.

Market Formation Starting with actual costs of the solar PV systems, in terms of module prices, Figure 4.28 shows that there was a stabilization in the prices of standard modules of around 4.7GBP/watt after 2001. Also, the number of projects connected to the grid shows a dramatic increase after 1999; thus, we can argue that there are signs that the supply side of the market was starting to form.

There were two main pieces of legislation introduced in this period in the field of climate change: the Renewables Obligation (RO) and the Climate Change Levy. The RO was adopted under the Utilities Act 2000, and was introduced in 2002, replacing the NFFO. It required an increase of 10% in the proportion of electricity provided by renewables by 2010. The system worked as follows: for each MWh of electricity produced by an electricity supplier, a certain amount would have to come from renewable energy sources.

Year	2001	2002	2003	2004	2005	2006	2007	2008
Standard module price(s): Typical [£/w]	4.7	4.7	4.5	3.9	4.7	4.1	3.8	3.2
Best price [£/w]					2.6	2.6	3.0	2.6
PV module price for concentration	N/A							

Fig. 4.28 Typical module prices in the UK (2001-2008)

Source: IEA

Then, for each MWh of renewable electricity generated, the supplier would produce a RO certificate, which could be offset against its commitment or sold to another supplier. In the case that a supplier did not produce enough renewable it could buy from another supplier or buy his commitment from the Office of Gas and Electricity Markets (ofgem). In other words, the market was left to generate the supply of RET in the most effective way.

In terms of the system's effectiveness, it could be argued that it strengthened government's commitment to renewables, but it was not specifically oriented to solar PV. Rather, the RO system let the market decide which technology to diffuse. However, as solar was still not technologically advanced enough to be competitive with the other technologies, there was a risk it would be excluded from the system, which is what happened. Figures 4.30 and 4.29 show that the number of RO certificates issued related mostly to wind, with solar PV accounting for less than 0.5% of total certificates issued in 2002-2011. However, this legislation provided the basis for further development and institutionalization of the market by forcing electricity suppliers to generate and sell renewable electricity.

Similarly, the UK Emissions Trading Scheme (ETS) (2002), which was part of the Climate Change Programme, was established. The ETS was a typical trading scheme, with permits allocated to companies which then are allowed to trade them with each other, and was initially proposed as a voluntary scheme, aimed at preparing UK companies for mandatory EU programme due to be launched in 2005.

We can observe institutionalization of the market and many activities in this function, potentially making it one of the best developed functions in the system, in this period. However, this system was not technology specific i.e. the market actors had to choose which RET they prefer.

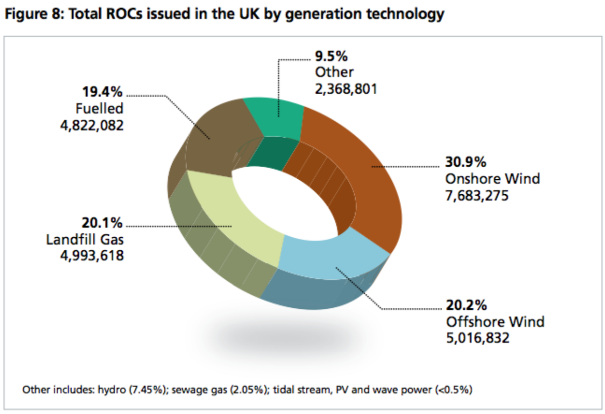


Fig. 4.29 Total ROCs issued in the UK (by generation technology) (2002-2011)

Source: Ofgem

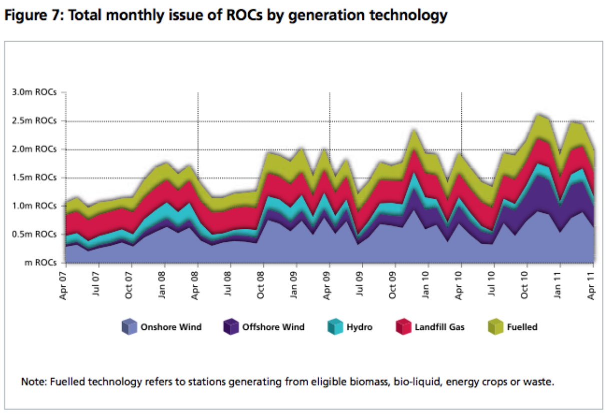


Fig. 4.30 Monthly ROCs issued in the UK (by generation technology)

Source: Ofgem

Conclusions from this phase KD is high, but not enough for the UK to be considered a pioneer. LE remained strong for RETs, but again not in favour of solar. However, this time, LE was so strong that it managed too influence policy makers to formalise their commitment to RETs by introducing the RO scheme. For solar in particular, the government introduced a major demonstration project. Nonetheless, there were not enough resources mobilised for it, and the technology was not of a major interest to UK entrepreneurs, who seemed to prefer wind systems as they were more profitable. That can explain the limited number of new entrants in the market. What we can again observe is the weakness of KD to influence LE, and then GS in such a way that it would stimulate the market formation.This evolution can be seen in Figure 4.31.

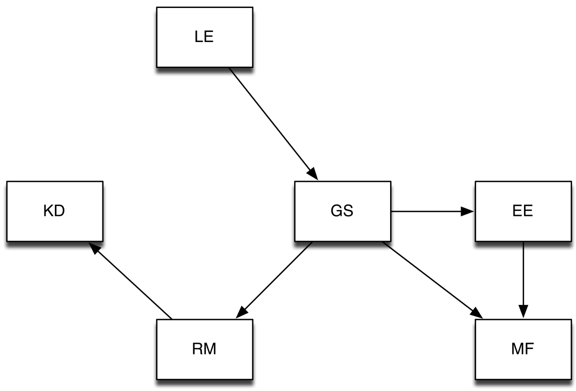


Fig. 4.31 TIS evolution in the UK in Dominant Design

Mass Market (2004-)

In this period, there is significant diffusion of solar PV and a relatively strong TIS, with strong development in almost all functions apart from entrepreneurial experimentation.

Knowledge Development The number of papers shows an upward trend, which indicates continuous development of knowledge. However, no major innovations produced in the UK in the field of solar, despite the very steep increase in the number of patents. An indication of the UK's inability to produce any commercially valid technologies is the number of solar panel manufacturers in the UK: 5, compared to 140 in Germany. Also, UK contributes just 2.6% of world innovation in solar PV (Dechezleprêtre, & Martin, 2010). Thus, we can conclude that there has not been a qualitative change in this function, but rather the Science and Technology knowledge that the UK has accumulated is unrelated to any commercial applications .

Legitimation A key document compiled in this period was the 2008 Climate Change Act, which is the first legally binding framework aimed at reducing Greenhouse Gas Emissions (GHG). It stipulates that the amount of GHG produced should be reduced by 80% of 1990 levels by 2050. This shows government's commitment to and acceptance of renewable energy as the path to a sustainable future. In October 2008, government established the Department of Energy and Climate Change (DECC), dedicated to renewable energy and heat issues. In 2009, the EU Renewable Energy Directive was published which required the UK to produce 15% of total electricity consumption from renewables by 2020. Thus, we can argue that the legitimation function strengthened in this mass market phase.

Guidance of Search Given that the dominant design had been established there is relatively little scope for activity in this phase. However, because solar technologies were not adequately diffused in the system, there was a development that can be considered to be guidance for entrepreneurs. They key for solar diffusion was the launch of the FIT scheme in 2010. This was a "programme aimed at promoting the diffusion of small-scale low carbon electricity generation" (Ofgem 2011, p.4). It requires some electricity suppliers to pay a fixed tariff to micro and small renewable generators for the electricity supplied to the national grid. The rates are set by DECC, but the system is administered by Gemserv and Ofgem. The idea was proposed in 2009, but the initiative was launched in April 2010. Similarly, the "the Low Carbon Buildings" programme (2006-2010), which supported microgeneration projects with funding of around £87 million. It was seen by policy makers as a way of establishing the market and launching some initial demonstration projects.

To comply with EU requirements, the UK was obliged to develop a National Renewable Energy Action Plan (NREAP), which was announced in July 2010. This plan translated the 15% energy target to 238 TWh, based on energy demand projections for 2020. This was complemented by the Renewable Energy Review, conducted by the government Committee on Climate Change, published in May 2011, and the Renewable Energy Roadmap (July 2011) conducted by the DECC. This established government's clear vision for the development of renewables, which facilitated the entry of new players and led to an increase of solar PV installations. However, the initial roadmap did not explicitly mention targets for solar, which undermines the development and diffusion of solar.

Therefore, again no major guidance was provided to UK solar entrepreneurs, until the end of the period when the FiT scheme was introduced.

Entrepreneurial Experimentation This activity is not relevant at this stage since the technology had already reached dominant design and the market was formed. Thus, there was not much scope for entrepreneurs to experiment in terms of technological variety. The data on entry (Figure 4.21) are more illustrative of market formation than experimentation.

Resource Mobilisation Since 2008, there has been an increase in the amount of resources dedicated to solar. In particular, we observe an increase in total funding for solar energy from £12.7 million in 2007 to £24.7 million in 2008 These resources came from various institutions and grants, including the Engineering and Physical Sciences Research

Council (EPSRC), the UK Energy Research Centre (UKERC), the Technology Strategy Board, the Carbon Trust, the Environmental Transformation Fund (ETF) and the DTI. In this period also we see a wider range of funding resources at both regional and national levels, but with much smaller amounts of funds. Examples include the E.ON sustainable energy fund which sponsors community groups, charities and NGOs up to £20,000 for microgeneration projects; the Gloucester Renewable Energy Grant Scheme which funds small-scale PV projects in south Gloucestershire; the Co-operative Group (2007 to 2008) which provided £1 million for the installation of PV systems at 100 schools nationwide. Lastly, a more recent development is the establishment of the UK Green Investment Bank in 2012, an institution responsible for attracting and allocating funds for renewable energy and other environmental investments. Therefore, there is enough evidence to suggest that there have been major improvements in the availability of resources.

Market Formation The major development in this period was the introduction of the FIT, which gave a huge boost to price competitiveness of the UK solar PV. In the first year, FIT were primarily given to solar PV, with 77.7MW of solar PV capacity registered with the programme (see Figure 4.32). Although the policy was not specifically designed to promote solar, it still made a substantial impact. Its success is illustrated Figure 4.33, which shows that, since the beginning of the programme, the number of installations has increased exponentially [20].

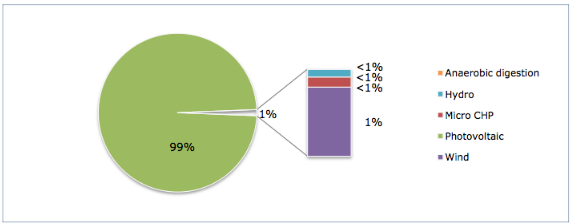


Fig. 4.32 The distribution of Total Feed-in Tariffs in the UK by technology (2010-2012)

Source: Ofgem

The huge success of the FIT programme led to an immediate revision of the policy in 2011, as the UK authorities realized that they were over-subsidizing the sector. The DECC decided that there would be a reduction in tariff rates from 1 April 2012 for all installations. Moreover, due to the unexpected reduction in the price of solar PV modules

[20]The data refer to installations of all technologies, but given that solar PV accounts for 99% of the total installations we can infer that the trend reflects solar development.

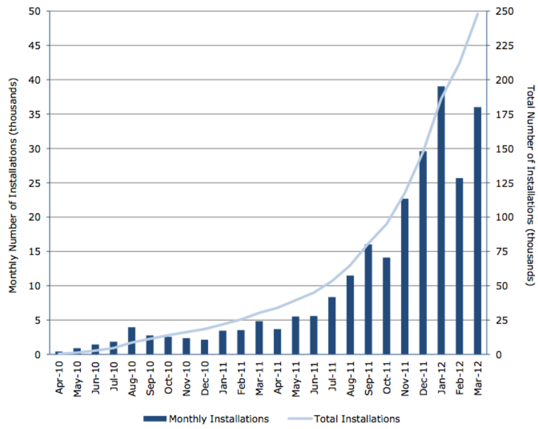


Fig. 4.33 Feed-in Tariffs impact on UK Solar

Source: Ofgem

(see Figure 4.34), DECC made a further downward revision to the FIT in August 2012.

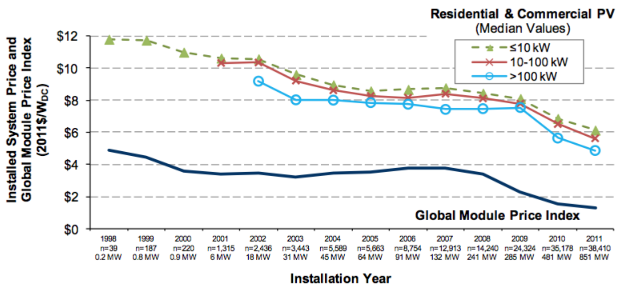


Fig. 4.34 Residential and Commercial PV prices (1998-2011)

Source: Feldman et al. 2012

This policy programme can be seen as fundamental for the formation of the market; essentially, it institutionalized demand for electricity for solar as it forced electricity suppliers to purchase whatever was produced by the panels. This creation of demand reassured suppliers that they could make investments and, thus, further stimulated the creation of a fully fledged market. However, the continuous revisions to tariff levels have created some uncertainty which arguably has destabilized the market. Thus, we can say that the performance of this function has been mostly positive.

Conclusions from this phase KD remains strong, but most of the knowledge generated from the UK seems to be unrelated to commercial applications, given the lack of patents. LE was strengthened further by international pressures towards RETs and it became so strong that the government established a separate department dedicated to RETs. The international pressure in favour of RETs forced the UK to introduce new legislation which committed itself towards RETs, thus solidifying the GS. The government also recognised the need for a diversified mix of RETs, so it started placing more emphasis on solar. To speed up the process of diffusion, it also introduced a FiT which increased the attractiveness of Solar. However, the prompt removal of the tariffs led to a standstill in the market. This shows once again that if a country has not managed to position itself as a technology leader, any destabilisation in the MF can lead to collapse of the TIS and a halt of the diffusion system. This evolution can be seen in Figure 4.35.

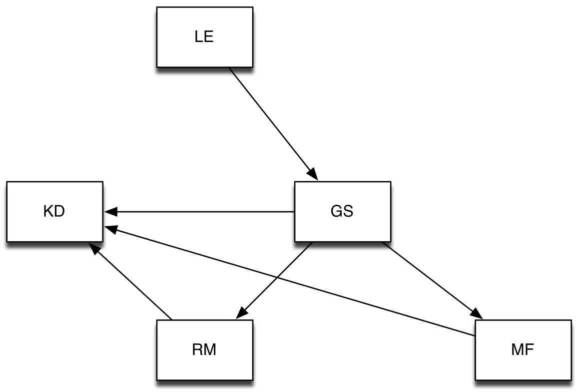


Fig. 4.35 TIS evolution in the UK in Mass Market

4.4.3 The Czech Republic: the late and Successful

Overview of Czech Solar Miracle

The Czech miracle refers to the Czech republic's achievement to install an incredible 2000MW of solar PV within only 4 years. The history of the Czech Miracle does not start as early as the German one for various reasons. For one, the socialist regime of Czechoslovakia did not worry neither about energy dependence nor about any environmental issues. After the collapse of the Soviet Union, there was a great extent of political turbulence in the republic, which eventually led to the breakdown of the Czechoslovakia, and the foundation of the Czech Republic (CZ) in 1993. The country had since been through major economic reforms that were related to its transition and at the same time a dramatic fall in energy consumption. What is particularly interesting about the case of solar in CZ is the fact that it is a very wealthy country in terms of coal resources and also has some uranium; therefore one could argue that it is a resource based economy, since it is energy sufficient.

However, greening the economy means reducing dependence on coal and either importing more energy resources or investing in renewable forms of energy. One of the steps taken was promotion of solar PV; CZ has become one of the most successful adopters of PV in a very short period of time (3-5 years). In absolute terms, it cannot be compared with Germany or the UK given that it has roughly the same geographic size as Ireland . However, in relation to solar PV per capita (see Figure 4.1), CZ was among the top three EU producers in 2011. Therefore, it can be considered a success in terms of solar diffusion.

Emergence of Technologies and Niche Market (1993-2000)

There is little to be said about solar before 1993, since at that time the CZ was part of the Czech and Slovak Federal Republic (Czechoslovakia). It is difficult and would be inefficient to try to trace development of solar in communist Czechoslovakia since the technology was in the experimental phase and data are nearly impossible to find. In addition, Czechoslovakia was focused more on nuclear and dependent on energy imports from the USSR, so seeking energy independence and lowering emissions were not major reasons for pushing solar PV. The only function that was active is legitimation. There was an active green movement, since the CZ was one of the greatest polluters in Europe and there were some internal pressures to make its energy sector more environmentally friendly. Since 1996, there is evidence that there was some form of knowledge development, proxied by the increasing number of publications from Czech institutes on solar PV (see Figure 4.37). Lastly, in terms of Entrepreneurial experimentation there is no reliable data showing the number of companies entering the CZ PV market across time. However, there is some evidence of companies in the 1990s producing PV cells and modules as well as silicon ingots and wafers, mostly as spin-offs from Tesla (the large, state-owned electrotechnical conglomerate in the former Czechoslovakia) (Bechnk, 2010). However, most companies had exited the market by the end of the 1990s. Thus, there is some evidence of entrepreneurial experimentation taking place.

Overall, in this period the only functions for which we can see some activity is legitimation and entrepreneurial experimentation, but clearly these were not enough to stimulate diffusion.

Dominant Design (2001-2003)

In this period, we observe a strengthening of the legitimation function, some elements of knowledge development, but no markets, no entrepreneurs testing the technology and no specific guidance from government.

Knowledge Development Some evidence of strengthening of this activity is evident in this period, proxied by the number of papers (Figure 4.37) and the number of patents (Figure 4.36), both of which show a slight increase in this period. However, both aspects remain limited.

Legitimation In 2001 the CZ became a member of the IEA, and the government ratified the Kyoto Protocol. According to the Kyoto Protocol, CZ had to reduce its GHG emissions by 8% by 2008-2012. However, no reference is made as to how this should be achieved and, thus, there is no explicit reference to solar. Ratifying the Kyoto protocol was an indication that government was moving towards a green energy policy, thus some form of legitimation can be perceived.

Towards the end of the period, we see a strengthening of the legitimation activity, with a bill passed in November 2003 to promote power and heat generation from renewable energy sources[21]. This bill was more a formalization/implementation of the Kyoto protocol than a new bill, since it formalized the CZ's commitment to an 8% share from renewables in electricity consumption by 2010. However, the bill laid the foundations for the later

[21]This was known as the "Bill on Promotion of Power and Heat Generation from Renewable Energy Sources". For more information, look at http://goo.gl/NPzknL

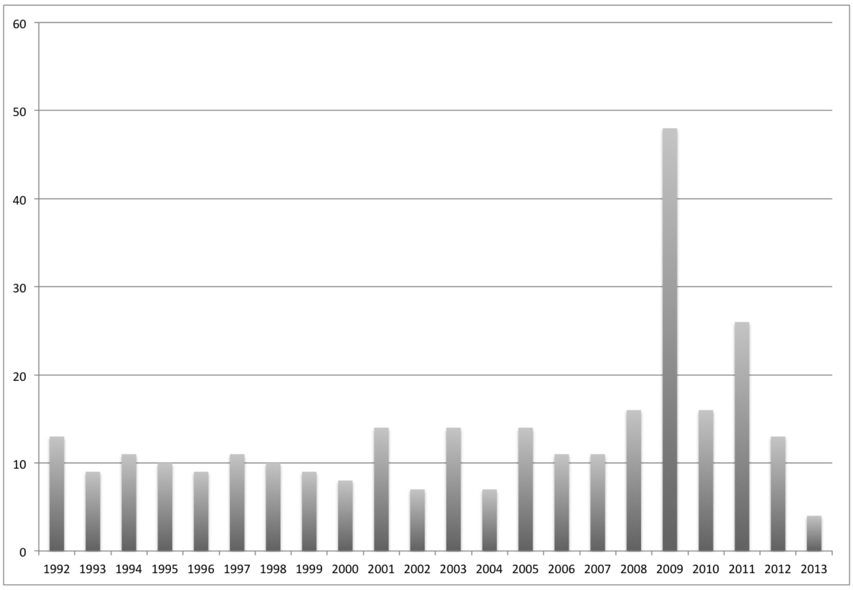


Fig. 4.36 Patents on Solar Technologies from the Czech Republic

Source: PATSTAT

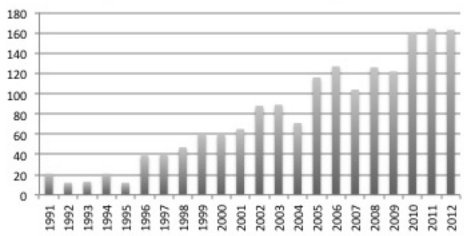


Fig. 4.37 Papers on Solar from Czech Institutions

Source: Scopus

imposition of FITs and Green Certificates which were implemented in 2006. Overall, we see a strengthening of the legitimation function in this period.

Guidance of Search No explicit guidance of diffusion can be identified. However, in 2002, the National Programme for Economical Energy Management and Use of Renewable and Secondary Energy Sources was ratified. This formalized the expectations of the CZ state in terms of short term renewable targets. The most important objectives included a target for renewable energies of 2.9% of energy consumption by 2005, and a reduction in energy intensity (IEA 2002). These can be perceived as an attempt to guide investors, and illustrate government's commitment to renewable energy, but still with no explicit guidance towards solar PV. Similarly, this can be also seen as an event that contributes also to strengthening the legitimation function.

Resource Mobilisation Official statistics on R&D expenditure[22] (Figure 4.38) show that CZ made no investments in solar PV in this period and there was no support for R&D. In addition, the lack of subsidies or any other financing and support mechanisms suggest that this activity was still completely underdeveloped. Therefore, we can argue that there are no signs progress in this activity.

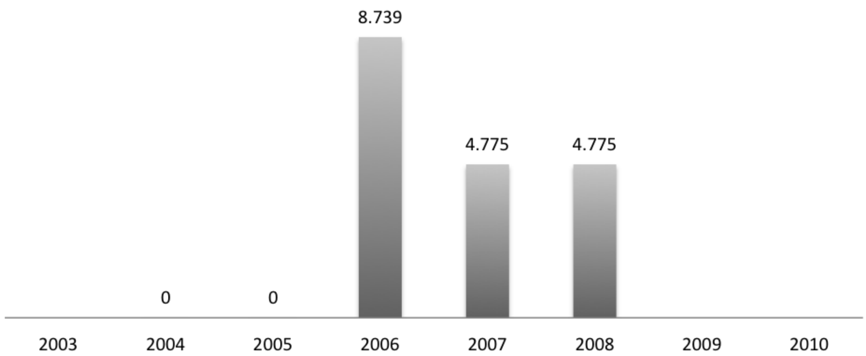


Fig. 4.38 Total Spending in Solar R&D (Million Czeck Korunas) (2003-2010)

Source: OECD

Market Formation Although there are no installations of solar PV in this period, we can see some evidence of market institutionalization. In January 2001, a New Energy Management Act (Act. No 406/2000 Coll.) was implemented, which radically changed the energy sector by liberalizing the electricity and natural gas markets, and established a new set of regulations, which, however, were targeted more towards CHP plants. (IEA 2001, p.8). Thus, although this did not have direct relevance for solar, it can be seen as helping to institutionalize the market for renewables, since it helped to clarify markets and allocated tasks and responsibilities to the various actors. Thus, some progress was made in this activity.

Conclusions from this phase This phase can be perceived as preparatory for the establishment of solar TIS. Although there is no major policy or technological breakthrough, we can observe an increasing interest of the government and of the society towards RETs, something reinforced by the international participation pressures to the

[22] 1 EUR is equal to approximately 25-30 Czech Korunas

CZ. At the same time, the liberalisation of the market can be viewed as a first step towards the establishment of a potential market for solar entrepreneurs.

Mass Market (2004-)

In this period, various developments contributed to the dramatic increase in solar PV in CZ. These include strong legislative incentives which took the form of generous FITs; at the same time, standardization of solar technology at the global level led to a collapse in the price of solar panels. These factors combined led to a fall in the cost of solar PV systems and an increase in their affordability. Specifically, we see that the first significant installations of solar PV in the CZ occurred in 2006, but the majority were installed in 2008. In the two years following this, we observe a five-fold increase in solar energy installed (Figure 4.39), and by 2010 the Energy Regulatory Office (ERU) declared that almost 1000MW of solar capacity had been installed, across 11,000 projects (Tsagas, 2013). This spurt in installations led to a total of 2022MW of solar PV installations by 2012. This made CZ one of the most successful producers of solar PV in Europe, ranked third after Germany and Italy, as shown in Figure 4.1.

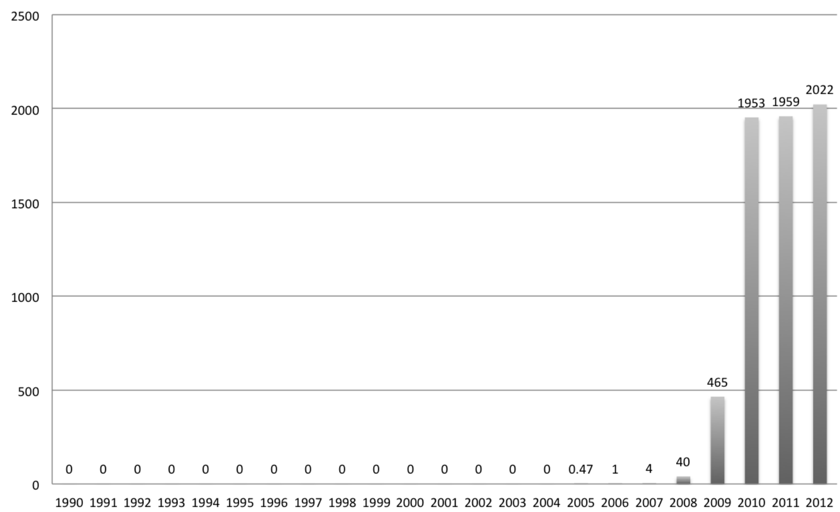


Fig. 4.39 Solar PV Capacity in the Czech Republic (1990-2012)

Source: IEA

Knowledge Development An increasing number of papers on solar were published in this period (Figure 4.37), and there was a huge spike in the number of patents for solar (Figure 4.36). This pattern is not unexpected since so many entrepreneurs entered the market and started installing solar systems, leading to some incremental innovations.

Therefore, we can conclude that there was satisfactory progress of the system in this activity.

Legitimation In this period, we observe that there was increasing pressure on CZ to comply with EU renewable energy implementation programmes. At the same time, there was a need to reduce energy dependency, which has shown signs of increasing in recent years (see Figure 4.40), primarily due to the implementation of the State Energy Policy, which was adopted in 2004. This led to the establishment of the Czech Renewable Energy Agency in 2004, whose aim was to promote renewable energy sources, especially PV. At the same time, the Czech RE Agency was involved in several international projects within the Intelligent Energy Europe programme including "the Photovoltaics in the European Union New Member States" and the "PV Legal". Also, in 2006, a new National Programme on energy management and use of renewable energy sources (amended in 2006 and 2011), was introduced aimed at promoting renewable energy and energy efficiency. Other programmes included the National Programme for the Reduction of Emissions of the CZ (2007), the National Programme to Abate Climate Change Impacts (2007) and the Climate Protection Policy (2008). However, no specific guidelines were given for solar; these acted simply as indirect pressures.

In addition, in 2009, the Czech Photovoltaic Industry Association (CZEPHO) was established, to increase connectivity among the various actors in the PV industry. In 2011, the CZ ratified the IRENA statute, which shows commitment to renewable energy in general, although not solar in particular. Lastly, we observe the participation of CZ in various European institutions such as the European renewable energy trade associations, the European Renewable Energies Federation (EREF), the World Wind Energy Association (WWEA), Eufores, and Eurosolar. All of these development demonstrate significant strengthening of the legitimation function, but also some formalisation of the supply side of the market.

However, the public perception of solar PV has recently (post 2009) turned negative. This public discontent with solar PV can be attributed to two main reasons. Firstly, there is a fear that the cost of financing the subsidies will be passed on to customers and businesses, and will increase electricity prices by 18% (Tsagas, 2013). Secondly, there is a belief that the main investors in solar PV are the politicians and energy distributors who have misappropriated funds that could have been used more efficiently had they been allocated to private investors (Tsagas, 2013). Therefore, we can observe an initial approval of solar PV in the CZ, evident in the organizations that were established, but

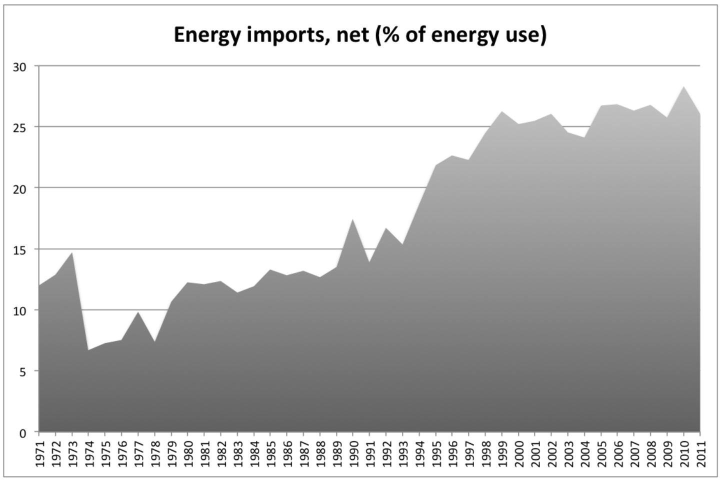


Fig. 4.40 Energy imports, net (% of energy use) (1971-2011)

Source: World Bank Development Indicators (WDI)

a reversal of this legitimation in recent years with public opinion turning against solar. The public believe the industry to be corrupt and responsible for increased electricity prices and wasted public funds.

Guidance of Search The beginning of this phase coincides with the introduction of the Feed-in Tariffs for Renewable Energy Sources in 2002 by Notice of the Ministry of Industry and Trade (No. 252/2001 Coll.), which was supplemented by the Energy Act (No. 458/2000 Coll.) and ensured priority connection, transmission and distribution of electricity from renewable energy sources. Initially the tariff was set at a very low and unprofitable level for PV[23]. This in part explains the ineffectiveness of this measure for promoting solar in this period. Most projects were either off-grid or ad-hoc based on municipal subsidies. An example of this is the "Sun to Schools or Operational Programme Environment" and in several cases by municipal subsidies (Bechnk, 2010). However, this was a first sign to entrepreneurs that government was moving towards renewable energy, and it removed some of the barriers to adoption of solar by ensuring priority connection to the grid.

The policy related to renewables was the State Energy Policy in 2004, which aimed to define a framework for sustainable development. It gave primarily three directions for the future of the CZ state; to maximize energy independence, maximize safety of energy sources, and advance sustainable development. For renewables, it set quite ambitious

[23] 6.00 CZK/kWh, equivalent to about 0.19 /kWh, depending on exchange rate CZK/EUR

targets for the promotion of RETs (e.g. for 8% of total electricity generation from renewables by 2010). Moreover, it proposed increased expenditure on R&D across all renewables. Further financial incentives for renewables were offered in 2005, by providing tax exemptions for owners of renewable energy sources which produced electricity for their own use. In addition, government approved the national programme to abate climate change impacts, mainly as a response to the adoption of the Kyoto Protocol. Lastly, there were some amendments to the 2001 Energy Act (Act No. 670/2004 Coll. - Energy Act), with the primary target energy market liberalization. However, most of these developments did not have a significant impact on the perceptions of entrepreneurs, and we observe no dramatic change in the PV industry.

Overall, there were no major developments until 2005, when the Act on Promotion of Power Generated by Renewable Sources (Act No. 180/2005) was put in place. This introduced further support for the use of renewable sources of energy by guaranteeing revenue for each unit of electricity produced for a 20 to 30 year period. This later became the Law on the Support and the Production of Electricity and Heat from Renewable Resources (Act No. 180/2005 Coll.), which revised the FIT scheme (No. 252/2001 Coll. Act) in 2006 and introduced the "Green Bonus", a scheme that. instead of guaranteeing producers a fixed price, provided them with a bonus over and above the market price. As far as the FIT is concerned, a common tariff of 13.20 CZK/kWh (0.45 EUR/kWh) for all categories and locations of PV was established; similarly, the Green Bonus offered 12.59 CZK/kWh (0.43 EUR/kWh). To put these subsidies into perspective, Figure 4.41 shows the CZ FIT is plotted against the German one. The top graph tabulates the support for large PV systems, and the bottom one refers to smaller systems. The most interest lines are the yellow and green ones, illustrating support in CZ and Germany. Up to 2005, as already mentioned, there were no major developments in the support policy, so the yellow line is well below the green one. However, after revision to the FIT in 2006 there was a massive jump in the amount of support, which overtook that in Germany. Since 2006, the difference between the two support mechanisms continued to grow until the eventual collapse in prices in 2011.

The scaling down of support for solar PV came in 2010, when the EU Directive 2009/28/EC forced member countries to draft National Renewable Action Plans (NREAPs), outlining the measures they would take to reduce their GHG emissions, increase energy efficiency, and meet the 2020 renewable energy targets. CZ set a target of 14% of total electricity supply from renewables. At the same time, there were strict caps enforceable for each category of renewables. Reaching the cap induced a freeze of funding for that partic-

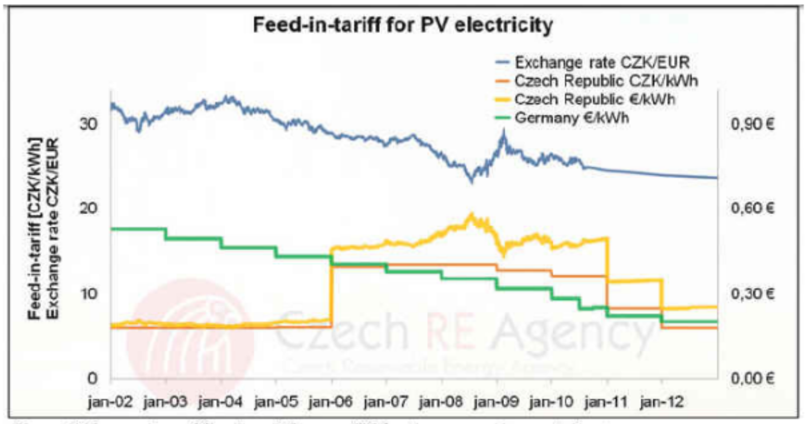


Figure 3. Comparison of Czech and German FiT for large ground-mounted systems (Source: Czech RE Agency)

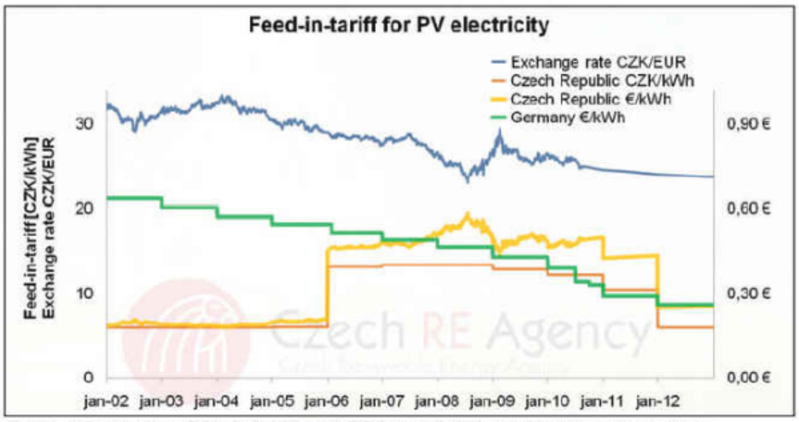


Figure 4. Comparison of Czech and German FiT for small rooftop systems (Source: Czech RE Agency)

Fig. 4.41 Feed-in Tariffs in the Czech Republic compared to Germany (2002-2012)

Source: Czech RE Agency

ular energy source. For PV, the NREAP defined a limit of 1,650 MWp for 2010 and the following years, the limit is incremented by 5 MWp yearly up to 1,695 MWp in 2020. However, the CZ had exceeded this target by 2010 (European Commission). Therefore, a subsequent decrease in support was to be expected, and came in the form of a reduced FIT of 12.15 CZK per kWh ($0.68 USD) in 2010, and a 6.00 CZK/kWh ($0.35 USD) in 2011. As of 1 January 2011, taxes for solar electricity producers were implemented[24]. These taxes although initially thought to be temporary, were set to continue beyond 2013. In addition, in September 2013, a bill was passed to end FITs and any other form of financial support for all renewables, except wind, hydropower, and biomass, from 2014.

In this period performance of guidance for search follows a bell-shape. At the beginning

[24] 26% tax on FiT, and 28% on those receiving green bonus. In addition,small scale installations of less than 30kW are tax exempt.

of the phase, its performance was relatively indifferent to the system; in the middle of the phase it became fully active, and then faded by 2011 with the abolition of the FITs. This illustrates the lack of a stable incentive system which would generate new opportunities over the long term. Instead, we see a pattern of boom and bust, which does not favour diffusion.

Entrepreneurial Experimentation There is no reliable data for entry and exit of companies in the solar PV industry, so it is difficult to assess performance in this phase. However, it can be argued that the function was fully active for a very short period of time, and not for the whole mass market phase. This is because some entrepreneurs were necessary to test the market, and introduce the first systems, something which probably took place in the early years of market development (around 2006 - 2008). The performance of this activity was good enough that allowed the tremendous increase in solar PV installations after 2009, which could allow us to argue that the function was fully functioning in this period.

Resource Mobilisation In terms of resources for knowledge development, there is some data showing evidence of R&D spending on solar in the 2006-2008 period (Figure 4.38). Various funding institutions were established in this period such as the State Environmental Fund and the National Fund for the Environment, which was aimed at producing funding for environmental projects. However, no major innovations, projects or publications came from the funding of these institutes, which implies that these resources were not very effectively used. At the same time, spending soon dried up as a result of the financial crisis.

In relation to funds for adoption, the main source of finance was the Green Investment Scheme (GIS) (2009-2012). This issued loans to the CZ government to finance renewable energy projects, and the FiT; the source of these funds was CZ's emissions permits surplus (known also as "Hot Air"). The Kyoto protocol allowed sale of this surplus to other Annex-I countries which could not meet requirements (Gorina, 2006). However, most countries were unwilling to purchase these surpluses unless assured that the revenue would go to funding environmental projects. The Green Investment Scheme (GIS) was established, and the World Bank Carbon Finance Unit (CFU) were set up to ensure that revenues went to finance "green projects". Although they promoted renewables in general, most of the finance was allocated to improving the energy efficiency of building projects, such as heat insulation, heat pumps, biofuel burners, etc. (World Bank 2014). Some small scale projects for solar were financed, but there was no major impact on the industry.

Overall, there is no evidence of major mobilization of resources in this period in terms of R&D. However, for a short period, funds for adoption in the form of subsidies were plentiful.

Market Formation Although the data were difficult to collect, Table 4.5 shows that the CZ market was relatively well developed and included at least one producer of solar cells, some manufacturers of modules, and around 200 installation companies (PV-NMS.net). Moreover, the introduction of the generous FiTs, increased the cost competitiveness of solar, and led to a huge boost to the supply side of the market. Last but not least, there were also various policies being implemented which contributed to the institutionalization of the market by allowing the integration of solar to the grid. Therefore, we can infer that there was a proper functioning market for solar PV in this period, and that the market formation function was completely active, at least until the removal of the FiTs.

Table 4.5 Main Producers in the CZ Solar PV Industry (2008)

Solar Cells	**Modules**	**Inverters/Transformers**
Solartec	SchottSolar Kyocera O & M Solar Fitcraft Production Solartec	Pouler Solar CZ Elektronika Fronius CZ

Source: IEA 2010a

Conclusions from this phase In a way, we can argue that all of the necessary actions for the developments of the Solar TIS took place within this phase. In the early period, we can observe strong legitimation, which stimulated guidance of search which introduced some pilot projects and some rudimentary legislation that would allow the introduction of the FiT in later phases. We can even see that there were some funds for KD. In the second period, we can see that the government introduced even higher subsidies which increased the attractiveness of solar, and thus stimulated the MF function. However, once the subsidies were removed, the industry collapsed, which points to the fragile nature of the CZ TIS.

Schematically, the interactions between the functions can be seen in Figure 4.42. LE stimulated GS, which was again the central function and influenced RM, EE and MF. EE was influenced also by the resources that were mobilised, while MF was shaped both by the government through GS but also through EE.

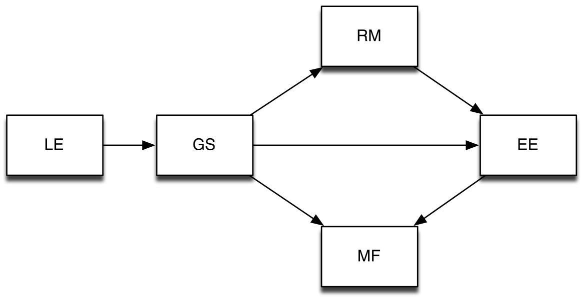


Fig. 4.42 TIS evolution in the CZ in Mass Market

4.4.4 Greece: the late and unsuccessful

Although Greece is not the worst performer for solar adoption, its solar PV performance is average and was a late adopter.

Overview of the Greek Solar Development

Greece began to establish a legal framework and mobilize resources long before its first solar PV adoption. However, diffusion was not as rapid as hoped for, and less widespread. Figure 4.43 shows that real diffusion (i.e. on a commercial not just a small scale experimental level) started in 2001, but it was not until 2009-2010 that the technology significantly penetrated the market. The diffusion process came to an abrupt halt in 2012 when government drastically reduced the subsidies and financial incentives for solar, primarily due to Greek financial crisis. In particular, the Greek Ministry of Environment, Energy and Climate Change (YPEKA) announced that FIT rates would be reduced by 40% for projects installed between 1 February, 2013 and 31 January, 2014 (Coats, 2013). As of August 2013, the FIT for interconnected systems on the mainland, smaller than 100kW, would receive 120Euros/MWh, while larger installations would receive 95Euros/MWh. For non-interconnected systems on the islands, the tariff was fixed at 100Euros/MWh independent of size. This made solar PV projects financially unattractive, since these cuts were not accompanied by corresponding decreases in costs.

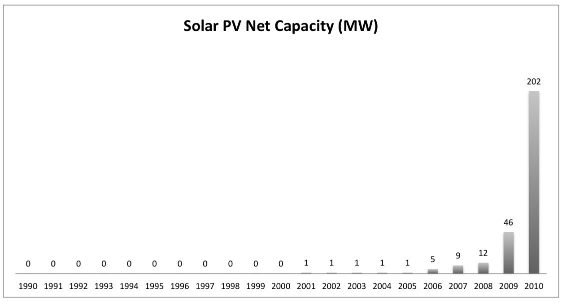


Fig. 4.43 Solar PV Capacity in the Greece (1990-2010)

Source: IEA

Emergence of Technologies (1980s-1993)

Overall, this phase is categorized by some activity in most functions. Although Greece would not appear to be a pioneer in solar PV technologies, we see that significant R&D resources were mobilized towards solar, and various institutions were developed to promote the technology. There was also some minor legislation to promote experimentation during this phase. We can conclude that Greece's performance is not dramatically different from the German model. However, it was not sufficient to trigger diffusion, due mostly to the technology being in the early phase of the life cycle and being very expensive, something which was not compensated enough from the functions of the system so as to promote diffusion.

Knowledge Development There were some papers published on solar developments, especially towards the end of the 1980s (Figure 4.44), and some patenting activity in 1990 (Figure 4.45). However, no major innovations took place. We would therefore argue that there was some knowledge development in this phase, but it was not particularly noteworthy.

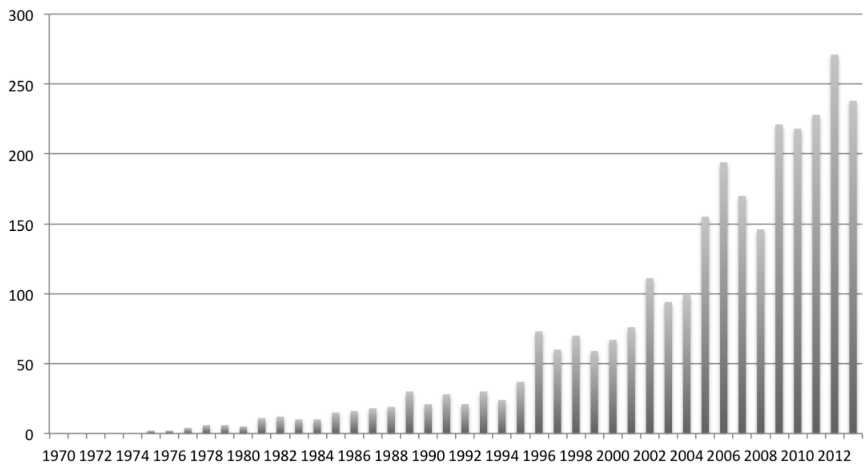


Fig. 4.44 Papers on Solar from Greek Institutions

Source: Scopus

Legitimation In this period, there was a general climate in favour of greening the economy, which was manifested both politically and socially. At the political level, legislation was passed to promote renewable energy generally. However, they were all specific to particular technologies. Thus, it can be argued that the legislation promoted a general environment in favour of renewables, rather than guiding entrepreneurial activity in solar. For this reason, these developments are grouped under the legitimation function. Examples include funding for CHP through Development Law (1982/90), the 1984 law on the exploitation of the Greek geothermal potential (Law 1475/84), and 1987 Law 2689/87 on the siting of wind turbines.

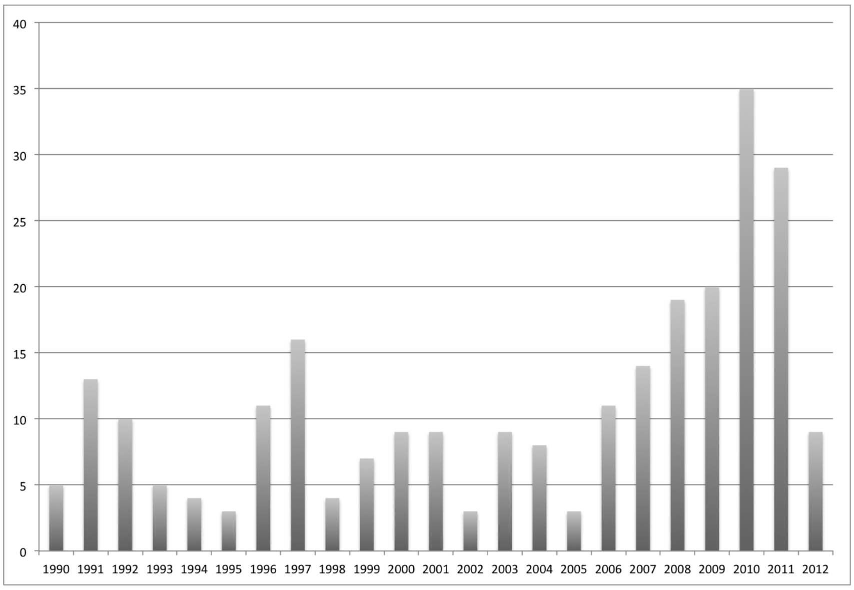


Fig. 4.45 Patents from Greek Authors

Source: PATSTAT

There have been several waves of environmental activism in Greece since the 1970s (Kousis, 1999), from both formal and informal organizations. Environmental movements started to become institutionalized and by the 1980s were finding support from over a hundred new environmental organizations, focused on various aspects of the green movement, such as air, water and soil pollution (Kousis & Dimopoulou, 2000). However, the impact on society was small and decreased over time as shown in the reduced number of environmental protests (Figure 4.46). We can conclude that there was some development in this activity, but, like knowledge development, nothing major.

Guidance of Search In 1987, the Centre for Renewable Energy Sources (CRES) was established, aimed at promoting research in the field of renewables. It was responsible for testing and experimenting in various renewable applications, with no commitment towards solar. This institution can be seen more as influencing policy and guiding action than developing new knowledge and, thus, is grouped under this function. Law 1559/85 (1985), which contributed to the establishment of a market for renewables, can be seen as providing guidance towards renewables, but with explicit provisions for solar. Therefore, we conclude that some but limited progress was made in this function.

Entrepreneurial Experimentation We observe some firms entering the industry in this period, but their number remained limited across the period (Figure 4.47). There

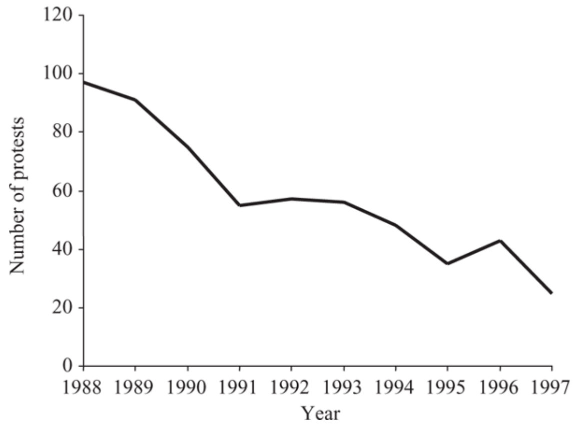


Fig. 4.46 Environmental Protests in Greece 1988-1997

Source: Rootes 2003

were no significant demonstration projects, so we would argue that this function was active, but limited.

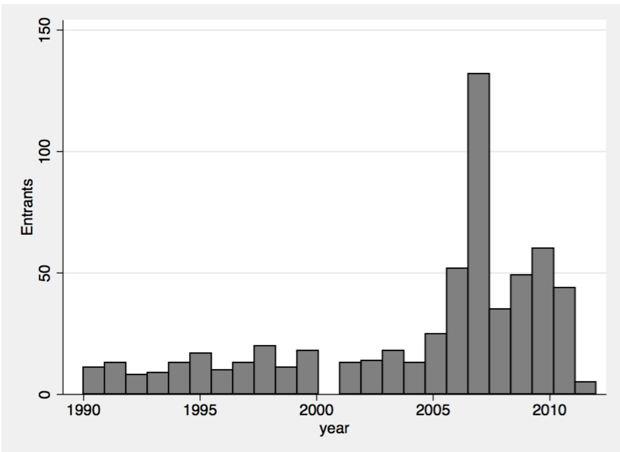


Fig. 4.47 Number of new Entrants in the Solar PV industry in Greece

Source: Amadeus

Resource Mobilisation Although Greece is a small country, the Greek government provided funds for solar R&D expenditure as early as the mid 1970s (see Figures 4.48 - 4.49), probably to try to exploit its ample solar resources. This trend continued to the end of this period. In addition, almost half of the Greek spending on renewables R&D was addressed to solar, and around 20% of total energy R&D was solar. This underlines the importance of solar for the Greek TIS and we can conclude that this function was very active.

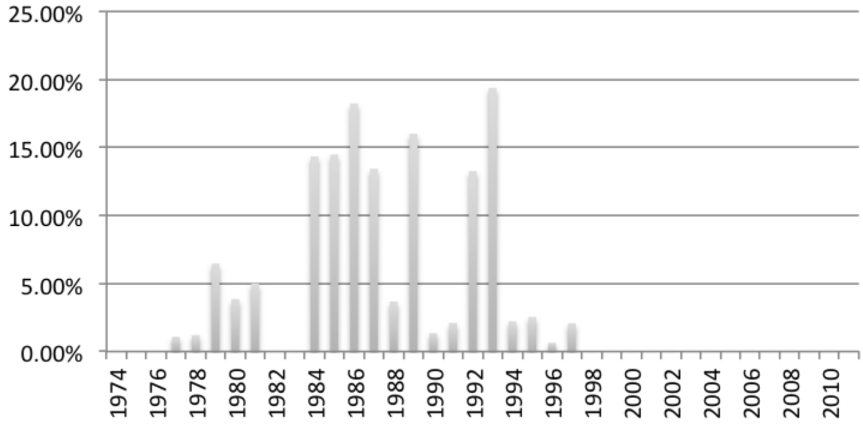


Fig. 4.48 Solar Spending as a % of total Energy R&D Spending) (1974-2011)

Source: OECD

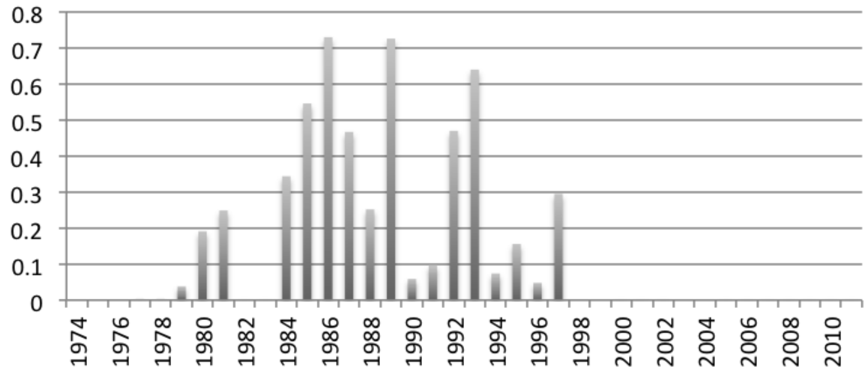


Fig. 4.49 Total Spending on Solar R&D (Million Euros) (1974-2011)

Source: OECD

Market Formation In 1985, government voted in Law 1559/85 (1985) which regulated the generation of renewable electricity. In particular, it allowed third parties to generate limited amounts of electricity from renewable energy resources and then sell them to the Public Power Corporation (PPC). This law contributed to institutionalization of the market by allowing integration of renewables to the grid. However, the prices of Solar PV systems was still prohibitively high, and the demand for such systems was very limited. Therefore, we could argue that there is some evidence of limited progress in this function.

Conclusions from this phase What we observe in this period is that all of the functions of the TIS were starting to develop - even MF. There was a general climate in favour of renewables, some guidance from the government, who established the CRES, and some elements of market being institutionalised. The most active function was RM, with the government devoting around 20% of total energy R&D on solar. However, the system was not particularly successful in the diffusion. A potential explanation for this is the lack of KD. Although, the system's activities were all functional, the one which was crucial in this phase is KD, given that the technology is still in its infancy. The government, although it poured a lot of resources in solar R&D, it did not accompany these resources with any specific guidance or other supportive policies (e.g. a demonstration program). Thus, the system did not manage to operate successfully in this phase. Therefore, what we can see is that the key function in this early period of the technology is knowledge development. If the TIS is not geared towards being at the technological frontier, there are no chances of success, even if there are enough resources mobilised. This evolution can be seen in Figure 4.50.

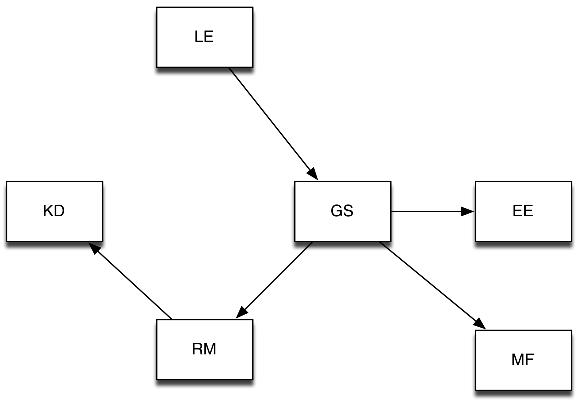


Fig. 4.50 TIS evolution in the GR in Emergence of Technologies

Niche Market (1994-2000)

This period starts with the introduction of the FIT tariff, and is characterized by an increase in the performance of activities in almost all functions in the system. However, there are still no evidence of any solar diffusion taking place.

Knowledge Development The number of papers produced in this period shows an upward trend (Figure 4.44), probably due to the increased importance of the CRES. The CRES, from a political/lobbying institution, became in this period the main performer of renewable energy R&D. Law 2702/99 appointed CRES "as the national coordinating agency for all activities related to renewables" (IEA, 2002). Its important role involved national coordination of renewable energy activities and responsibility for feasibility studies on the potential for diffusion of renewables. It became a knowledge hub and guiding force behind the dissemination of information on the potential for the diffusion of renewable energy. It initiated numerous pilot projects, but not focused on solar PV, and there was not a huge increase in number of patents produced. Overall, we can conclude that there were some events that helped knowledge development, but these were not enough to generate any notable innovations in the field.

Legitimation A major development in this period was the Climate Action Plan (1995). According to this, the government set a target to increase the share of renewables to 10% of the primary energy supply by 2000 (IEA, 2002). This provided general guidance for policy on renewables, but no specific targets in terms of technologies. However, it demonstrated the commitment of government to diversifying the energy mix.

At the societal level, in October 1995, the Network of Environmental Organizations was created, which aimed at facilitating and formalizing the political nature of the environmental movement. This led to the formation of various political ecology groups and networks. Examples, include "Oikologiki Kinisi Thessalonikis", "Enallaktiki Kinisi Oikologon" and the "Pan-Hellenic Environmental Non-Governmental Organization" (Kousis, 2003). However, none of these parties managed to get elected to government or have a major impact on society as shown by the reduced number of protests in this period(Figure 4.46).

Therefore, we can say that this function is showing some signs of strengthening given the reinforcement of the government's commitment towards RETs and the establishment of green political functions.

Guidance of Search The beginning of this period is marked by the introduction of Law 2244/94 (1994), which established FITs for the first time in Greece. Its aim was to stimulate production of electricity by private entrepreneurs, by clarifying the conditions under which renewable energy producers could access the grid, and the size and duration of subsidies.

Other legislative developments in the period included Law 2364/95 Greece (1995), which provided tax exemptions for users of renewable technologies. However, this applied mainly to small-scale domestic projects, and primarily solar heaters. In 1999, government announced the Plan for Domestic Action, which was another attempt to establish a comprehensive plan for renewable energy diffusion. Lastly, in the same year the Law 2773/99 obliged the Transmission System Operator and the PPC to provide connection to new generators and resulted in an upward revision of the FIT rate. However, the new tariff was still too low for solar PV, and there were many transmission problems with the grid which did not encourage the establishment of new projects[25].

There seems to have been a climate conducive to renewable energy in Greece during this period, based on various financial incentives and commitments from the government about future diffusion. Also, there were few actions aimed specifically at solar PV. Thus, there were some signs of guidance from the government in this period.

Entrepreneurial Experimentation The main investor in renewables was the PPC, through its subsidiary PPC Renewables. In particular, it had a 10-year Development Plan for the period 1994-2003, which was focused mostly on hydro and wind (IEA 2002). At the same time, we can observe a slight increase in the number of companies entering the solar industry in Greece (Figure 4.47), which allows us to argue that this function was active in this period, although relatively limited[26].

Resource Mobilisation Total spending on solar R&D was cut drastically in this period, according to the official data by the OECD (Figures 4.49). The main source of funding for pilot programs was the EU Operational Programme for Energy (OPE), which provided grants to various renewable energy projects. However, by 1999, only eight solar PV projects had been completed (IEA, 1994).

The lack of R&D funding was due to shift of resources for renewables from research to commercialization, induced by Law 2244/94, which subsidized RETs. This subsidy came from two main funding sources: Development Law 2601/98 and the Operational Programmes for Energy and Competitiveness. At the same time, the introduction of the FiT can also be considered as evidence that more funds became available for the deployment of solar. Since the funding was only awarded for commercialization of the technology and not for other purposes such as knowledge development or deployment,

[25]In 2001, the Greek FIT was 0.0731 Euros per kWh, while in Germany it was more than 0.5 euros per kWh

[26]Caution is needed in interpreting this graph: many of these companies deal with both solar and other technologies. Since we do not observe any major increases in solar electricity production, the entry data like correspond to companies not wholly focused on solar.

the performance of this activity remains at an average level.

Market Formation There is the basis for some demand creation from the introduction of the FiT. However, according to official data and Figure 4.43 no electricity was produced from solar[27]. However, most of the evidence shows that solar energy was used primarily to produce hot water (IEA 2002a).

Looking at the supply side, the basis that was set in the previous phase was still in place. However, there were many rules, guidelines and regulations in place to allow renewable electricity installations, making the process very bureaucratic. For example, in order to begin construction of a renewable installation, the developer needed approvals from the Forest Management Services, the Archaeological Services, the Ministry of National Defence, radio and television broadcasting authorities, and the Civil Aviation Authority, which, on average, took 19 months. Also, the Law 2773/99 stipulated that generation authorization must be acquired from the Ministry of Development based on a recommendation submitted by RAE (Regulatory Authority for Energy) to the ministry. The government estimates that the process will take 4-12 months (IEA, 1999). Lastly, another barrier to market development was the underdeveloped grid infrastructure which made the process of feeding electricity into the grid very costly.

Overall, we can conclude that there is some demand and some institutionalised supply, but many rigidities remained in the market.

Conclusions from this phase The key observation from this phase is the adverse effect of complementarities between GS, RM and MF. On the one hand, partly because of the strengthening of the LE function, the government is trying to stimulate demand through the introduction of subsidies (GS and RM) and demonstrations projects. On the other hand, it does not allow the supply side of the market to operate, by imposing various bureaucratic barriers (MF). This in turn prevents the development of EE and thus the development of the whole system. Once more, this is a clear illustration of the importance of the complementarities between the functions of the system: even if one function is not properly aligned with the direction of the rest, the system can stop to function efficiently. This evolution can be seen in Figure 4.51.

[27] Some sources suggest that limited amounts of energy were produced from by solar. In particular, according to the IEA report (IEA 2002a), some 0.45 TWh were produced from wind and solar combined. However, it is not clear how much is due to solar.

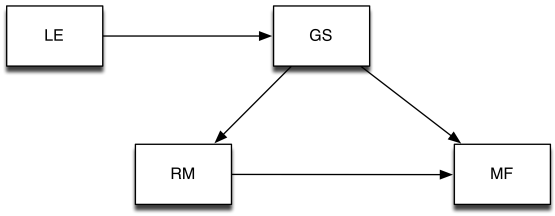


Fig. 4.51 TIS evolution in the GR in Niche Markets

Dominant Design (2001-2003)

In this period, we observe minor advances and failures in the system, most notably decreased legitimation, resource mobilization and guidance of search. This is rather surprising since, at the global level, a dominant design and standardization of the technology were emerging. We would have expected better functioning of the system, while in reality it deteriorated in almost every function.

Knowledge Development There was an upward trend in the number of papers produced, which potentially indicates further improvement in this activity. However, there were no major technological breakthroughs in Greece in this period, and no increase in number of patents. Therefore, performance in this activity was relatively limited.

Legitimation In general, there was opposition to some forms of renewables, especially wind power, which forced government to introduce a 2% tax on renewables in July 2001. The revenue derived was to be used to subsidize various local community activities. It was hoped this would increase the public's acceptance of renewables, however this did not happen until the late 2000s. We can conclude that this general opposition against RETs weakened the legitimation function.

Guidance of Search As mentioned in relation to the legitimation function, in July 2001 a 2% tax on renewables was introduced, without however reducing the FiT that was last updated in 1999 and with an average buy-back tariff was € 0.0616/kWh in the interconnected system and € 0.0731/kWh on the islands. This tax disadvantaged renewables since they were only marginally competitive on price with conventional energy sources. In September 2001, Greece complied with the EU Directive (2001/77/EC) and set a target of 20.1% of electricity from renewables by 2010, which is a sign of strengthening of this function. However, there was no specific guidance towards solar in the Directive; thus, we cannot argue that it had a major impact on the function. So, no major progress was made in this activity.

Resource Mobilisation In this period, R&D spending on solar PV came to a halt. There were increased subsidies, but also an imposition of a tax rate on electricity production from RETs at the local level. Therefore, we can conclude that there was a very significant lack of resources and the activity was inadequate.

Entrepreneurial Experimentation In this phase, there are no major new entries and, thus, no major changes or developments in this activity over the period, despite standardization of solar technologies. Of the 1GW of new renewable capacity that was planned for Greece, only 1MW was solar PV (IEA 2006), which illustrates the lack of interest from the entrepreneurs.

Market Formation The first installations of solar PV amounted to 1MW (Figure 4.43). The RAE awarded licences for new power plants running on renewable energy sources, representing a combined total capacity of 1,155 MW: from this, only 1MW was planned for solar, while the vast majority was given to wind (912MW) (IEA 2002). Thus, there is some evidence of demand generation. At the same time, the dominant design emerged, which led to a decrease in the cost of solar. However, this was offset by the imposition of the 2% tax.

In terms of the supply side, we see that government improved the functioning of some market mechanisms. For example, Law 2491/01 tried to reduce the bureaucracy by reducing the number of licences required. The Common Ministerial Decision 1726/2003 accelerated the licensing procedure by stipulating a specific time for a decision, which, if exceeded, meant that permission for the project was automatic.

Conclusions from this phase In this period, we see a completely unbalanced development of the system, which can potentially explain the lack of diffusion. Firstly, legitimation was weakened; the government tried to use GS to strengthen it, but in this way hindered the development of MF and EE. To improve the performance of MF, there were some attempts to remove some of the barriers, but at the same time eliminated most of the R&D funding. All these actions again illustrated the importance of government as a coordinator of the various functions. In terms of the functions, we can see the importance of legitimation clearly, as well as that of resource mobilisation and guidance of search. This evolution can be seen in Figure 4.52.

Fig. 4.52 TIS evolution in the GR in Dominant Design

Mass Market (2004-)

In this phase, we see a fully functioning TIS, which allowed for rapid stimulation of solar diffusion. However, the functioning of the system came to an abrupt halt when government imposed a series of taxes and reduced subsidies towards the end of the period.

Knowledge Development This period is characterized by continuous knowledge developments evidenced by the increased number of papers and patents. However, towards the end of the period, especially after 2008, the CRES and other knowledge institutions stopped operating as funding was depleted. The apparent paradox between the increased numbers of papers and patent applications and the elimination of funding sources is related to the time lag between paper publication dates and patent awards. This function was performing well in the early period, but declined across time, probably due to the lack of financial resources.

Legitimation In this period we see a strengthening of the legitimation function. In particular after recognizing the importance of renewables, government set up the MEECC/ YPEKA to be responsible for renewable energy policy in Greece. The Ministry was set up in November 2009 and merged the Ministries for the Environment, Physical Planning and Public Works, and Development (IEA, 2011). There is some evidence that the technology was increasingly being accepted as producers began organizing in lobby groups such as the Hellenic Association of Photovoltaic Companies (HELAPCO). In 2012, Greece ratified the International Renewable Energy Agency (IRENA) statute, which is further evidence of Greece's commitment to a sustainable energy future. This clearly would involve solar and thus strengthened the legitimation function.

Some local/regional opposition to renewables persisted, in particular, in relation to infrastructure issues, especially connectivity and transmission. The Renewable Energy Law (3851/2010) redirected some of the revenue from taxes on renewables to local authorities, in order to try to reduce these complaints.

We can see strong performance of this activity with some minor signs of weakening.

Entrepreneurial Experimentation In this period, we observe the highest number of new entrants. However, this did not necessarily mean that entrepreneurs were testing the technologies. This testing had been mostly accomplished since the technology had entered the dominant design phase and there was no need for further testing by entrepreneurs. Instead it was about testing the market, which probably happened in the early years of this period. The increased number of entrants from after 2005 was probably attributable to market formation rather than entrepreneurial experimentation. Therefore, we can conclude that this function was active at the beginning of this period and, later, became unimportant.

Guidance of Search This period starts with generous incentives for solar PV. For example, according to Development Law 3299/2004 (2004), either 20%-40% of initial investment in RET installations would be covered by the state, or there would be a 100% tax exemption on the cost of a new installation. A milestone in this period was the upward revision of the FITs which took place in 2006, according to Article 13 of Law 3468/2006. FITs were to be awarded on a monthly basis and, for solar, the price was 450-500 Euro/MWh for units with an installed capacity of less than or equal to a maximum of 100 kW, and 400-450 Euro per MWh for units with installed capacity greater than 100 kW maximum. This law included further provisions for RETs by allowing preferential access to the grid, etc. It contributed to the institutionalization of the RETs by establishing publication of an annual national report on RETs and energy efficiency issues.

Joining the EU forced Greece to adopt some binding requirements for renewable energy. In particular, in 2009, following EU Directive 2009/28/EC9 (2009), Greece agreed to generate 18% of total electricity from renewables by 2020. This was announced in a special law (FEK 1079/2009), which promoted solar PV, but focused on small rooftop PV systems up to 10 KW, but with aim of achieving an additional 750MW of solar PV. This law guaranteed a FIT of 550 Euro per MWh, guaranteed for 25 years and adjusted annually for inflation (see Figure 4.53).

In 2010, the Renewable Energy Law (3851/2010) increased the target for electricity from renewables to 20% of gross final energy consumption. The National Renewable Energy Action Plan (NREAP), which did not provide explicit provisions for solar PV, provided guidance on how to achieve this. More importantly, the law imposed a downward revision of the FIT for solar. In particular, for installations of less than 100kW, the tariff started at 351.01 Euros/MWh in 2012 and reduced to 260.97 Euros/MWh in 2014, while for larger installations the tariff started at 419.43 Euros/MWh in 2012 and reduced to 293.59 Euros/MWh in 2014. The tariffs for solar are depicted in Figure 4.53, with rates guaranteed for 20 to 25 years. However, given that the average wholesale electricity price in Greece for 2007-2009 was 69EUR per MWh (IEA, 2011), it could be argued that these tariff levels for solar PV were very generous.

Feed-in-tariffs for PV in Greece

Year of signing of contract	Rooftop systems <10 kWp (€/MWh)	Month	Mainland grid (€/MWh)		Autonomous island grids (€/MWh)
			> 100 kWp	≤100 kWp	
2009	550	February	400	450	450
		August			
2010		February			
		August	392.04	441.05	441.05
2011		February	372.83	419.43	419.43
		August	351.01	394.88	394.88
2012	522.5	February	333.81	375.53	375.53
		August	314.27	353.56	353.56
2013	496.38	February	298.38	336.23	336.23
		August	281.38	316.55	316.55
2014	471.56	February	268.94	302.56	302.56
		August	260.97	293.59	293.59
Tariff Payment	25 years		20 years		
Inflation adjustment	Adjusted partially (25% of last year's Consumer's Price Index) annually				
Other incentives	The residential PV system is no longer considered a business activity, and the income from the sale of electricity is tax free.				

Fig. 4.53 Feed-in tariffs for Solar PV from 2009 to 2014 in Greece

Source: The Hellenic Association of Photovoltaic Companies

We can conclude that performance of this activity was very high, with some signs of weakening towards then end of the period.

Resource Mobilisation In this period, official statistics show that there is a complete absence of funding for solar R&D (Figures 4.48 and 4.49). This followed the general reduction in funds for research on renewables. For example, towards the end of the period, Law No. 4093/2012 stipulated a reduction in researchers' salaries. However, we can observe that the number of patents and papers produced in this period continued to increase. This shows that there were some resources supporting research in the field, which are nonetheless not captured by the IEA official statistics. Moreover, some of these patents might be the result of accumulated knowledge and experience from the previous phases. Therefore, we can conclude that there were some resources supporting knowledge development.

At the same time, the FITs provided to producers were generous for at least part of this period, but continued only for a very limited period, as shown in Figure 4.53.Therefore, we can argue that at the beginning of the period there were some resource mobilised towards the diffusion of solar, however by the end of the period, this function has but lost some momentum.

Market Formation In this period, we see a wide range of institutions around the deployment and commercialisation of RETs. Thus, this is evidence that function was active; whether it was fully active is questionable. In particular, an essential part of the proper functioning of the market is related to the licensing process. The bureaucracy meant that obtaining a licence for a solar installation was an arduous process, which is evident from the previous discussions of functions. However, in this period we see that Greece made further attempts to simplify the process through Law 3851/2010, which simplified the process and imposed deadlines for decisions. Nonetheless, several agencies were involved in licence application process; the RAE issued licences at country level, but the municipal, prefectural and regional authorities were also involved in the process. The law decreed that the process should not exceed 30 months. Some evidence of further strengthening is that producers were organizing themselves, and established a solar industry association (Helapco).

Apart from connectivity issues, a key element in market formation is cost competitiveness. The guidance of search function demonstrates that there were various support policies that made solar PV financially attractive to investors, and its cost competitiveness increased, especially with the introduction of the FiTs. From the evidence on penetration of solar PV installations in the market in this period, we can assume the market was fully formed. Thus, we conclude that this activity was almost in full operation in this period. However, the reduction of the FiT reduced the attractiveness and thus exerted a negative impact on this function.

Conclusions from this phase This period is characterised by the introduction of the very generous FiT, which led to a very high diffusion of solar. This was combined by increased LE, and high RM, as well as an improvement in the conditions of the market.

However, the abrupt removal of this support policy brought about a complete halt in the system. This illustrates that the Greek TIS was based primarily on the subsidisation of government rather than on any other incentives. Once again, the importance of GS is highlighted in this activity, primarily with respect to its impact on MF and RM. This evolution can be seen in Figure 4.54, whereby legitimation influenced guidance of search, which in turn influenced resources, market formation and entrepreneurial experimentation. At the same time, resource mobilisation influenced entrepreneurial experimentation, which also influenced market formation.

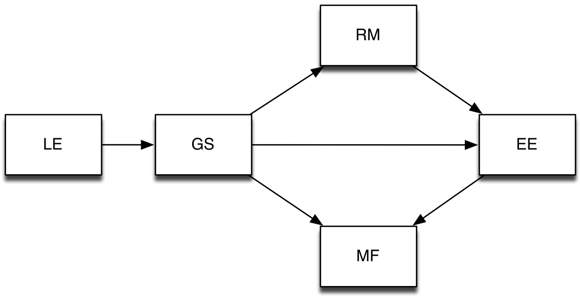


Fig. 4.54 TIS evolution in the GR in Mass Market

4.5 Summarising the Findings from Case Studies

Given the length of the case studies, we use the methodology used in the previous section to summarise the evolution of the TIS across time. This means that using the coding criteria that we summarised in appendix C.8, and the findings from the case studies, we assigned a value for each function for each period for each country. The results of this work which demonstrate the TIS evolution in these countries is depicted in Figures 4.55 to 4.58.

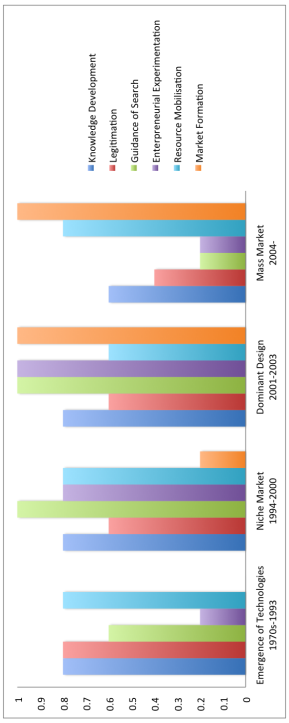


Fig. 4.55 Solar PV TIS Evolution in Germany

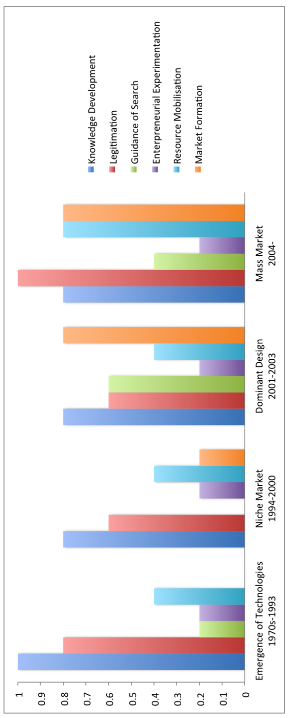


Fig. 4.56 Solar PV TIS Evolution in UK

Fig. 4.57 Solar PV TIS Evolution in Czech Republic

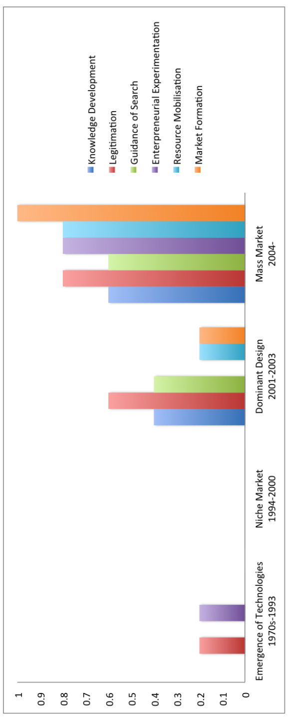
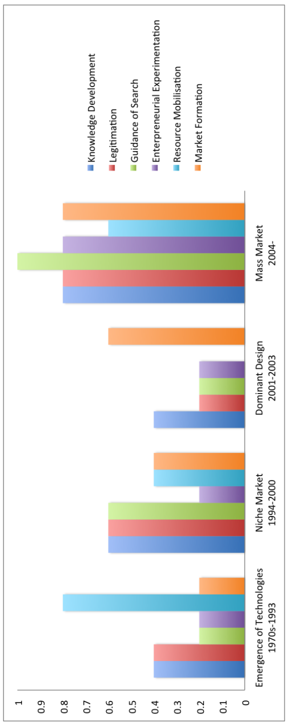


Fig. 4.58 Solar PV TIS Evolution in Greece



If we look in the case of Germany in more details, we observe a gradual diffusion of solar, which followed the establishment of a strong KD, LE and GS. Then, as the technology became standardised, the GS moved towards supporting EE and MF, eventually making Germany the most successful country in solar. As far as the UK was concerned, the initial progress in KD did not seem to influence GS in such a way that it would mobilise sufficient resources to maintain UK research edge in solar. The TIS in the UK seemed to pick up after the technology entered the dominant design phase, and the government decided to stimulate EE and provide support policies specifically targeted to solar. However, once these support policies were removed, the solar TIS came to an abrupt halt. If we look at the performance of Greece, the early phases were characterised by very high RM, the second phase was characterised by weak MF, and the third phase by weak LE, all of which were the result of inefficient GS. The last phase was characterised by extremely generous GS and RM, which managed to temporarily stimulate diffusion. Similarly to Greece, the TIS evolution in the Czech republic can be viewed as a boom and bust story, with very generous support for solar, which stimulated MF. However, the support was not kept in place long enough to allow the industry to be established, which meant that the removal of the subsidies brought the diffusion to a standstill.

An interesting finding that emerges from the graphs which summarise the TIS evolution is a confirmation of Hekkert et al. (2007), who suggested that some functions might be more important than others in different time periods. In this work, we find that in all four cases, MF becomes necessary in the TIS after the dominant design starts to emerge. Conversely, KD is important in the early phases of TIS, while it becomes less important as the technology becomes standardised.

Other functions also seem to have a difference in the way they operate as the system evolves. Although it is necessary for all phases, RM seems to influence KD in the early phases, then influences EE, and eventually is used for financing of new installations. Similarly, EE seems to be vital in countries which are testing the various technologies in the early phases, while after the emergence of the dominant design its role becomes one of testing the market. This is transitory nature of EE is similar to the idea offered by Baumol et al. (2011), who suggest that there are two types of entrepreneurs: the innovative and the replicative. The former is responsible for developing technological breakthroughs, while the latter is not trying to develop radically new products as it is suggested in the original Schumpeterian view, but rather develop highly similar product to the existing ones by refining the existing technologies.

Despite the time varying property of the activities, we can observe a pattern with respect to the sequence of actions necessary for evolution of the TIS. In every phase of the TIS evolution of each country that we discussed in the case studies, we presented a diagram which illustrated how the functions interacted. By looking at all of them in combination, we observed a general pattern that emerges. In more details, we can see is that in all countries the TIS had to establish social support for the technology (LE), which then influences and stimulates policy (GS). The aim of policy is then to mobilise enough resources (RM) to stimulate entrepreneurs to start commercialising and testing the technology (EE), eventually establishing a market for the technology (MF).

This process was observed in the CZ, where it happened within one period. In Germany, this transition occurred gradually as the technology moved across the time period. In the UK, a similar pattern was followed, with LE influencing GS, and then GS influencing EE and MF. Lastly, the Greek case also confirms this general pattern, but similarly to the CZ, all of this process took place within the last phase of the solar PLC. Schematically, this pattern is illustrated in Figure 4.59.

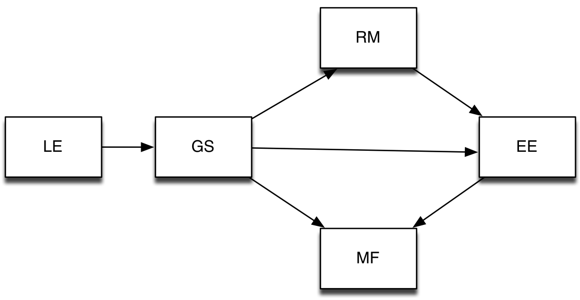


Fig. 4.59 The Evolution of the TIS

Each box represents one function and the arrows illustrate the direction of complementarities. The first function of the left is LE, which influences GS, and then this influences RM, EE and MF. At the same time, there is a possibility that RM will influence KD, and KD will in turn influence legitimation.

This visualisation of the TIS illustrates the importance of GS. In particular, we can see that GS interacts initially with LE, and as the technology matures, GS influences EE and MF, and eventually interacts solely with MF. The reason it interacts with different functions as the system matures points also to the changing nature of its role. In the early phases, its role is to guide researchers towards the particular technology, while in the later phases and after the introduction of the dominant design, it aims at helping the commercialisation and mass adoption of the technology. Its changing nature is so significant that we can argue that the function can be renamed Guidance of Search and Diffusion, illustrating that initially it guides technology development, and then guides technology diffusion.

GS is in most cases synonymous with policy and government intervention. As frequently mentioned in the literature, support policies need to be generous, clear and persistent, otherwise their effect will be very small. In all countries apart from the UK, FITs were established early on, but were either too undeveloped, too uncertain, or not specifically tailored to solar and, as a result, were not effective for stimulating diffusion. Clarity refers not only to the type of guidelines provided by policy but also to attempts to reduce bureaucratic barriers and eliminate bottlenecks in the market. The case studies show that the most effective policies in the initial phase of the technology are demonstration programmes, irrespective of pricing. A typical example is Germany's 1,000 Rooftops and 100,000 Rooftops programmes. These programmes had a local content requirement, so they promoted entrepreneurial experimentation and contributed to the institutionalization of the market by establishing a local supplier sector. However, having a local manufacturing base does not guarantee diffusion. For example, CZ had local manufacturers but most of their production went to exports, while Germany's local production went mostly to the local economy. Thus, having local production capacity is not a sufficient condition for the diffusion of a new technology, especially in a globalised world.

Another implication for policy is related to the case of "induced diffusion", where diffusion is motivated by very strong profit incentives, usually stimulated by extremely generous government subsidies. Subsidies do not constitute a barrier in the system; however, if they are too high, they can distort the system and their sudden removal can cause the system to collapse. The cases of Greece and CZ confirm this finding. For example, the boom in the CZ market occurred after 2006 when the government increased the subsidies, but soon after the market came to a complete halt. Similarly, the boom in the Greek market occurred after 2009 when the Greek government introduced very generous tariffs. However, when the tariffs were reduced a few years later, the market collapsed. The collapse of the system is due to other system functions especially market formation being insufficiently developed to allow the system to operate after reduction or removal of subsidies. On the basis of these two cases, we can conclude that strong policy and ample resources for a limited period of time are not sufficient to enable successful diffusion of TIS because there is not enough time for all the other functions to develop and allow the system to operate in the absence of government support.

The next major observation we can make from the case studies is related to the period of the dominant design, which is proven to be a crucial event in the evolution of the TIS. Looking at the summary graphs, we can see that in all countries after the emergence of the DD there was significant changes in the TIS configuration.

Nevertheless, the impact of the DD varies across the countries. Starting from Greece, we can see that the emergence of the DD has virtually no beneficial impact on the TIS evolution; the only function that was positively influenced was that of market formation. Looking at the other three countries, we can see that the DD had a significant positive impact on the evolution of the TIS. Starting with Germany, we see that the dominant design had an immediate impact on the TIS, by stimulating market formation, reducing entrepreneurial experimentation and increasing resource mobilization. In the UK, a similar situation can be identified, where the emergence of the dominant coincided with the stimulation of the guidance of search, and market formation. Lastly, the impact was the greatest in the CZ, where the emergence of the dominant design coincided with the stimulation of almost all functions of the TIS, other than entrepreneurial experimentation.

A potential explanation for this has to do with the nature of the DD. In particular, the emergence of the DD signifies a technical feasibility of the technology, but does not guarantee a clear economic potential for the technology. The economic potential is more complicated and depends on local market conditions. The fact that these local market conditions influence the TIS illustrates that the TIS should be perceived as complementary to the other innovation systems; in particular, the TIS is embedded within and, thus, is influenced by the other innovation systems (e.g. national and sectoral) (Johnson and Jacobsson, 2001; Hellsmark, 2010; Cooke, 2010).

Similar to our findings in Chapter 3, where we identified different types of configurations based on the country's distance from technological frontier, we also suggest here that the nature of the functions is linked with whether the country is an adopter or an innovator of a particular technology, a principle that can also be found in the technology-gap literature (e.g. Verspagen, 1991; Papageorgiou, 2002). In this Chapter, we argue that a country that is on the technological frontier will be an innovator, while the one behind is a laggard. This distinction helps us to understand why some functions are not active in some countries in different points in time. For example, the CZ is unambiguously an adopter of the technology. There, we can see that in the emergence of technology period, the TIS did not need to have knowledge development and resource mobilisation functions active. Rather, the only functions necessary were legitimation and entrepreneurial experimentation. The TIS was marginally operational, with some support and acceptance for the technology from the public, but it was just limited to some entrepreneurs who were producing some of the components for solar PV, and no major attempt for testing the market for solar. In contrast, Germany, which was a pioneer, had almost all functions active apart from market formation.

The fact that a country is a pioneer seems to influence the way the TIS evolves. If we think in terms of the TIS in Figure 4.59, we can introduce a slightly modified configuration. This is illustrated in Figure 4.60. The main difference is the introduction of the KD function, which becomes indispensable in initiating the TIS development.

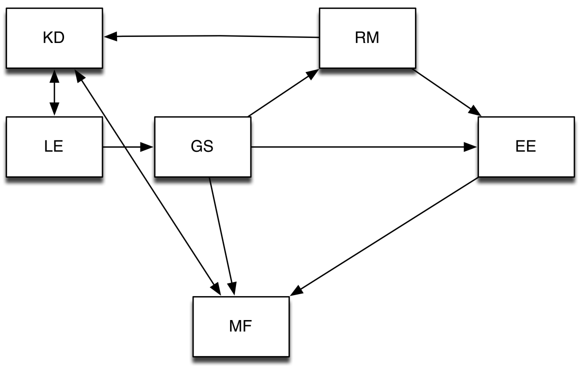


Fig. 4.60 The Evolution of the TIS for Pioneers

In our sample, we have only one country which is a pioneer in solar technologies: Germany. The main way to identify the pioneers is by looking at their adoption pattern, which follows a steady up-trend rather than a sudden jump in solar installations. This implies that the adoption started from the emergence of technologies period rather than after the emergence of the dominant design.

From this observation about followers and adopters, we can see that KD is a central function, but only for countries that are pioneers. However, KD is a necessary but not sufficient condition for the pioneer. For example, in the UK, although one of the most important innovations took place, this was not followed up by the other functions and thus made no major impact. In particular, we can argue that for a pioneer there needs to be positive complementarities between KD and GS.

Another characteristic of the pioneering countries is related to the fact that Germany was the only country where the reduction of subsidies did not lead to a collapse of the market. Maybe the reason is that it was a pioneer and not a follower. So, an established knowledge base and industry can lead to a maintenance of the TIS, even after the removal of the subsidies.

Our findings on this distinction between adopters and pioneers is very interesting and does not invalidate the TIS framework, but rather complements it. It could be argued that the original conceptualisation of the TIS fits better with countries which are pioneers, rather than followers. The main difference in terms of functions between the two systems is related to the importance of KD. What our findings suggest is that KD is the only function that is not necessary for followers. Overall, the differences between the functions of Pioneers and Followers are summarised in Table 4.6.

Table 4.6 Summary of the Differences in the functions between Pioneers and Followers

Function	Pioneers	Followers
KD	necessary for TIS development since the emergence of technology influences legitimation and GS	no significant complementarities with any other functions, and in general not a key function at late stages of mass market, there is some impact from MF
LE	necessary for TIS development influences KD, and GS after extensive diffusion, it might start to exert a negative effect on TIS International character of diffusion	International character of the function strong influence on GS
GS	Necessary for EE and KD until the emergence of the DD Changes in nature after DD, aiming to support the MF	Not necessary until the emergence of the DD Supporting the diffusion by stimulating the demand side and MF, and makes no contribution to KD
EE	Innovative Entrepreneurship Replicative Entrepreneurship	Replicative Entrepreneurship
RM	Necessary to stimulate KD and EE in the early phases Useful in stimulating the demand side of MF	Necessary to stimulate MF
MF	starts developing from the niche phase of the TIS strong link with EE	even if it starts developing before the DD, it makes no impact on TIS development
other	Gradual Diffusion of the technology Lengthy Process	Most of the functions underdeveloped until the emergence of the DD

Other interesting characteristics about the functions of the TIS are related to their transnational nature. In particular, by observing the number of papers in all 4 countries, we can see that they follow a similar pattern of development, with all showing an upward trend since the late 1980s, and a significant increase in the number of papers since 1995. This brings justification to our initial assumption that the emergence of the DD is a universal phenomenon. Another function which seems to exhibit a transnational character is legitimation. Its transnational character can be seen by the influence of various international organisations on the beliefs and attitudes of the domestic actors (e.g. Kyoto Protocol, National Energy Plan).

Our findings are similar to those proposed by Gosens et al. (2015) who examine how the

TIS needs to be adopted when applied to emerging markets, and in particular emphasise the importance of the transnational dimension. Our work adds to this finding and suggests that the transnational nature of some of the functions needs to be considered when investigating the TIS in developed countries. As they also implicitly suggest, it is not so important whether the country is an emerging market or not, but rather whether or not it is a pioneer. The reason for this is related to the time dimension of the TIS, whereby at the early stages of the TIS the processes are localised, whereas as the TIS develops these processes become more globalised, as more and more countries develop and adopt the technology. Evidence for the increasing globalised nature of the TIS as the technology matures can also be be seen by the fact that the DD emerges in all countries in the time way.

In the context of methodology, from the case studies we see that similar events can be ascribed to different functions according to the stage of the technology. For example, subsidies for a technology can be categorized as resource mobilisation, since it involves financial capital becoming available for the technology. At the same time, their introduction can be viewed as contributing to guidance of search in the niche market phase by signalling to entrepreneurs that government is committed to promoting this technology. Once the technology advances to the next phase, subsidies become part of the market formation function since their primary impact is to increase the cost competitiveness of the technology. Another example comes from the number of entrants. In the early stages of the life-cycle, this is used to capture the effects of entrepreneurial experimentation. However, after the emergence of the dominant design, this data becomes part of the market formation function as it is used to illustrate the intensity of competition in the market rather than just the number of users experimenting with a potential commercialisation of the technology. Therefore, taking account of the stage in the technology life cycle identifies the functions that a particular event/indicator affects; in other words, we can classify the events into functions in a more meaningful way by considering the stage of the PLC.

4.6 Conclusions

The aim of this Chapter was examine how the TIS evolves across time. Moreover, we wanted to identify how the complementarities between the functions were operating, and whether differences in functional strengths can explain differences in TIS evolution. Building upon Chapter 3, it can be seen that not all functions are necessary for the effective TIS development at any point in time. What this chapter adds to our prior findings is that it shows how the importance of functions varies across time, and provides a dynamic picture of TIS evolution.

To understand this evolution, we decided to conduct an in-depth qualitative investigation of the model using four cases from Solar PV. The selection of countries was not random; rather we decided to select Germany which was one of the earliest adopters of solar PV and is widely considered as the most successful country in it. The next country was the UK, which was also an early adopter but was not particularly successful in diffusion. The other two countries were Greece and CZ, both late adopters, and the former unsuccessful and the latter successful.

The main finding from our work is that the nature of the functions of the TIS varies across time, with some functions being more important in the early phases of a technology's life cycle, and others being more important in the later. In particular, we find that KD, LE and GS are important when the technology is at the early phase of its development, while EE and GS of search are important in the niche market period. After the emergence of the dominant design the main function which remains significant is MF.

The reason why some functions are more important than others has to do with the maturity of the technology. As in earlier chapters, the point in time which is pivotal for the change in the nature of the functions is the emergence of the dominant design. In particular, what we find is that after the emergence of the DD, the role of GS changes; instead of guiding entrepreneurs towards testing different technologies, its role is to facilitate the diffusion of the technology, usually by subsidising it. KD is not geared towards generating radical innovations but focuses on incremental process innovations. The entrepreneurs instead of innovating they replicate technologies. Lastly, RM is not targeted to KD but rather towards supporting the MF.

Independently of the stage of the technology however, our findings suggest that the TIS of any country has to follow a certain functional pattern (Figure 4.59), whereby LE stimulates GS, which in turn influences RM, EE and MF. This was found to be the case in all four countries. However, we realised that the configuration and functioning of the TIS can be distinguished between countries which develop the technology and countries that simply adopt it. For the former, we suggest that the TIS operates in a different way than the latter as it can be seen in Figures 4.60 and 4.59. The key difference between these two patterns is related to the role of KD, which, in pioneers, interacts with LE to stimulate GS. Both these points are a novelty in the TIS literature which neither examines the dynamic evolution of functions, nor distinguishes between adopters and pioneers.

Lastly, our findings also point to the transnational character of functions[28]. Firstly, KD is influenced by different international factors as the technology advances. Secondly, the LE function seems to get a lot of influence from international developments (e.g. world nuclear accidents, disruptions in world oil supply). Lastly, GS is directly shaped by supranational forces, such as when a country joins the EU which imposes limits on pollution, or is forced to sign international treaties (e.g. Kyoto Protocol). Furthermore, this function can be thought of as indirectly affected by the international forces that shape LE.

Further expansions to this work can be similar to the one conducted by Castellacci & Natera (2013) on national innovation systems. They conducted a cointegration approach to identify the evolution of the national innovation system. Achieving this in the context of the TIS is a harder however due to the lack of data, and the extremely time consuming nature of gathering enough data across time for a large enough sample of countries that would allow a robust cointegration analysis.

[28] A similar finding was proposed in Chapter 2, where we found that transnational factors were important determinants of diffusion.

Chapter 5

Formalising Dynamics in TIS

5.1 Introduction

Our work in the previous chapters illustrated that the factors that influence diffusion vary across time, and also that the performance of the functions of the TIS framework varies as the system evolves. In addition, we illustrated that the performance of one function in one period influences the performance of the other functions in the next period. However, we were not able to quantify the effect one function has on the performance of the other functions, neither in one point in time, nor in a period across time. To get a more formal understanding of system dynamics, the aim in this chapter is to create a model that will allow us to examine how the functions affect each other, and how this in turn influences the TIS, thus gaining a more systematic understanding of the TIS evolution. To achieve this, we draw upon history-friendly models (e.g. Nelson & Winter, 1982; Silverberg et al., 1988; Malerba et al., 1999), which are models that "aim to capture, in stylized form, qualitative and "appreciative" theories about the mechanisms and factors affecting industry evolution, technological advance and institutional change" (Malerba et al., 1999, p.3).

Such an approach has not previously been attempted in the TIS work, and we believe that this can increase our understanding of how the TIS operates. By creating the model, we aim at getting a better understanding of the dynamics of the TIS evolution and their complementarities[1]. In particular, by developing a model, we can reduce some of the complexity of the TIS, and focus on key elements of the process. What our work in the previous chapters illustrated is that the performance of the TIS depends on three key elements: the initial values of the functions in a period, the performance of the func-

[1] Like in Chapters 3 and 4, we use the word functions and activities interchangeably

tions, and the strength of the complementarities between them. What we were not able to examine in the previous work is how a weakness in any of these elements influences the overall performance of the system, something necessary in the TIS literature, as one of its key tenets is to identify the reasons for system failure, and provide appropriate policy recommendations (Carlsson & Jacobsson, 1997; Woolthuis et al., 2005; Bergek et al., 2008; Foxon & Pearson, 2008; Negro et al., 2012). By creating a model of the TIS evolution, we can then deal with the aforementioned issue and thus increase the usefulness of the TIS framework.

The model that we develop originates from the field of statistical mechanics, and is known as the Ising model. This was initially proposed to study the behaviour of spins in magnets, but has been extensively adapted across disciplines to model numerous processes which involve interacting agents in a large complex system (Brush, 1967). Conceptually, we argue that the key components of the model are the initial conditions[2] of the system, as well as the complementarities between the functions. In this way we bring together one of the fundamental tenets of evolutionary economics, path dependence, and the key premise of the system analysis, interdependence.

At the same time, our prior work on the evolution of the TIS in the solar technologies has also illustrated a significant weakness in the TIS framework. In particular, the framework fails to take into account explicitly factors exogenous to the system, which are technology specific and influence the evolution of the TIS. In the case of RETs, we argue that a key function is the availability of renewable energy sources of that country. To deal with this, we propose the introduction of a new factor in the TIS: the potential for technology diffusion. We call this a factor instead of a function because of the way it interacts with the system; in particular, it influences the TIS but it is not influenced by the TIS.

The remaining of this chapter is structured in the following way: Section 2 presents some stylised facts of TIS diffusion and the reference model, Section 3 discusses a new factor that needs to be included in the TIS, Section 4 presents our mathematical model and its various extensions, and Section 5 concludes.

[2] Initial conditions in this context are in essence values which capture the performance of the functions in the first phase of system evolution

5.2 The Reference Model

The starting point to create a history-friendly model is to identify the stylised facts related to the phenomenon we want to examine. This would serve as a basis to generate a reference model of TIS evolution. The initial model should be able to replicate most of the parameters of the history (Yoon & Lee, 2009). In this case, we go a step further and create an idealised version of TIS evolution, which we call the reference model. This is necessary so that we can design the model and set its initial parameters. Given that the behaviour and logic of the mathematical model will be guided by the reference model and not by some abstract oversimplifying assumptions, we can argue that this is a history-friendly model.

This idealised version was formulated inductively, based on the empirical work on TIS. In particular, to build this model, we follow Kaldor's approach (1959, p.178), who suggested that "the theorist, in my view, should be free to start off with a "stylised" view of facts - i.e. concentrate on broad tendencies, ignoring individual detail, and proceed on the "as if" method, i.e. construct a hypothesis that could account for these "stylised facts", without committing himself of the historical accuracy, or sufficiency, of the facts or tendencies thus summarised". Our stylised facts for diffusion were identified from reviewing the literature on TIS, and the diffusion of RETs, but also from our work on the previous chapters. These are:

1. Diffusion follows a S-shaped pattern, whereby at the beginning there are many technologies, many entrepreneurs, and very little adoption. With time, there is a shakeout in the market, a dominant design emerges, and there is an exponential increase in the adoption rates of the new technology (Rink & Swan, 1979; Gort & Klepper, 1982; Anderson, & Tushman, 1990; Audretsch & Feldman, 1996; Agarwal & Gort, 1996; Klepper, 1996; Geroski, 2000);

2. The more developed the country's knowledge base for a particular technology, the faster its diffusion will occur (Jacobsson et al., 2004; Jacobsson, & Bergek, 2004; Hekkert et al., 2007; Bergek et al., 2008; Krafft et al. 2014). This is because the uncertainty surrounding the technology will decrease earlier than in other countries which have a less developed knowledge base and thus a less developed understanding of the technology in question.

3. Social acceptance and public support are crucial for successful diffusion[3] (Ryan & Gross, 1943; Rogers, 1962; Wüstenhagen et al., 2007; Mallett, 2007).

[3]This point has also been illustrated in Chapter 3, with the results from QCA on legitimation.

4. For a technology to diffuse in a system, it first needs to become commercially available. Diffusion to a large scale can only take place through the establishment of a fully formed market (Jacobsson et al., 2004; Bergek et al., 2008; Negro et al., 2008; Dewald & Truffer, 2011).

5. Lastly, an implicit assumption in the model concerns the availability of the technology in question. Clearly, for the innovation to be diffused it needs to be available to the potential adopters (Griliches, 1957; Rogers, 1962). However, in some technologies, like RETs, this assumption becomes a bit more extensive and includes not simply the availability of the technology, but also the availability of raw materials necessary for this technology to operate. For example, if we are investigating the TIS for solar PV, the country has to have access to the relevant solar technologies, but also needs to have ample solar resources that would allow it to generate electricity from these resources.

Our conceptualization of the idealised TIS evolution starts with the phase we label "emergence of technologies" and is shaped by the various knowledge institutions that explicitly or implicitly influence their development and diffusion. In the early stages when market demand is in a critical bottleneck, these institutions need support from government, resources, and a form of social acceptance. At the same time, the country needs resources in order to develop the technology in the future, otherwise it is unlikely that research will begin. Therefore, we hypothesize that in this first phase, knowledge development and legitimation need to be fully active, and accompanied by targeting of activities (guidance of search), resource mobilization, and potential for technology diffusion.

The next phase starts when the actors in the system begin to attempt to commercialize the new technologies. In particular, we assume that some of the technologies started to attract the attention of entrepreneurs, who look for markets to try them. For them to believe in the potential of these technologies, they need to see some potential for mass adoption in the country. In the meantime, the government, in an attempt to reduce the uncertainty surrounding the technologies, tries to provide incentives for the deployment of new technologies which serve as guideposts for the entrepreneurs. This process leads to the formation of market niches or areas of initial deployment of new technologies which are still below critical mass for full deployment. Clearly, entrepreneurial experimentation is the key function in this stage, followed by guidance and potential for diffusion. Knowledge development and legitimation remain important, albeit less so than in the previous phase, while market formation starts to emerge as an activity.

Eventually, through trial and error and competition among the various designs, one technology will dominate the system, and becomes known as the dominant design[4]. The activities in this stage are focused towards the establishment of a mass market for the technology and its future penetration. Therefore, the key activity in this period is market formation.

An interesting characteristic of this phase has to do also with the concept of guidance of search. Until the dominant design's emergence, the aim of this function was to guide the entrepreneurs towards identifying which of the competing technologies they should experiment with. However, after the dominant design emerges this activity becomes redundant. Rather, the aim of the policies is to provide certainty that the government will continue to support the existing technology. In a way, the search for a particular technology is over. Therefore, it could be argued that the nature of the function is different; from guiding search, it is now guiding diffusion. Consequently, the actual naming of the function as guidance of search is no longer relevant. Rather, the name could be changed into guidance of the diffusion process. However, in this work, we will stick to the nomenclature used by traditional TIS approach and continue to label this function across all phases as guidance of search.

In the last phase, the conditions are being created that facilitate the further diffusion of the technology and the creation of a mass market. For this to happen, there needs to be a fully functioning market (i.e. properly established regulatory and other institutional requirements), and acceptance by society given that there will be a process of radical change which may affect people's habits (life styles). Knowledge becomes less important in this phase since it is now an outcome rather than a process. In other words, the TIS does not need extra knowledge to diffuse the technology, because all the know-how has already been absorbed by the system and the users. In contrast, firms using the technology and helping it diffuse in the system produce incremental innovations and generate knowledge related to process rather than products. Thus, the key activities are market formation, followed by legitimation and resource mobilization.

A graphical representation of the evolution of the TIS is illustrated in Figure 5.1. This is a bar chart which clusters each of the activities according to the phase of the technol-

[4]In reality, more than one technologies will be used, but there will be only one which has the majority of market, and eventually all the others will disappear. In the case of RETs, the most typical example is the dominance of the three-blade wind turbine, compared to the alternative designs.

ogy with respect to the PLC model. In particular, we identify four distinct phases that each TIS system goes through: Emergence of Technologies, Niche Markets, Dominant Design, and Mass Market. Since in this work we are focusing on solar PV, we have given the dates for each of the phases, based on the observation of the history of solar PV development discussed in Chapter 1. Given the interconnectedness of our world, we have assumed that these phases are common across countries; in other words, the phases and the dates are a characteristic of the technology system under consideration[5].

For each period, we have created bars that represent the performance of the each function in the system. The height of the bar represents the performance of each activity at each time period, with greater height denoting better performance (intensity) of the activity[6]. The values given are based on the coding we performed in Chapter 3, and the actual meaning of each value can be found in Appendix C.8.

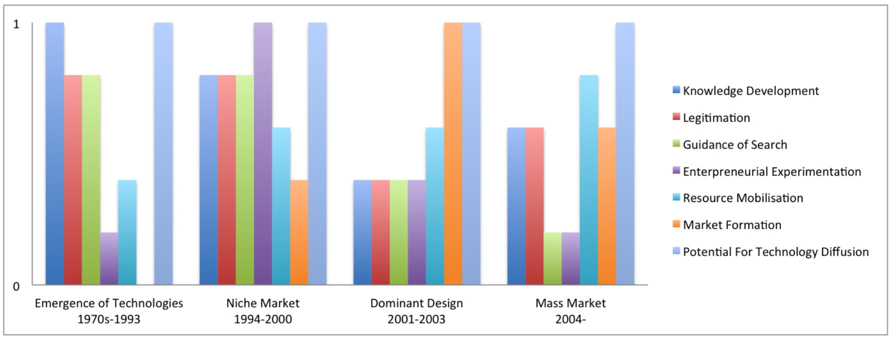


Fig. 5.1 The Revised Technology Systems Framework: The Stylised Model

This conceptualisation of the TIS theorises that not all functions are fully active across time. Rather, it suggests that the importance of the functions varies across time, and in particular as the technology evolves. This should be not viewed as contradicting the findings in Chapter 3, where we suggest that not all functions are necessary for the successful operationalization of the TIS; it should rather be viewed as expanding this observation and building upon the findings of Chapter 4.

[5]We recognise that this is an oversimplifying assumption, but given that the original TIS approach did not distinguish between pioneers and followers, we decide that this is a suitable assumption. In the later part of our analysis, we allow for a modification of this assumption, and recognise that there are different functional configurations for followers and pioneers.

[6]An alternative graphical illustration of the evolutions of functions across time is provided in Appendix D.2

5.3 Accounting for Technology Specificities

One weakness of the TIS is the fact that it does not explicitly account for specific factors which can influence the way a TIS will develop based on the technology specific characteristics it possesses. To deal with this, we propose to incorporate a new factor that influences the TIS, but is not influenced by it. We label this new factor as "The Potential for Technology Diffusion". This proxies for the physical potential for technology diffusion of a country.

After examining the empirical work on TIS we noted a gap between the traditional diffusion and the systems literatures; in the former body of work on diffusion studies, one of the key determinants of diffusion of innovation is the availability of the innovation in the region under consideration (Griliches, 1957, p. 507). Similarly, in Rogers' DOI framework, this effect is also indirectly captured by the relative advantage and the compatibility. Nonetheless, in the context of the TIS, this is not clearly formulated. Probably the main reason for this omission is due to the fact that this factor cannot be influenced by the system, but simply influences it.

In our view, the lack of its explicit incorporation into the framework reduces some of the framework's explanatory power. Influenced by mainstream econometric modelling, this factor can be perceived as country-specific (or fixed effects), and needs to be explicitly controlled for. The reason we believe this factor is so important is because of the way it influences the functions of the TIS. For example, it might influence the direction of search by helping to shape government's expectations. A typical example is Greece, in which the government decided to support RETs, and instead of focusing on wind, which was more cost competitive, it decided to support solar, potentially because of Greece's ample solar resources. Another example which illustrates the functions interaction with the TIS can be found in the case of wind. When comparing the TIS of wind and solar, legitimation is more important for wind due to NIMBY effect, compared to that of solar. Clearly, this effect is technology specific and although it influences the system, it cannot be captured by any of the existing functions. Thus, it needs to be captured separately, which is done by *the potential for technology diffusion*.

This factor is technology specific, and therefore there is no single list of indicators that can be used to assess them. For RETs in general we can argue that the effect of the factor is captured by the country's endowment of resources specific to the technology. To provide an illustration of how this factor can be measured in the TIS context, we apply this new factor and measure its performance on Germany, which was a country used in chapter 4.

To assess the endowment of resources in Solar PV, we have data on global irradiation [kWh/m2] since this is typically used in feasibility studies of solar PV systems installations, and solar electricity potential in Germany (Figure 5.2)[7]. This data shows that, apart from the south of the country, Germany does not have significant solar resources[8]. It is clear that solar cannot be the predominant energy source for Germany, but has the potential to make a contribution to the country's energy mix.

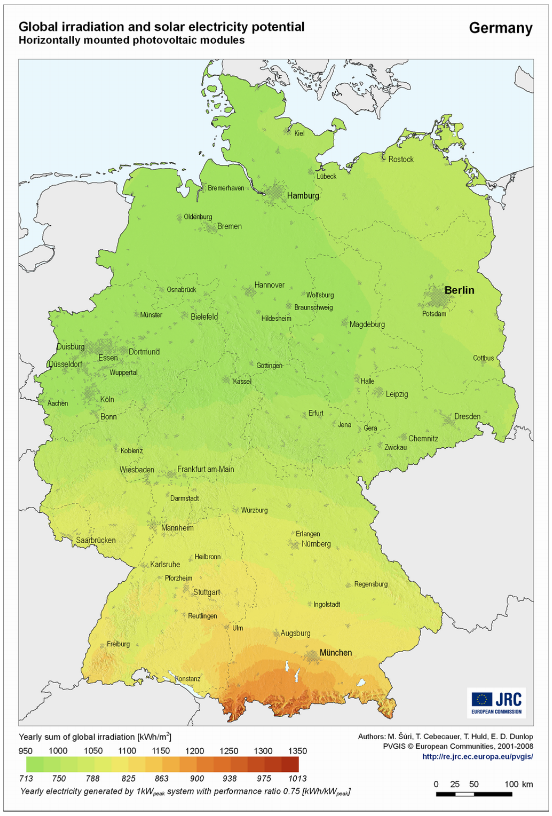


Fig. 5.2 Global Irradiation and solar electricity potential in Germany

Source: PVGIS

[7]The data used to construct the map are based on an 18 year history of using the solar and meteo database, SolarGIS; the survey looks at the solar resource potential of each country. Figure 5.2 shows Global Horizontal Irradiation (GHI) data, which are the main data used to calculate amount of electricity from solar PV (Beták et al., 2007). To ensure consistency, we use the same indicator for all four case studies.

[8]However, this map needs to be put into perspective in order to compare with other countries; e.g. Germany has an area of 357,000km^2, the proportion of the country ideal for solar is small, but in absolute terms is quite significant.

5.4 Formalising the TIS

To develop the model and run the simulations, the starting point is to assign initial values for each activity in the first stage, then to define the strength of the complementarities among the activities (functions), and finally to apply the model to trace the evolution of the system. We start with a base model, and introduce some advancement and elaborations[9].

5.4.1 The base model

In order to formulate a mathematical expression for our proposed model, we make a few initial assumptions based on the reference model:

- our model will consist of 6 functions[10] and 1 factor, which for simplicity we will model as if it was a function[11].
- the functions can be assigned a numerical value in the interval [0,1] for each of the phases, with 0 indicating inactivity and 1 full activity of the function;
- the functions interact with each other, but to varying degrees of strength, which we categorize as very strong, strong, weak or very weak. This interaction is not symmetric, i.e. the effect of function F_i to function F_j may differ from the effect of function F_j on function F_i;
- the activity of a function in every phase affects the evolution of other functions to the next phase;

With these assumptions in mind, we propose a model that formulates them in mathematical terms. Bearing in mind the complementarities and interactions between the seven functions, we propose the following model, which predicts the value of each one of the functions in the next phase:

$$F_i^{(t+1)} = F_i^{(t)} + \frac{1}{N-1} \sum_{j=1}^{N} J_{ij}^{(t)} \left(F_j^{(t)} - F_i^{(t)} \right) \tag{5.1}$$

[9]The work in this section is developed with the help of M.Kitromilidis, and will be published under joint authorship. His contribution was the development of the mathematical model, while running the simulations, the analysis, and the interpretation of the results was entirely my own work.

[10]Most TIS approaches use six functions: Knowledge Development and Diffusion, Entrepreneurial Experimentation, Market Formation, Resource Mobilization, Influence on the Direction of Search, and Legitimation. For more information see at Chapter 3

[11]A particularity of this factor is that its value is not influenced by the other functions of the system, an assumption which influences its operatatioinalisation within the model as we demonstrate below.

In the above expression, $F_i^{(t)}$ is the value of the i-th function at the t-th phase (so we assume that the functions are sorted so that F_1 is knowledge development, F_2 is legitimation, etc. [12]), and $J_{ij}^{(t)}$ is the effect the j-th function has on the i-th function during the t-th phase and will therefore affect the evolution of the particular function to the next phase.

We also include a normalisation factor $\frac{1}{N-1}$, where N is the number of functions. This factor exists in order to ensure that the value of the function will remain in the interval [0,1]. This condition can be better understood through the following extreme example. Let's assume that

- $F_{knowledge}^{(t)}$ =1 (i.e. knowledge development is fully active)
- the complementarities with all other functions on it are extremely strong ($J_{j1} = 1$ for $j = 2, \ldots 7$)
- all other functions are fully inactive ($F_j = 0$ for $j = 2, \ldots 7$).

Without the normalisation factor, our model would then predict the value of knowledge development to be "dragged" to -6 in the next phase, since it would absorb the negative effect from all other functions, and thus our model would collapse. However, by creating the normalisation factor and setting $N = 7$, the normalisation factor becomes $\frac{1}{6}$, and therefore each of the six functions reduces F_1 by $\frac{1}{6}$, thus bringing it to zero in the next phase.

Establishing The Complementarities Among The Functions

Of crucial importance in this model are the particular values assigned to the complementarities J_{ij}. These are exogenous to the model, as we have explicitly set their values using the following list of assumptions and rationale.

1. The value of the complementarity between function F_i and F_j is different from the value of the complementarity between function F_j and F_i, i.e. $J_{ij} \neq J_{ji}$.
2. The values of the complementarities vary across time, i.e. , i.e. $J_{ij}^t \neq J_{ij}^{t+1}$.
3. The values of the complementarities do not vary across countries. We recognize that this is a very strong assumption, and not always true as we showed in the

[12]For full notation see Appendix D.3

previous chapter. Nonetheless, we believe that this assumption is in line with the core of the TIS approach which suggests that the complementarities are primarily determined by the nature of technology system rather than solely by the institutional features of countries. This line of thought also finds justification in the notion of technological regimes (Malerba & Orsenigo 1993), which underpins systems of innovation.

Based on six functions and a factor, this generates a matrix of 49 different values of the complementarities. In turn, since we assume that the values of these complementarities vary across each phase, there are three matrices of 49 different values. All of these values are provided in the matrices below. In terms of their theoretical justification, we decided not to justify the value of each complementarity separately because this would require $(49 \times 3) = 147$ justifications. Instead, we provide justifications for the most important interactions, and we do this in the form of assumptions for the model, which were drawn from the evidence of the case studies and our review literature.

Regarding knowledge development, our case studies showed that in the initial phase this activity is closely linked to legitimation and entrepreneurial experimentation. In particular, the more there is accumulated knowledge, the greater the potential acceptance of the system, and the lower the uncertainty of the new technologies, which will stimulate entrepreneurs to experiment. Our case studies, as well as theoretical papers like Rosenberg, (1996), confirm this relationship. For example, in Germany, the increased number of patents and publications in solar was accompanied by a rise in the number of industrial and lobbying institutions, which in turn, influenced both the legitimation of solar PV. Moreover, until a commercially viable technology was established, entrepreneurial experimentation could not take off, something clearly demonstrated by the weakness of this function until the early formative phases of technology (see Chapter 4).

At the same time, we can argue that knowledge development has quite a strong impact on the guidance of search, especially when technological breakthroughs emerge which suggest the technology's commercial viability. Then, policy makers turn to knowledge institutions for guidance on which technologies need to be supported, what are the impacts the new technology might have on the economy, etc. so that they can identify whether the particular TIS should be supported. This situation is clearly seen in many TIS studies (Praetorius et al 2010, van Alphen 2010a, Vasseur et al. 2013), which use as proxies for the guidance of search "belief in growth potential", "publications on R&D outcomes", "expectations and opinions of experts", etc.

Lastly, we assume that the impact that KD has on GS remains strong even as the technology enters the mass market. New research findings influence policymakers and their decisions to support the technology and consequently the resources to be mobilised. A representative example can be seen at the level of policy support for solar PV. As the technology matures and the cost of PV decreases, we can see that the degree of policy support for the technology decreases, a situation present in all four cases that we examined in the previous chapter.

The legitimation function is one of the driving forces in the system especially in the first phase, without which there would be no political support for the development of the TIS, and consequently, no institutions would be established to help it. Hence, we can assume that it has a significant impact on all functions in the first phase, as this is key to kick-start the process (Hughes 1987; Carlsson & Stankiewicz 1995; Bergek et al. 2008).

From the case studies, it was evident that lobbies and all other institutions supporting public opinion were necessary to stimulate government support for the system development. For example, in the emergence of technology phase in Germany, institutions such as the EUROSOLAR, the German Society for Solar Energy, and the German Association for the Promotion of Solar Power were all key to the initiation of several demonstration projects in that period. Similarly, in the UK, the Green movement, and the general anti-nuclear attitude of the UK public opinion, could be perceived as a way for the government to stimulate the development of the TIS system. Thus, LE can be seen as having a very strong impact towards GS, and consequently RM, EE, and MF.

However, as the system develops, the effects of legitimation on the other functions decrease, again due to its decreasing utility, and we expect other factors (e.g. market formation) to be more important for how the system develops. In this way, technology diffusion moves from the stage of social acceptance to commercial acceptance, that is, it is driven more by economic than by socio-political factors. An example of this is solar PV in the UK and Greece, which even though it enjoyed unyielding public acceptance (i.e. Legitimation was very strong and active) in the early phases, this did not prevent the government from decreasing the tariffs substantially, and from the entrepreneurs to stop investing in solar PV projects.

A relation of particular interest is that of legitimation on knowledge development, since the greater its social acceptance, the more knowledge development is stimulated, and vice-versa. For example, the anti-nuclear movement was a key element that mobilised resources towards RETs in Germany, and consequently stimulated the development of many solar research institutes in Germany. However, this interaction takes place at a decreasing rate as the TIS develops, that is, it is initially positive, but the effects of the interaction become relatively smaller in subsequent stages due to decreasing utility rates of legitimation. Eventually, when the TIS is fully developed, it can be expected to have some opponents, such as the NIMBY movement against the wind, although this could be argued to have started before wind entered the mass market phase.

Guidance of search is considered a key function throughout the whole development of the TIS. As previously discussed, this function acts as a guide to the various components of the system so that the TIS can grow and develop. Given this theoretical definition, it is only natural to expect to have very strong complementarities with all other functions throughout the system's evolution. However, it could be argued that since its role varies over time, so does the impact it has on other functions.

Starting from the early phase of the TIS evolution, we can assume that it has a very strong link with every other function. For KD, we assume that the link is not as strong as with the others, because often technological breakthroughs happen by chance, rather than through a conscious effort and guidance by the government. An example of this is the innovation in 1985 from the University of South Wales, which managed to break the 20% efficiency barrier for silicon solar cells. This breakthrough was achieved, with some funding and resources from the government, but without the government having as a direct objective the development of the solar PV knowledge base. Nonetheless, as the technology matures we would expect GS to have a stronger link with KD, especially after the introduction of the dominant design. At this stage the technology has proven its economic viability and its potential for diffusion. Then, these results would be acknowledged by the policy makers, and they would make direct efforts to promote it. An example of this comes from the case study on the Greek solar PV TIS, where the role of the Center for Renewable Sources gets elevated after the emergence of the DD, with more funding and more recognition by the policy makers.

Regarding RM, we can argue that its link with GS is particularly strong. In the early phase, the main reason resources are mobilised towards the particular system is because of GS. However, it is unlikely for the government to target a specific technology and TIS before that technology has emerged. For example, we can see that in the UK, there was some R&D spending towards RETs in general, but not specifically for solar PV. That is why we argue that the impact on RM is not very strong, but just strong. However, in the niche market and dominant design phases, the government will make a conscious effort to stimulate the resources towards the system, as it is relatively clear which technology has emerged that characterises the TIS. After the emergence of the dominant design, GS is not the sole mobiliser of resources, as there might be some other factors that can stimulate resources. For this reason, we argue that its complementarity with RM is slightly weaker than in the previous phase.

The main impact that entrepreneurial experimentation has is on the market formation. This impact is due to entrepreneurs being crucial although not the only agents involved in market formation[13]. So across all stages, we can argue that this relationship remains very strong. Nonetheless, EE influences the other functions as well, in a way that changes across time.

In the initial phase, when entrepreneurs are not yet major players, EE cannot exert influence on other functions, so we can safely assume that it has feeble complementarities with the other functions[14].

In the niche market phase, entrepreneurs and the state, as a procurer, become the dominant actors, and this function can be seen as complementing all the others (Bergek & Jacobsson, 2003.; Bergek et al., 2008). The best way to understand the impact of EE on the other functions is by referring to examples of demonstration projects that we analysed in Chapter 4. The most representative example was the 1,000 rooftop program in Germany. This program was a major success as it established the market for solar PV, gave policymakers and the public a very clear idea about the potential of the solar PV while also led to the substantial accumulation of the knowledge both regarding patents and papers. Thus, we can argue that it had a very strong impact on MF, KD, GS, LE. Moreover, the entrepreneurs are the ones who are primarily using the available resources in this phase, so the impact EE has on RM is also very strong.

In the final stage, this function becomes less important, and the complementarities with other functions weaken, since the entrepreneurs are not the drivers of diffusion once the technology has become standardised, and its uncertainty has been drastically re-

[13]Markets are also formed by institutionalizing new rules and regulations, resource mobilization, as well as by other activities.

[14]More on theoretical grounds, we have left the complementarity between EE and MF as very strong, but because they are both inactive we have no way of testing this. Theoretically, as the one function is a necessary precondition for the other, we would expect this two way interaction to remain strong even in this early formative stage.

duced. This does not mean that the entrepreneurs are not important, but the way entrepreneurs are perceived in the TIS, as those who test the new technology and reduce the uncertainty become less important. On the contrary, the entrepreneurs as agents are important, but the market formation function now captures their activities. This point was developed more in Chapter 4, where we showed that the nature of entrepreneurship changes after the emergence of the dominant design with the entrepreneurs being transformed from innovative to replicative[15].

Resource mobilization is a crucial function for the evolution of the TIS, as it is a precondition for its development (Carlsson and Stankiewicz, 1995; Edquist and Johnson, 1997; Bergek et al., 2008). However, in contrast to the other functions whose impact on the TIS vary across time, RM can be perceived as having a constant strong relation with KD, EE and MF. Undoubtedly, resources are necessary for knowledge development, something clearly seen in the case studies, whereby higher R&D spending is usually accompanied by very active knowledge development[16], but also in other works such as Oltander and Perez Vico (2005) on the Swedish security sensor. As shown in the case studies, these complementarities are very strong, initially in upstream and later on in downstream stages of PLC. However, the returns from these linkages decrease over time as TIS becomes more established and as initially increasing returns to complementarities are replaced by decreasing returns.

Similarly, resources are necessary for entrepreneurs to experiment with the new technologies, and for the creation of markets, therefore, it strongly impacts both entrepreneurial experimentation and market formation. In the final phase, resources are necessary primarily for knowledge development (which now is related to technical improvements and process innovations), and market formation. It could be argued that it would influence EE, but as we discussed above, the transformed role of the entrepreneurs places their activities in the MF function rather than the EE.

Lastly, as far as the impact between RM and GS is concerned, we can argue that the relationship is weak from RM to GS, but strong from GS to RM. In other words, the guidance of search is what mobilises the resources towards a particular system, and not the opposite.

[15]For a more lengthy discussion of this topic, refer to Chapter 4

[16]However, as it is widely illustrated in the innovation literature, resources are not a sufficient condition for knowledge to be developed.

Market formation, in the literature, has been assumed to pass through stages, from nursing to mass market, and at each phase the nature of the function is different (Jacobsson & Bergek, 2004; Dewald & Truffer, 2011), and, therefore, its interactions with the other functions is different.

In the first phase we assume that market formation does not have a significant impact on any function, primarily because no market is yet developed (Carlsson and Stankiewicz, 1995; Dahmen, 1988; Galli and Teubal, 1997). In the second phase, we do not see any particular impact that this function has on any other, apart from its interaction with the guidance of search, whereby the latter can influence the former by removing obstacles and/or creating demand for the technology.

The actual impact that this function starts having on the other functions comes when the market begins to get established. In this situation, we would expect the market to have an impact primarily on KD, and LE, and to some extent on GS. The reason it would affect the KD and LE is similar to the rationale according to which EE influenced this functions. In our view, the MF captures the activities of the replicative entrepreneur, as well as the consumers and their demands. The way these requirements evolve and based on the actions of the entrepreneurs, we would expect the public perception of the system to be affected (i.e. LE), as well as the quantity and quality of the knowledge base. In other words, the market formation can be seen to influence knowledge development, supporting the idea of demand led technology development, whereby the requirements of the market dictate the direction of research. An example of this comes from the solar PV industry in Greece, where initially the focus was on large scale installations, but with time and as a result of the financial crisis, the focus for solar PV turned to small-scale rooftop projects.

We further assume that the factor potential for technology diffusion has a significant influence on various functions, but, given that it is fixed for each country, we argue that any other function[17] does not influence it. Regarding its impact on other functions, we can expect that it has a close relationship with knowledge development in the early phase, entrepreneurial experimentation in the niche markets phase, and legitimation and guidance in the final stage. When the technology enters the mass market phase, the

[17]It could be argued that in some very few cases, some developments can influence this factor, especially knowledge. For example, new technological developments can change the perceived resource potential of a country (e.g. the shale oil and gas revolution). However, given the theoretical approach to this element, where we argue that it is a factor as it is not influenced by the TIS but only influences it, we have decided to keep the impact of the other functions on it zero.

government has to decide whether to promote the technology and its deployment. For example, in the case of solar, once the technology became standardized at the global level and cost competitive with traditional resources, the government had to decide whether or not there was potential for solar on a massive scale a decision heavily in influenced by the country's solar resources. Similarly, if a country has the potential for solar, and the technology has become cost competitive, and then we can expect much public support for it and thus strong legitimation emerges.

Lastly, we should highlight the value of self-interactions, that is, the impact of each function on itself. For simplicity, this is usually assumed to be zero, i.e. $J_{ii} = 0$. If we employ this assumption, this implies no increasing returns to the activity itself in the absence of interactions with other functions. For example, the existence of high resource mobilization at time t, does not necessarily lead to high resource mobilization at time t+1. Similarly, we assume also that there are no decreasing returns to the activity itself. Both of these assumptions seem rather unrealistic, therefore, we hypothesize about the various values of the feedback mechanisms within individual activities (functions). Having done all the modelling and simulations, we compared the results with a model with our hypothetical values of self-interactions with a model whose values were equal to zero. We found virtually no difference in the model's performance, thus, we can argue that this point is more theoretical than practical. This is because the overall results depend largely on the performance of the whole system and the initial conditions. To avoid unnecessary complexity, we assume that the values of the self-interactions are zero.

Visually, the values of the complementarities described above can be illustrated in the following matrices. In terms of presentation, each matrix follows the following pattern:

$$J^{(t)} = \begin{pmatrix} F_1 \Leftarrow F_1 & F_1 \Leftarrow F_2 & F_1 \Leftarrow F_3 & F_1 \Leftarrow F_4 & F_1 \Leftarrow F_5 & F_1 \Leftarrow F_6 & F_1 \Leftarrow F_7 \\ F_2 \Leftarrow F_1 & F_2 \Leftarrow F_2 & F_2 \Leftarrow F_3 & F_2 \Leftarrow F_4 & F_2 \Leftarrow F_5 & F_2 \Leftarrow F_6 & F_2 \Leftarrow F_7 \\ F_3 \Leftarrow F_1 & F_3 \Leftarrow F_2 & F_3 \Leftarrow F_3 & F_3 \Leftarrow F_4 & F_3 \Leftarrow F_5 & F_3 \Leftarrow F_6 & F_3 \Leftarrow F_7 \\ F_4 \Leftarrow F_1 & F_4 \Leftarrow F_2 & F_4 \Leftarrow F_3 & F_4 \Leftarrow F_4 & F_4 \Leftarrow F_5 & F_4 \Leftarrow F_6 & F_4 \Leftarrow F_7 \\ F_5 \Leftarrow F_1 & F_5 \Leftarrow F_2 & F_5 \Leftarrow F_3 & F_5 \Leftarrow F_4 & F_5 \Leftarrow F_5 & F_5 \Leftarrow F_6 & F_5 \Leftarrow F_7 \\ F_6 \Leftarrow F_1 & F_6 \Leftarrow F_2 & F_6 \Leftarrow F_3 & F_6 \Leftarrow F_4 & F_6 \Leftarrow F_5 & F_6 \Leftarrow F_6 & F_6 \Leftarrow F_7 \\ F_7 \Leftarrow F_1 & F_7 \Leftarrow F_2 & F_7 \Leftarrow F_3 & F_7 \Leftarrow F_4 & F_7 \Leftarrow F_7 & F_7 \Leftarrow F_6 & F_7 \Leftarrow F_7 \end{pmatrix}$$

In particular, every entry illustrates the interaction between function F_i and F_j, where each function takes the following label:

Label	**Function**
(F_1)	Knowledge development
(F_2)	Legitimation
(F_3)	Guidance of search
(F_4)	Entrepreneurial experimentation
(F_5)	Resource mobilisation
(F_6)	Market formation
(F_7)	Potential for Technology diffusion

In each cell of the matrix, instead of the function labels, the values of the strengths of the complementarities are illustrated. In particular, the J_{ij}-th entry denotes the effect the j-th function has on the i-th function. For example,for $J_{14} = VW$, which means that the effect entrepreneurial experimentation has on knowledge development is very weak in this phase. Conversely, as $J_{41} = VS$, the effect knowledge development has on entrepreneurial experimentation is very strong[18].

The complementarities in the first phase (emergence of technologies) can be seen in the following matrix.

$$J^{(1)} = \begin{array}{c} \\ F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \\ F_7 \end{array} \begin{array}{c} \begin{array}{ccccccc} F_1 & F_2 & F_3 & F_4 & F_5 & F_6 & F_7 \end{array} \\ \begin{pmatrix} 0 & VS & S & VW & VS & VW & 0 \\ VS & 0 & VS & W & VW & W & 0 \\ W & VS & 0 & W & VW & W & 0 \\ VS & VS & VS & 0 & VS & VW & 0 \\ VW & VS & S & VW & 0 & VW & 0 \\ S & VS & VS & VS & VS & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \end{array}$$

In the second phase (niche market towards dominant design), the corresponding matrix is

[18] VW means very weak and takes numerical values in the interval [0 - 0.1], W means weak and takes numerical values in the interval [0.2 - 0.4], S means strong and takes numerical values in the interval [0.5 - 0.7], VS means very strong and takes numerical values in the interval [0.8 - 1]

$$J^{(2)} = \begin{array}{c} \\ F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \\ F_7 \end{array} \begin{array}{c} \begin{array}{ccccccc} F_1 & F_2 & F_3 & F_4 & F_5 & F_6 & F_7 \end{array} \\ \begin{pmatrix} 0 & S & S & VS & S & W & 0 \\ VS & 0 & VS & VS & W & S & 0 \\ VS & VS & 0 & VS & W & W & 0 \\ VS & S & VS & 0 & VS & W & 0 \\ W & S & VS & VS & 0 & W & 0 \\ W & S & VS & VS & VS & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \end{array}$$

In the third phase (dominant design towards mass market) the matrix of complementarities is

$$J^{(3)} = \begin{array}{c} \\ F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \\ F_7 \end{array} \begin{array}{c} \begin{array}{ccccccc} F_1 & F_2 & F_3 & F_4 & F_5 & F_6 & F_7 \end{array} \\ \begin{pmatrix} 0 & S & VS & VW & VS & VS & VS \\ VW & 0 & S & VW & W & VS & VS \\ VS & VS & 0 & VW & W & S & VS \\ VW & VW & VW & 0 & VW & VW & VW \\ VS & W & S & VW & 0 & W & VS \\ S & W & S & VS & S & 0 & VS \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \end{array}$$

To incorporate these values into the model, we had to convert them into numbers. For practical purposes, these numbers were chosen within the 0 1 interval, and specifically the numerical values for each level of strength are given in Table 5.1. For robustness, the value for each J_{ij} is randomly assigned to any value within the interval inclusive, using a random function in the spreadsheet calculator[19]. After picking the random value for each complementarity, we conducted a monte-carlo simulation so that we can decide whether the randomisation of the values of the complementarities within the predefined intervals made a significant impact on the results. However, it was found that even in the extreme cases where the top and bottom values in the intervals were selected, the results remained virtually unchanged.

[19]The numerical version of the full list of complementarities across all functions can be found in Appendix D.5

Strength of Complementarity	Range of Values
Very Strong (VS)	0.8 - 1
Strong (S)	0.5 - 0.7
Weak (W)	0.2 - 0.4
Very Weak (VW)	0 - 0.1

Table 5.1 Scale Measuring the Strength of the Complementarities

Testing the base model

Based on our previous work in this thesis, we hypothesise that the evolution of the system takes place across 4 distinct phases:
1. The Emergence of Technologies
2. Niche Markets
3. Dominant Design
4. Mass Market

The first step in applying the model is to identify the initial performance of each function. To do this, we assign to each function a numerical value within the interval [0, 1], depending on how active each function is during this particular phase in the country under investigation. For the reference model, the estimates for the initial phase, based on the section above, are provided in Table 5.2.

Notation	Name of the Function	Strength
(F_1)	Knowledge development	Very Strong
(F_2)	Legitimation	Very Strong
(F_3)	Guidance of search	Strong
(F_4)	Entrepreneurial experimentation	Weak
(F_5)	Resource mobilisation	Weak
(F_6)	Market formation	Very Weak
(F_7)	Potential for Technology diffusion	Very Weak

Table 5.2 Stylised Model: Initial Conditions

Using the values in the first phase, and the complementarities between the functions, the model proceeds by calculating a predicted value for each function in the second phase, niche market, using equation (5.1). The result is a set of predicted values for the activity of the functions in the second phase which are used in combination with the second-phase complementarities to predict values for the third phase, dominant design using again (5.1); this process is repeated once more for the final phase of mass market.

The results of our simulation for the reference model are illustrated in Figure D.11, while for the countries of the case studies in Appendix D.8.

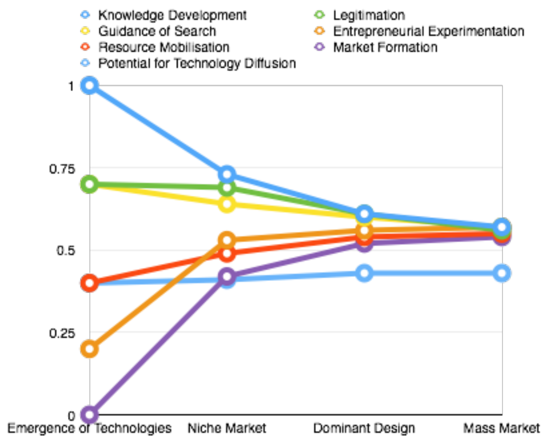


Fig. 5.3 The Evolution of Functions in the Idealised Model

Note the behaviour of the functions based on this graph. First, our model predicts that the new value of each function will depend on its difference with other values. Similar to the theory of unbalanced growth, the bigger the gaps between levels of activities, the bigger the potential for interaction and, thus, for increasing returns due to greater opportunities or greater "marginal productivity" at undeveloped functions. Second, due to the nature of the model, as the TIS evolves we can expect that eventually the six functions will converge to a common value, as the differences between them will continuously decrease. This outcome is due to the simplicity of our base model where the configuration or portfolio of values of the activities are the same. However, our case studies suggest that the values of the functions in the last stage are not the same and we should expect some functions (e.g. entrepreneurial experimentation) to be very weak and others to be very strong (e.g. market formation).

The next step in our analysis is to apply the model and assess its performance in predicting the evolution of the TIS in the case studies. To achieve this, we started by coding the data from the four case studies of Chapter 4, the results of which we illustrate in tables: D.2, D.3, D.4, D.5, in the Appendix D.6. Using these values in the first phase and the base model, we produced the models estimates for the TIS evolution for these four cases. The results are presented in Tables: D.6, D.7, D.8, in the Appendix D.7.

To assess the performance of our the base model, we decided to take the difference between the predicted and the actual values of each function in the final stage. The results are presented in Table 5.3, where we can see that the model underestimates the performance of the functions. Also, we see that this underestimation is particularly high for Greece and CZ, and relatively smaller for the UK and Germany. This points to misspecification of the model, related perhaps to the fact that the UK and Germany were early adopters and innovators of the technology under examination, while Greece and CZ are latecomers and diffusers, an issue which our model with the existing specification cannot take into account.

	Deviations of the Base Model
Greece	-0.29
Czech Republic	-0.53
UK	-0.17
Germany	0.08

Table 5.3 Assessment of the Base Model

The above analysis illustrates that the model works relatively well for countries at the technological frontier. However, the base model does not explain well the performance of laggard countries. For these reasons, in the next section we make extensions to the model.

5.4.2 Extensions to the base model

Introducing the Convergence Potential

An improvement to our base model is the incorporation of the convergence potential, which is a measure of a country's distance from the technological frontier. By introducing this new term, we can differentiate between countries that are creating the technologies, which we call "innovators", and countries which are only adopting the technology, which we call "followers". Without this new measure, the base model is unable to explain TIS evolution in Greece and CZ which are examples of follower economies.

We assume that a country's convergence potential is positively related to the distance from the technology frontier. This means that the further away countries are from the technological frontier, the faster they will be able to catch up with those that are the technology frontier. This is because we assume the existence of the "advantage of backwardness" (Gerschenkron, 1962), and expect the marginal returns to adoption are greater than of technology leaders, given that technology is well diffused and known as it has been developed by technology leaders. This follows the literature on technology frontier (Howitt & Mayer-Foulkes, 2002; Acemoglu et al., 2006), which suggests that relatively backward economies can catch-up to the technology leaders faster by adopting already invented technologies.

To capture this convergence potential, we propose the following model 5.2:

$$\tilde{F}_i^{(t)} = F_i^{(t)} + \alpha_c^{(t)} \left(TF_i^{(t)} - F_i^{(t)} \right) \tag{5.2}$$

where $\tilde{F}_i^{(t)}$ is the value of function i in period t, and the value of F_i comes from our base model (Equation (5.1)). Effectively, this extension adds another term to the predicted value of each function in each phase, which accounts precisely for the effect of innovation on other countries. Namely, our base model assumes a closed economy, while this extension aims to account for technology transfer in an international context, i.e. accounting for the fact that technology latecomers can benefit from technology developed by technology leader.

The $\alpha_c^{(t)}$ term can be viewed as the coefficient of convergence or a proxy for absorptive capacity, which depends on whether a country is an innovator or an adopter. For simplicity, we assume that its value does not change across functions, but does change across time and varies across countries. It can take any value from 0 to 1, with 0 being complete lack of adoption or convergence potential and 1 indicating excellent adoption probability or high convergence potential. In other words, if the country is not able to absorb the technology, it has a low value of $\alpha_c^{(t)}$, and a high value if the country is very good in absorbing the technological developments around the technology in question, or generates the technology itself.

To set the values of α, we follow an approach similar to that by Howitt & Mayer-Foulkes (2002) who introduced a multi-country Schumpeterian growth model, and separated the countries into three distinct groups. The first group of countries is known to reach an R&D steady state, as it to absorb the technology from abroad and generate its own; the second group is those countries which achieve the implementation steady state, and are able to use technologies invented abroad. Lastly, the group of countries with no ability to absorb technology will be also stuck to a low growth phase unable to catch up with the leaders. With this in mind, we also have three separate categories for the value of α, based on whether the country has high, medium or low absorptive capability. These values are presented in Table 5.4.

	Coefficient of Adoption		
	Niche Markets	Dominant Design	Mass Market
High Absorption	0.3	0.6	0.9
Medium Absorption	0.2	0.5	0.7
Low Absorption	0.1	0.4	0.6

Table 5.4 The values of α

Lastly, $TF_i^{(t)}$ is the value of the function i of the technology leader in time t. In this case, we assume that the reference model is the same as the technology leader, so the value for each $TF_i^{(t)}$ is the same as the value of the function of the stylised model in Figure 5.1. The values for all the functions can be seen in Table 5.5.

The Stylised Model				
	$TF_i^{(1)}$	$TF_i^{(2)}$	$TF_i^{(3)}$	$TF_i^{(4)}$
Function	Phase 1 Values Emergence of technologies	Phase 2 Values Niche Markets	Phase 3 Values Dominant Design	Phase 4 Values Mass Market
F_1	VS	VS	W	VW
F_2	VS	VS	W	W
F_3	S	VS	W	VW
F_4	W	VS	S	VW
F_5	W	VS	S	S
F_6	VW	W	VS	S
F_7	VW	VW	S	VS

Table 5.5 The values of TF_i

The equation from the model suggests that if a country is very far from the frontier, then the value of $\left(TF_i^{(t)} - F_i^{(t)}\right)$ will be large, and according to the value of $\alpha_c^{(t)}$, this can help the value of the function to increase substantially. In an extreme case, where the value of $F_i^{(t)}$ is zero, but the value of $\alpha_c^{(t)}$ is 1, then the country can manage to catch up fully and instantly with the technology leader. Thus, the model shows that the greater the value of $\alpha_c^{(t)}$ and the greater the distance of the country from the Technological Frontier, the faster will the value of the function catch up. Therefore, this equation 5.2 can be seen as describing the extent to which adoption of a certain function in a country can be brought up towards the value of the technology leader. This value should depend on assumed distance of country from technology frontier, and its absorptive capacity.

To assess the new model's performance, we calculated again the model's predictions for each of the case studies. Then, we subtracted the predicted values from the actual values in order to get a measure for the model's efficiency. Also, for completeness, we calculated the values of the TIS for each country under all three possible values of α; i.e. if the country has low, medium or high absorptive capacity. The results are illustrated in Table 5.6. Overall, we see that there is a significant improvement on the base model, especially for the case of the Czech Republic, which is the laggard country, assuming that its absorptive capacity is high.

Deviations of the Models from the Case Studies				
	Base Model	New Model	New Model	New Model
		High Absorption	Medium Absorption	Low Absorption
Greece	- 0.30	- 0.29	- 0.29	- 0.30
Czech Republic	- 0.53	- 0.32	- 0.35	- 0.39
UK	- 0.16	- 0.13	- 0.13	- 0.14
Germany	0.08	- 0.00	0.02	0.03

Table 5.6 Assessing the New Model

Diminishing Returns to Complementarities

Although the convergence factor presents an improvement to our base model, there is scope for even further improvement. In particular, we can assume that the strength of the complementarities decreases across times. In other words, as the system evolves, the functions still interact with each other, but it could be argued that the strength and importance of these interactions decreases. This can be explained by the fact that the difference in the performance and strength of each function decreases as the system evolve. For example, as the TIS enters the period of mass market, we can expect most of the markets to be active, albeit to different degrees. For example, there would already be some knowledge institutions, the market institutions would be in place so that the functioning of the market will continue, some form of legitimation and public acceptance for the technology should exist, and there would be some resources available to the users and adopters. In this phase, we can expect the impact of guidance of search on market formation to be much less important compared to the early phase of technology emergence, where there was virtually no market and any demand was policy driven.

To model this new theoretical proposition, we assume that the nature of the complementarities remains the same, but the numerical values of these interactions decrease across time. For simplicity, we assume that they decrease linearly across each phase, by 20%. The impact of this on the numerical values of the complementarities is presented in Table 5.7.

Complementarities Table				
Strength of Complementarity	Phase 1 Values	Phase 2 Values	Phase 3 Values	Phase 4 Values
	Emergence of technologies	Niche Markets	Dominant Design	Mass Market
Very Strong (VS)	0.8 - 1	0.64 - 0.8	0.51 - 0.64	0.41 - 0.51
Strong (S)	0.5 - 0.7	0.4 - 0.56	0.32 - 0.45	0.26 - 0.36
Weak (W)	0.2 - 0.4	0.16 - 0.32	0.13 - 0.26	0.1 - 0.2
Very Weak (VW)	0 - 0.1	0 - 0.08	0 - 0.06	0 - 0.05

Table 5.7 The Values of Complementarities

Table 5.8 shows the potential improvements in efficiency that the introduction of this new theoretical proposition has with respect to the performance of the model. In particular, the last column shows the difference between the predictions of the new model with the assumption of decreasing returns to complementarities and the actual results of the case studies. If we focus on comparing these results with the original base model, we can see that the new model does not provide an improvement to the base model, and is inferior to the models with the new functions of knowledge absorption.

Deviations from Case Study Data					
	Base Model	New Model (High Absorption)	New Model (Medium Absorption)	New Model (Low Absorption)	Complementarities Added Model
Greece	- 0.30	- 0.29	- 0.29	- 0.30	- 0.31
Czech Republic	- 0.53	- 0.32	- 0.35	- 0.39	- 0.53
UK	- 0.16	- 0.13	- 0.13	- 0.14	- 0.17
Germany	0.08	- 0.00	0.02	0.03	0.07

Table 5.8 Assessing the Decreasing Complementarities

The results of this modelling suggest that our theoretical proposition on the decreasing importance of complementarities as the TIS evolves was not validated by our data. This could have two potential explanations. The first one suggests that the way functions interact and influence each other remain highly significant independently of the stage at which the TIS is. A second more technical one is that the number of countries in our sample is too small to allow us to test the hypothesis satisfactorily.

5.5 Conclusions

The aim of this chapter was to provide a formalisation of the mechanisms of the TIS evolution which we developed in Chapter 4. Through formalisation, we can get a deeper understanding of how differences in the initial conditions of the system (i.e. differences in technological levels) of a TIS influence the evolution of the system. Moreover, we also wanted to get an understanding of how the process of TIS evolution is influenced by the value/strength of the complementarities between the functions.

In terms of this chapter's theoretical contributions, this chapter develops a model that can identify how weaknesses in some functions of the system influence the overall performance of the system. In this way, it is possible for the TIS practitioners to better understand system failures, or system successes. Also, we recognise that the TIS literatures does not explicitly take into account technology specific factors which are external to the system, but exert a great impact on it. To deal with this "practical inconvenience", we introduce a new element in the TIS, which we label "potential for technology diffusion". This is more a factor rather than a function, since it is not determined by the system, but solely influences the system. In the case of RETs, to measure this potential, we use indicators that capture a country's resource potential.

After introducing this new factor, we construct a base model which illustrates how a system can develop. This model was built using the history friendly approach of evolutionary economics, where a stylised set of facts guides the building of the model, rather than some oversimplifying assumptions. In particular, we created a reference model, which captures stylised facts of TIS evolution, which we got from reviewing the literature and investigating the case studies. Then, a mathematical model was created which uses the initial values of the functions of a system in the first phase (emergence of technologies), the various complementarities between the functions, and then estimates how the functions should perform as the technology diffuses. The advantage of such a model is that allows us to take into account path dependence and the complementarities between system functions, both of which are key tenets of evolutionary economics and TIS. At the same time, the model allows us to understand how the weaknesses or the failures of one function can influence the performance of the system as a whole; this way to analyse the system and the impact of its failures has not been attempted before, and this is the key contribution of this Chapter.

Our next step was to test the predictions of the model. To do this, we used the data from the case studies on solar PV that were analysed in Chapter 4, and compared the model's predictions with the actual data. Our initial comparison showed that the model was accurate in predicting the evolution of the UK and Germany, but not efficient in the case of Greece and the Czech Republic. We hypothesised that a potential explanation for this divergence in results might be related to the fact that the model did not differentiate between adopters and innovators. To deal with this, we introduced a proxy for the country's distance from the technological frontier, and then the results significantly improved.

In an effort to achieve even greater accuracy between the model's prediction and the actual results from the case studies, we also tried to incorporate into our analysis an extra assumption: that of Diminishing Returns to Complementarities. However, we found little evidence that this improved the performance of our model. This showed that complementarities between functions remain important across all phases of the TIS evolution. This finding reinforces the relevance of the TIS approach in analysing diffusion, which emphasises the important role of the complementarities in the process of system evolution.

In our view, some of the most interesting directions for further search including the testing of the same model to a larger dataset and potential to a new RET (e.g. wind). In this way, the efficiency of the base model and its extensions can be further verified. In terms of other model extensions, a very interesting expansion would be to incorporate various factors that could identify system failures, negative complementarities, and a modification of the model to account for the TIS development in emerging markets.

Chapter 6

Conclusions

6.1 Summary Findings

The aim in this work is to investigate the reasons why some countries have more renewable energy than others within a dynamic framework. In other words, the main argument of this thesis is that the diffusion determinants vary across time. To address this question, we decided to focus on only new renewable energy which was close to commercialization, that is, solar PV and wind. In the course of the research, we were led to the look at the literature on the diffusion of innovation, which, as discussed above, we decided to combine with the ILC/PLC literature.

The analysis of such a complex system can only be achieved efficiently by using a multi-method approach (Norgaard, 1989). Therefore, instead of focusing only on quantitative or qualitative methods, this work on diffusion brings together a mix of quantitative and qualitative approaches. Chapter 2 takes a purely quantitative approach to identify how the determinants vary across time, Chapter 3, uses both quantitative and qualitative methods to identify how the determinants vary across difference technology systems, and Chapter 4 uses a purely qualitative approach to examine how the nature and performance of the functions varies across times, while Chapter 5 creates a model to simulate how the TIS evolves across time.

Throughout the research process, various innovations, modifications and improvements to the traditional diffusion models emerged at both the theoretical and methodological levels. This section starts by presenting the findings on a chapter by chapter basis to show the complementarities between them. Then, this chapter proceeds by illustrating the contributions of this work on theoretical, methodological and empirical level, while the last two sections provide policy recommendations and avenues for further research.

6.1.1 Chapter 2 - Determinants of adoption and diffusion of Wind Energy: competing theories and frameworks

Chapter 2 examines the diffusion of wind. Our primary aim is to understand the characteristics of the innovation and the consumers/adopters that influence first adoption and also diffusion, and how this vary across time. To achieve this, we combined two theories of diffusion (neoclassical and DOI) with the conceptual framework of life cycle models. By including the stages of the PLC and the ILC, we have managed to capture some of the dynamics of the industry and technology and to build a theoretical model that explains the determinants of first adoption and diffusion.

We constructed a dataset of 130 countries over the time period 1990-2009, using multiple international sources. With the help of econometric analysis, our results confirm the neoclassical approach that both actual and potential profitability is a key property of the technology necessary for its diffusion. Moreover, policy was found to be important, but decreasingly as the technology moved through the PLC.In terms of the DOI, we found that observability was important, as well as the efforts of the change agent. Energy sector specificities, such as carbon-lock in were also found important determinants.

Although our approach is econometrically robust, it does not capture many of the dynamics of the coevolution of the elements. In addition, the dataset includes many outliers which cannot be examined in depth using this approach; in some cases they are excluded from the analysis (e.g. to increase the model fit).

6.1.2 Chapter 3 - Investigating the Technology Innovation System

Chapter 3 tries to understand how the components of the system interact together and lead to the outcome of diffusion. To achieve this, we focus on the performance of the functions as conceptualized in the TIS. For completeness, we investigate both solar PV and wind.

The TIS literature has various theoretical and practical weaknesses. Some of the key problems are the treatment of time, the empirical and conceptual overlap between functions, and lack of consensus on the exact number, properties and indicators used to measure them, and the names of the system's functions. In relation to functions, there are no studies that investigate the complementarities between functions, which is a crucial element in the operation of a system.

To deal with some of these issues, we decided first to use QCA, a methodology designed to bridge the qualitative-quantitative gap. Our sample consisted of 20 countries. For each of these, we had to assess the performance of each function, which required consistent and appropriate indicators and clarification of the contributions of each to the performance of the function. By applying QCA, we eventually came up with different configurations of the functions that can lead to efficient diffusion. Crucially, we found that for the successful operation of the TIS, not all functions need be fully active. Interestingly, although we compare two very similar technologies, we found that the functions necessary for the system to operate vary with the technology.

Our findings suggest that different configurations of functions can lead to the same outcome. This could be surprising to the reader, who might assume that all functions are necessary for the efficient evolution of the TIS. However, QCA illustrates that not all functions are necessary. However, this method cannot investigate the dynamic nature of the TIS and the complementarities among functions, and how these functions vary across time, something which was the subject of Chapters 4 and 5.

6.1.3 Chapter 4 - Diffusion as Evolution of Technology Systems

The aim of the chapter is to propose a dynamic model of TIS evolution and identifies how the TIS evolves across time. This is achieved by looking at four case studies of solar PV diffusion. The main advantage of this case study research is that it allowed us to open the black box of the configurations presented in Chapter 3, and identify the mechanisms behind their operation.

To explore this dynamic nature of TIS, we took two examples each of successful and unsuccessful cases and incorporated the criterion of speed of adoption, splitting successful and unsuccessful countries into early and late adopters. Our cases are Germany, Greece, the UK and the Czech Republic. This allowed us to find various interesting propositions. For example, we distinguished between adopter countries and pioneers, and found that different configurations of functions were necessary for each country. We also identified the phenomenon of induced diffusion, whereby a system fails to develop if its development is stimulated for a short period of time purely by subsidies.

6.1.4 Chapter 5 - Formalising Dynamics in TIS

After developing a deeper understanding of the mechanism of the TIS evolution through the case studies in Chapter 4 , this chapter adapts a mathematical model of ferromagnetism from statistical mechanics (Ising model), into the context of TIS. Through this, it becomes possible to study the dynamics of interactions and complementarities among functions. The model is then used to demonstrate how weaknesses in some functions in early phases can be compensated for by other, stronger functions, which act to "pull" these functions until harmonization of the system and full convergence of all functions at the same level is achieved.

Moreover, in this chapter we decided to introduce a new factor in the TIS: the potential for diffusion. This captures the technological and physical potential for technology diffusion. We argue that this is less a function and more a factor, since it influences the TIS, but is not influenced by it. This factor acts as a bridge between traditional scholarship in diffusion studies and the systems approach, as it incorporates a fixed factor into an ever changing socioeconomic system. Its exclusion by TIS scholars is likely because it cannot be changed within the system, i.e. it is fixed. Nonetheless, it is a key issue because it influences the functions in so many ways that it cannot be ignored. Moreover, it is the factor that serves as a proxy for the physical and technical limits of diffusion, and could be argued that it sets the limits to the TIS.

Lastly, influenced by the findings in Chapters 3 and 4 about adopters and pioneers, we decided to include a proxy for a country's distance from the technological frontier, which we we label Convergence Potential. Clearly, only a very small number of countries can be pioneers in solar PV since it is a very sophisticated technology that requires high levels of knowledge capacity and significant resources. Consequently, there is a large number of adopter countries, but, as the empirical evidence shows, there is a huge difference in the performance of their TIS. We argue that this is related to the absorptive capacity of these countries with those with high levels of absorptive capacity achieving the fastest diffusion.

6.2 Our Contributions

6.2.1 Methodological Contribution

Given the complexity of the process of diffusion which we have described above, this research adopts a multi-method approach to examine the diffusion phenomenon. The key advantage of mixed methods is the ability to get a deeper understanding of the dynamics of a multi-level complex process while also achieving empirical and descriptive precision. In addition, the use of quantitative and qualitative analysis to support our conceptual framework allows us to examine the suggested processes in more depth, and achieve greater validity in our results through triangulation. Triangulation implies that given the limitations and biases of each method, using that particular one to discuss a particular phenomenon will lead to biased results. This issue can be resolved when using "two methods in combination which have different biases as this will then increase the validity of inquiry findings is enhanced" (Greene et al., 1989, p.256). In this way, this research contrasts with the incompatibility thesis, a term coined by Howe (1988) in an attempt to frame the endless debate between the "quantitative purists" and "qualitative purists", where each advocates an exclusive qualitative or quantitative scientific paradigm and no combination of the respective methodologies in any type of scientific work. However, this debate rests on misuse of the concept of epistemology as synonymous with method, where the former is a philosophical and the latter a technical issue (Howe, 1988; 1992; Onwuegbuzie & Leech, 2005). In particular, epistemology deals with "the appropriate foundation for the study of society and its manifestation" (Bryman, 1984, p.75) and does not suggest what methods and data collection processes the researcher should use; this is clearly the task of methodology. (Howe, 1988)

In Chapter 2, we distinguish between first adoption and the process of diffusion, and use in hazard models, and General Method of Moment (GMM) regression to identify the determinants. Hazard models have been used in previous work, but our innovation was to use them not just to identify first adoption but also as a means to measure diffusion. In addition, the use of hazard models allows us to identify the determinants of diffusion in the early stages of the life-cycle. GMM models are a recent addition to the econometrics field and, to our knowledge, have not been used to study the diffusion of innovation.

In the context of the TIS literature, we make the innovation of using Qualitative Comparative Analysis (QCA), a method not so far used in this context, but which is a very good fit for system analysis. The advantage of this method is that it allows to bridge the qualitative-quantitative gap, and helps identify different combinations of functions which can lead to a successful TIS.

However, QCA does not capture the dynamics of system evolution and provides a rather static picture which does not show how the functions interact to achieve a successful TIS. To overcome this, in Chapter 4, we use a stage model to investigate how the TIS evolves across time. Case study research is not a novelty in the field of TIS, but the way we use this method is decidedly novel. In particular, we focus on one TIS, and four countries, which allows a very deep understanding of the process, and look at the evolution of all the functions of the TIS across each of the four stages suggested by the life-cycle model.

Having achieved a deeper understanding of how the TIS works and how its functions interact across time, in Chapter 5, we decided to develop an algorithm to simulate evolution of the TIS system[1]. To the best of our knowledge, this is the first work to provide a mathematical conceptualization of the evolution of the TIS. The main advantage of this modelling approach is that it allowed us to formalize and investigate the complementarities between the functions of the system.

6.2.2 Empirical Contributions

In Chapter 2, our main empirical contribution was that the diffusion of wind is influenced by energy specific institutional factors (e.g. carbon lock-in), which vary across time. To achieve this, we had to combine two different theoretical approaches (neoclassical and DOI), and construct a dataset of 130 countries over a 20 year period. The dataset combined various international and macro databases and created a unique database with diffusion related variables.

In Chapter 3, we compiled databases from scratch, combining information from policy documents, academic papers, business reports, news websites, expert interviews, etc. for both wind and solar PV. After analysing them with QCA, we found that a successful TIS can be achieved through various combinations of functions, something which is a major contribution to TIS since most of the literature assumes implicitly that for the system to operate all functions have to be active simultaneously. For example, for a solar PV TIS to be successful, there are two potential configurations of functions. The first configuration consists of legitimation, entrepreneurial experimentation, and market formation. The second configuration needs to have knowledge development, entrepreneurial ex-

[1]The actual formulation of the mathematical model was done by M.P.Kitromilides, a PhD student from Imperial College London, studying complex systems.

perimentation, and resource mobilization.

In Chapter 4, we discussed how the different functions of the TIS interact with each other across time. These insights were developed by in-depth investigations of four case studies of Solar PV diffusion. The countries were selected based on time and success of adoption. The early adopters were Germany, which was an early and successful adopter of solar PV, and the UK, an early but unsuccessful adopter. The late adopters were, Greece which was late and unsuccessful, and the Czech Republic which was late and successful country.

Lastly, in Chapter 5, our model illustrated that the countries that are behind the technological frontier are likely to catch up with the pioneers in terms of success of diffusion, as long as they have high absorptive capacity. This was confirmed by looking at the data of the four countries we analysed in Chapter 4.

6.2.3 Theoretical Contribution

Our findings from Chapter 2 illustrated the importance of the dominant design as a point in time which influences the diffusion process. In particular, we found evidence to suggest that the diffusion determinants vary before and after the DD emergence. For example, in the case of wind, we found that institutional factors are more important in the early phases of a product's life cycle rather than economic.

In Chapter 3, we showed that the nature and performance of individual functions are determined by their interaction with other functions in the system. We find that not all TIS functions are necessary for diffusion; in solar PV TIS, in the presence of market formation, legitimation and entrepreneurial experimentation all other functions become unnecessary. However, in the absence of market formation and entrepreneurial experimentation, knowledge development and resource mobilisation become necessary for the successful TIS.

The major theoretical contribution in Chapter 4 which extends the approach of Chapter 3, is the integration of the element of time in the TIS, something which has been attempted by existing literature, but not sufficiently. Thus, the present work advances the ways in which a dynamic approach to TIS can be applied. In this way, we find that the nature and performance of functions does not depend solely on the interaction with other factors, but also on time. For example, the role of guidance of search before the

Table 6.1 Theoretical Contributions

Chapter 2	We illustrated how the emergence of the Dominant Design influences the determinants of diffusion.
Chapter 3	The nature and performance of individual functions are determined by the interaction with the other functions of the system and they are never determined by themselves.
Chapter 4	The nature and performance of the functions vary across time. Moreover, a common pattern of TIS evolution was identified. However, country specific patterns emerge based on a country's institutional characteristics and distance from the technological frontier.
Chapter 5	The TIS evolves through the interaction of the initial conditions and complementarities.

Table 6.2 Methodological Contributions

Chapter 2	Application of GMM and survival methods in diffusion of RETs.
Chapter 3	Application of QCA in the context of TIS.
Chapter 4	We develop a stage method to investigate how the TIS evolves across time.
Chapter 5	We developed an algorithm that formalises the evolution of a TIS.

emergence of the dominant design is to guide entrepreneurs towards testing different technologies, while after its role is to facilitate the diffusion of the technology, usually by subsidising it.

Moreover, in this Chapter, we found a common pattern in the evolution of TIS. What we observed is that in all four cases, legitimation was necessary in the early phases of the TIS, which then stimulated guidance of search, which in turn influenced resource mobilisations, entrepreneurial experimentation and market formation. In addition, we found that country specific patterns emerge based on a country's institutional characteristics and distance from the technological frontier.

Lastly, Chapter 5 brings together the results from Chapters 3 and 4 and creates a model which illustrates that the evolution of the TIS is the result of the interaction of the system's initial conditions and complementarities.

A summary of our contributions in this work can be seen in Tables 6.1, 6.2 and 6.3.

Table 6.3 Empirical Contributions

Chapter 2	We constructed a dataset of 130 countries over the time period 1990-2009, using multiple international sources to test the diffusion of wind. We found evidence illustrating the importance of energy specific institutional factors as barriers to diffusion of RETs.
Chapter 3	We found that different configurations of functions are possible for the successful TIS evolution. We compiled databases from scratch, combining information from policy documents, academic papers, business reports, news websites, expert interviews, etc.
Chapter 4	We conducted an in depth investigation of 4 case studies in solar TIS, which gave us insights on how the different functions interact with each other across time and lead to TIS diffusion.
Chapter 5	We tested our algorithm with data for 4 countries: UK, DE, CZ, GR. The model demonstrates that countries behind the technological frontier are likely to catch up with the pioneers.

6.3 Thoughts on Technology Policy for Diffusion

Any supporter of the greater need in modern economic systems of a wider use of RETs has views on how this process can be stimulated. The impression one gets by reading about RETs in policy documents and non-academic material is that almost all believe that all that is necessary is a government subsidy to support the technology to make it competitive on price with conventional technologies, something which can explain why more than 45 countries have adopted this support mechanism over the past two decades[2]. Nonetheless, in this doctoral research we did not find any strong evidence on the direct influence of subsidies.

Our findings suggest that policy cannot be proxied as binary variable; in other words, it is not sufficient to argue that supportive policy exists or does not exist in a certain system. Rather, the quality of the policy matters. By quality in this context, we understand the way the policy is designed so that it influences the other components of the energy system. For example, if the government introduces generous subsidies for a technology that is still in the introductory phase, but does not initiate any demonstrations projects, then the effects on diffusion are likely to be limited. In other words, in a situation of an underdeveloped system, policy aimed at stimulating only a particular element of a system, is usually not enough to stimulate adoption of RETs. This implies that policy should not be designed in such a way that it influences only a particular activity in the system,

[2]For a detailed representation of the international history of FiT adoption see Figure A.1 in Appendix A.1

since system performance is the outcome of several interrelated activities or functions.

Based on our findings we would recommend that any country which is interested in stimulating the development of solar TIS should develop it based on the common pattern that we illustrate in Figure 4.59. In particular, there should be some public acceptance for the technology in question, which the government can then view as a reason to start supporting the technology. The support should be designed in such a way that it would stimulate both financial and human capital resources for the technology, encourage entrepreneurs to experiment with the technology, but also make sure that there are the appropriate institutions that would allow for market development.

Lastly, even though we found a common pattern of TIS evolution, this does not mean that there is a unique policy mix that can be applied to all countries. Rather policy is dependent on the stage in the technology's life cycle and the country's distance from the technology frontier. The most characteristic example of this distinction can be found when looking at the pioneers and followers in solar PV. For pioneers, policy needs to be designed in such a way that activities around knowledge development are supported, in addition to all other functions. An example of such a case is Germany which was a pioneer in Solar PV, and the TIS was successful as policy was supportive since the beginning towards knowledge development. On the contrary, in Greece the government was supportive of knowledge development since the early phases of the technology, but the TIS did not manage to develop until the technology was at the later stages of the life-cycle.

6.4 Limitations of and Issues for Further Research

One of the next steps researchers in the field could do is to incorporate agent-based modelling (ABM) into this work. This method is capable of capturing the dynamics of the interactions between agents within a complex system. ABM is based on the idea that macro phenomena can be explained by looking at the way individuals interact at the micro level (Garcia & Jager, 2011). By setting certain rules, computerised algorithms can predict how agents interact with institutions and a given outcome is achieved. In the context of diffusion research, ABM can be used to identify various phenomena that we discussed in this work. For example, if we look at the DOI theory, we can model the behaviour of potential adopters and incorporate explicitly the assumption of observability. In other words, the fact that one agent has adopted the technology will influence the probability that the other agent will adopt it, and the more agents adopt it the stronger will the observability effects be. This reinforcement mechanism, although hard to model in traditional econometric techniques, is relatively easy to model with ABM (Gilbert, 2008). ABM can also help better explain how the interactions and complementarities between the functions of a TIS operate. If we think about the relationship between guidance of search and entrepreneurial experimentation, the way information spreads from among the entrepreneurs and from them to the government can be nicely modelled using ABM.

For the work on Chapter 3, an alternative methodology that could be used is structural equation modelling (SEM). In this way, the researcher will be also able to measure the indirect effects of the functions within the system. For example, in our configurations we found that only some functions are necessary for diffusion; however, this does not necessarily mean that the other functions are not important for the system, but simply that they are not directly influencing diffusion. In reality, they might influence diffusion, but in an indirect way, through other functions. Using SEM could help deal with this problem, but for this technique to work the sample size has to be very large, something which can be proven unrealistic in the context of TIS.

An alternative to SEM is Partial Least Squares (PLS). This technique allows to capture not only the impact of the independent variable on the dependent but also the impact that the dependent has on the independent, as well as any impact the independent variables have on each other. In addition, they allow for modelling indirect effects of independent variables on both the dependent and the other independent. Nonetheless, we view this as an expansion rather than an improvement of the QCA approach. PLS is not appropriate when the researcher tries to identify factors which do not influence the dependent variable. Therefore, QCA is necessary to identify which functions are necessary and sufficient.

For Chapter 4, future researchers could conduct an analysis similar to that proposed by Castellacci & Natera (2013) on national innovation systems. They conducted a cointegration approach to identify the evolution of the national innovation system. Achieving this in the context of the TIS is a harder however due to the lack of data, or the extremely time consuming nature of gathering enough data across time for a large enough sample of countries that would allow a robust cointegration analysis.

Other expansions to our work are related to the algorithm that we developed in Chapter 5. Some of the most interesting expansions to our model are the testing of the same model to a larger dataset and potential to a new RET (e.g. wind). In this way, the efficiency of the base model and its extensions can be further verified. In terms of other model extensions, a very interesting expansion would be to incorporate various factors that could identify system failures, negative complementarities, and a modification of the model to account for the TIS development in emerging markets.

Lastly, one of the main weaknesses of the methodologies proposed to identify the boundaries of the stages in life-cycles models is their inability to determine the limits to stages. In this work, we partly address this issue by proposing a way to identify the limits between the introduction and the growth phases. However, due to the nature of our technologies which have not yet reached maturity, we were unable to propose any ways to capture the limits of the growth phase. To deal with this, future research could investigate an energy technology that has achieved maturity, and could try to identify the limits to every stage in its diffusion. Examples of such technologies could be hydropower, or geothermal since both these are renewable energy technologies, and have arguably reached their maturity phase.

Appendix A

A.1 History of Feed-In Tariff Adoption

	Year of Adoption	Country
Western European Adoption	1978	United States
	1990	Germany
	1991	Switzerland
	1992	Italy
	1993	Denmark, India
	1994	Spain, Greece
	1997	Sri Lanka
	1998	Sweden
	1999	Portugal, Norway, Slovenia

	Year of Adoption	Country	City, State, Province
International Adoption	2001	France, Latvia	
	2002	Algeria, Austria, Brazil, Czech Republic, Indonesia, Lithuania	
	2003	Cyprus, Estonia, Hungary, South Korea, Slovak Republic	Maharashtra (India)
	2004	Israel, Nicaragua	Prince Edward Island (Canada), Andhra Pradesh and Madhya Pradesh (India)
	2005	China, Turkey, Ecuador, Ireland	Karnataka, Uttaranchal, Uttar Pradesh (India)
	2006	Argentina, Thailand	Ontario (Canada)
	2007	Albania, Bulgaria, Croatia, Macedonia, Uganda	South Australia (Australia)
	2008	Kenya, Philippines, Poland, Ukraine, Switzerland	Queensland (Australia), California (USA), Gujarat, Haryana, Punjab, Rajasthan, Tamil, Nadu and West Bangal (India)
	2009	South Africa	Australian Capital Territory (Australia), New South Wales (Australia), Gainesville, FL (USA), Hawaii (USA), Maine (USA), Vermont (USA)
	2010	India, United Kingdom	Western Australia (Australia)

Fig. A.1 History of Feed-In Tariff Adoption

Source: Institute for Building Efficiency

Appendix B

B.1 Variables that were tested in the Models

profitability	dummy for the imposition of FITs	fits_sts
price of fossil fuels/gas	world price of crude oil	crude_oil_brent
	world price of crude oil in Local currency	LCU_crude_oil_brent_sts
cost of wind turbine	cost €/kw for Danish Turbines	cost_wind_eur
size of the market	calculated electricity consumption/capita	ele_tot_cons_cap_sts
availability of the resource (supply)	weighted average the area of load hours per capita	wind_res_cap_sts
	weighted average the area of load hours per capita (average in the period)	a_wind_res_cap
	weighted average the area of load hours	wind_res
carbon lock-in	what % of electricity is produced by fossil fuels	fossil_fue_ener_consu_sts
	interaction between oil price and oil dependency	oil_fossil_sts
market lock in	natural resource rents as % of GDP	nat_res_prc_gdp_sts
	oil rents as a % of GDP	oil_rents_prcGDP
openess	trade as a % of GDP	trade_prc_GDP_sts
capability	FDI as a % of GDP	fdi_prc_GDP_sts
observability	distance from Denmark	dist_den
	trade with pioneers	M_Denmark_sts
	interaction between distance and trade from Denmark	den_dis_imp_sts
	interaction between distance, trade from Denmark, and development	den_dis_imp_gdp_sts
development	gdp_capita	gdp_capita_PPP_2005_sts
democracy	polity2	polity2_sts
environmental awareness indicator	green party	greenparty_sts
interaction var to measure the strength of green party	green party * polity2	pol_gp
	kyoto protocol dummy	sign_kyoto_sts
change agent	EU membership dummy	eu_sts
	interaction between kyoto and EU	eu_kyoto_sts
Human Capital	Primary and Secondary education total (years)	y_sc_total_sts
	Primary and Secondary education total (years) (average)	a_y_sc_total
R&D / capita expenditure	Research and development expenditure (% of GDP)	RnD_expend
Energy Efficiency	Energy use (kg of oil equivalent) per $1,000 GDP	energy_use_GDP_sts
Energy Dependency	Energy imports, net (% of energy use)	imp_energy_prcenergy_sts
	interaction between oil price and energy import dependency	oil_impdep_sts
	interaction between oil price and energy import dependency and % of electricity produced from fossil fuels	oil_impdep_fos_sts
Cleaningness of the country	CO2 emissions (metric tons per capita)	co2_emissions_capita_sts
	CO2 intensity	co2_intensity_sts

Fig. B.1 All variables used in this chapter

B.2 All models for the Introduction Phase in the ILC Model

	(1) Model_1	(2) Model_2	(3) m6	(4) m9	(5) m10	(6) m22	(7) m25	(8) m26	(9) m29	(10) m30	(11) m31	(12) m33
	b/se	b/se	b/se	b/se	b/se	b/se	b/se	b/se	b/se	b/se	b/se	b/se
a_y_sc_total	1.0202	0.996	0.9423	1.0733	1.0349	0.9739	1.0991	1.0671	1.0524	0.9799	0.7419	1.1074
	(0.3140)	(0.3210)	(0.3047)	(0.3279)	(0.3162)	(0.2893)	(0.3440)	(0.3362)	(0.3503)	(0.3290)	(0.2683)	(0.3433)
co2_emissions_capita	0.9883	0.9928	0.9934	0.9866	0.9879	1.0126						
	(0.0089)	(0.0075)	(0.0080)	(0.0092)	(0.0094)	(0.0089)						
ele_tot_cons2_cap_st	1.0001***	1.0000**	1.0000**	1.0001***	1.0001***		1.0000**	1.0000***	1.0000**	1.0000**	1	1.0000**
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)		(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
energy_use_GDP_sts	0.9999	0.9998	0.9998	0.9998	0.9999	0.9997	0.9995*	0.9995*	0.9994**	0.9994**	0.9992**	0.9995*
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
fdi_prc_GDP_sts	0.9912	0.9866*	0.9878	0.9909	0.9913	0.9882*	0.9870*	0.9875*	0.9820**	0.9825**	0.9844**	0.9874*
	(0.0068)	(0.0074)	(0.0074)	(0.0068)	(0.0069)	(0.0070)	(0.0070)	(0.0072)	(0.0074)	(0.0079)	(0.0075)	(0.0070)
LCU_crude_oil_brent_	1	1	1	1	1	1	1	1	1	1	1	1
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
polity2_sts	1.0017	1.0002	1.0007	1.0018	1.0017	1.0039	1.0021	1.0004	1.0006	0.9991	0.9998	1.002
	(0.0050)	(0.0048)	(0.0049)	(0.0048)	(0.0050)	(0.0050)	(0.0045)	(0.0048)	(0.0045)	(0.0047)	(0.0041)	(0.0045)
trade_prc_GDP_sts	0.9987*	0.9986*	0.9987*	0.9987*	0.9987*	0.9989	0.9983**	0.9982**	0.9980**	0.9981**	0.9987*	0.9984**
	(0.0007)	(0.0007)	(0.0008)	(0.0007)	(0.0007)	(0.0007)	(0.0008)	(0.0008)	(0.0008)	(0.0008)	(0.0007)	(0.0008)
eu_sts	0.9012	0.924	0.9319	0.8958	0.8985	0.9695	0.9296	0.9283	0.9418	0.9482	0.9191	0.931
	(0.0711)	(0.0744)	(0.0740)	(0.0721)	(0.0720)	(0.0773)	(0.0696)	(0.0685)	(0.0727)	(0.0708)	(0.0619)	(0.0696)
fits_sts	1.1758**	1.1761**	1.1710**	1.1787**	1.1750**	1.1803**	1.1732**	1.1713**	1.1892**	1.1853**	1.1464**	1.1684**
	(0.0810)	(0.0826)	(0.0822)	(0.0814)	(0.0816)	(0.0779)	(0.0785)	(0.0789)	(0.0816)	(0.0809)	(0.0692)	(0.0781)
greenparty_sts	1.1365***	1.1158***	1.1227***	1.1331***	1.1366***	1.1106**	1.1019**	1.1117***	1.1030**	1.1137***	1.0799*	1.0991**
	(0.0484)	(0.0467)	(0.0474)	(0.0498)	(0.0495)	(0.0468)	(0.0452)	(0.0445)	(0.0447)	(0.0446)	(0.0430)	(0.0452)
sign_kyoto_sts	1.0486	1.0291	1.0353	1.0445	1.0473	1.0696	1.0626	1.0673	1.0439	1.0526	0.9964	1.0604
	(0.0475)	(0.0474)	(0.0470)	(0.0475)	(0.0474)	(0.0456)	(0.0459)	(0.0457)	(0.0468)	(0.0461)	(0.0435)	(0.0457)
dist_den	1	1	1	1	1	0.9999	1	1	1	1		1
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)		(0.0001)
a_wind_res_cap	7.94E+264						1.30E+114	6.49E+133				
	(6.2327e+267)						(9.2832e+11	(4.4959e+136)				
nat_res_prc_gdp_sts	0.9958		0.9947		0.9959	0.9937*		0.9922**		0.9916***		
	(0.0034)		(0.0035)		(0.0034)	(0.0037)		(0.0031)		(0.0031)		
wind_res		1.0009***	1.0008***						1.0010***	1.0009***	1.0008**	
		(0.0003)	(0.0003)						(0.0003)	(0.0003)	(0.0003)	
imp_energy_prcenergy_sts		1.0006*		1.0003			1.0006**		1.0007***		1.0007***	1.0006**
		(0.0003)		(0.0003)			(0.0003)		(0.0003)		(0.0003)	(0.0003)
wind_res_cap_sts				2.41E+21	1.44E+23	0						0.0063
				(2.5113e+23	(1.5002e+25	(0.0000)						(0.5842)
gdp_capita_PPP_2005_sts						1						
						(0.0000)						
co2_p_kg_2005PPP_sts							1.2141*	1.2606**	1.2532**	1.3071**	1.2951**	1.2121*
							(0.1230)	(0.1326)	(0.1302)	(0.1420)	(0.1467)	(0.1230)
M_Denmark_sts											1.0000***	
											(0.0000)	
eu_kyoto_sts												
pol_gp_sts												
den_dis_imp_sts												
Sample Size	1317	1317	1317	1317	1317	1317	1317	1317	1317	1317	1263	1317
Log Likelihood	-147.5491	-142.3596	-143.3436	-147.5315	-147.6925	-151.1888	-146.6687	-145.8247	-140.4171	-140.4243	-127.6602	-146.73
aic	325.0982	314.7193	316.6872	325.0629	325.385	332.3776	323.3373	321.6494	310.8341	310.8485	283.3203	323.46

	(13) m34	(14) m37	(15) m38	(16) m39	(17) m41	(18) m42	(19) m43	(20) m45	(21) m46	(22) m47	(23) m54
	b/se	b/se	b/se	b/se	b/se	b/se	b/se	b/se	b/se	b/se	b/se
a_y_sc_total	1.0773	1.1015	1.0674	0.7601	1.0537	0.9846	0.7529	1.109	1.0761	0.7859	0.9653
	(0.3369)	(0.3464)	(0.3355)	(0.2733)	(0.3551)	(0.3334)	(0.2746)	(0.3469)	(0.3364)	(0.2790)	(0.3110)
co2_emissions_capita											0.9944
											(0.0080)
ele_tot_cons2_cap_st	1.0000***										1.0000**
	(0.0000)										(0.0000)
energy_use_GDP_sts	0.9995*	0.9994**	0.9994**	0.9991**	0.9993**	0.9993**	0.9991**	0.9994**	0.9994**	0.9991**	0.9998
	(0.0003)	(0.0003)	(0.0003)	(0.0004)	(0.0003)	(0.0003)	(0.0004)	(0.0003)	(0.0003)	(0.0004)	(0.0002)
fdi_prc_GDP_sts	0.9877*	0.9866*	0.9864*	0.9884	0.9813**	0.9807**	0.9845**	0.9867*	0.9865*	0.9886	0.9892
	(0.0072)	(0.0070)	(0.0073)	(0.0074)	(0.0072)	(0.0080)	(0.0077)	(0.0070)	(0.0073)	(0.0074)	(0.0076)
LCU_crude_oil_brent_	1	1	1	1	1	1	1	1	1	1	1
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
polity2_sts	1.0004	1.002	1.0005	1.0005	1.0008	0.9994	0.9999	1.002	1.0005	1.0005	1.0008
	(0.0047)	(0.0044)	(0.0046)	(0.0040)	(0.0044)	(0.0046)	(0.0040)	(0.0044)	(0.0046)	(0.0040)	(0.0049)
trade_prc_GDP_sts	0.9983**	0.9985**	0.9984**	0.9989	0.9982**	0.9982**	0.9988	0.9985*	0.9984**	0.9989	0.9987*
	(0.0008)	(0.0008)	(0.0008)	(0.0007)	(0.0008)	(0.0008)	(0.0007)	(0.0008)	(0.0008)	(0.0007)	(0.0008)
eu_sts	0.9291	0.944	0.9339	0.9006	0.9456	0.9441	0.9205	0.9436	0.9335	0.8996	0.8864
	(0.0688)	(0.0731)	(0.0721)	(0.0600)	(0.0759)	(0.0741)	(0.0632)	(0.0731)	(0.0722)	(0.0604)	(0.0995)
fits_sts	1.1676**	1.1757**	1.1784**	1.1465**	1.1942***	1.1944***	1.1523**	1.1727**	1.1758**	1.1439**	1.1714**
	(0.0786)	(0.0762)	(0.0772)	(0.0658)	(0.0795)	(0.0795)	(0.0692)	(0.0761)	(0.0773)	(0.0657)	(0.0804)
greenparty_sts	1.1097***	1.1009**	1.1043**	1.0977**	1.1019**	1.1079**	1.0912**	1.0992**	1.1029**	1.0994**	1.1330***
	(0.0445)	(0.0465)	(0.0457)	(0.0466)	(0.0455)	(0.0453)	(0.0451)	(0.0470)	(0.0462)	(0.0478)	(0.0504)
sign_kyoto_sts	1.0663	1.0817*	1.0834*	1.0031	1.0595	1.0633	0.9984	1.0808*	1.0827*	1.0031	1.0221
	(0.0455)	(0.0453)	(0.0452)	(0.0427)	(0.0463)	(0.0458)	(0.0434)	(0.0453)	(0.0452)	(0.0428)	(0.0497)
dist_den	1	1	1		0.9999	1		1	1		1
	(0.0001)	(0.0001)	(0.0001)		(0.0001)	(0.0001)		(0.0001)	(0.0001)		(0.0001)
a_wind_res_cap		4.93E+197	6.75E+182	.							
		(3.4274e+20	(4.6008e+18	(.)							
nat_res_prc_gdp_sts	0.9922**		0.9930**			0.9921**			0.9930**		0.9947
	(0.0031)		(0.0031)			(0.0031)			(0.0031)		(0.0035)
wind_res					1.0011***	1.0010***	1.0008**				1.0008***
					(0.0003)	(0.0003)	(0.0003)				(0.0003)
imp_energy_prcenergy_sts		1.0005**		1.0006**	1.0006**		1.0007**	1.0005**		1.0006**	
		(0.0002)		(0.0002)	(0.0002)		(0.0003)	(0.0002)		(0.0002)	
wind_res_cap_sts	224117.517							8.09E+13	1.70E+14	3.02E+40	
	(20351354.2745)							(7.5465e+15	(1.5499e+16	(2.4104e+42)	
gdp_capita_PPP_2005_sts		1	1	1	1	1	1	1	1	1	
		(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	
co2_p_kg_2005PPP_sts	1.2608**	1.2562**	1.3127***	1.3080**	1.2891**	1.3499***	1.3375**	1.2584**	1.3155***	1.3095**	
	(0.1331)	(0.1255)	(0.1381)	(0.1468)	(0.1314)	(0.1453)	(0.1511)	(0.1259)	(0.1386)	(0.1464)	
M_Denmark_sts				1.0000***			1.0000***			1.0000***	
				(0.0000)			(0.0000)			(0.0000)	
eu_kyoto_sts											1.0897
											(0.1353)
pol_gp_sts											
den_dis_imp_sts											
Sample Size	1317	1317	1317	1263	1317	1317	1263	1317	1317	1263	1317
Log Likelihood	-145.9066	-149.163	-148.2524	-130.137	-142.5004	-142.1052	-128.0654	-149.2971	-148.3621	-130.4186	-143.0893
aic	321.8131	328.326	326.5047	288.2741	315.0008	314.2105	284.1308	328.5942	326.7242	288.8371	318.1785

Survival Analysis with standard errors in parentheses

all models | all models (exp) | models with lowest aic | models with lowest aic(exp) | models with lowest aic(std) | models with lowest aic(std)(exp | models for paper

Fig. B.2 All models for the Introduction Phase in the ILC Model

B.3 All models for the Diffusion in the Growth stage of the Industry (GMM)

Variable	m17	m167	m168	m169	m161	m1611	m151	m1512	m1511	m1517	m15178
wind_prc											
L1.	.84397002***	.84263822***	.83400407***	.85176437***	.80252321***	.79707398***	.77304583***	1.1349851***	1.1363377***	1.1359947***	1.0732338***
L2.	.32380025*	.32557783*	.32783805*	.30473499	.34974821*	.35600103*	.36067575*				
L3.											
fits											
--.	-.00009332	-.00009456	-.000026	-.00007031	-.00006807	-.00004441	-.00005194	-.00002079	.00003587	.0000337	.00011663
L1.	-.00013392	-.00013424	-.00009529	-.00003838	-.0000917	-.00009684	-.00007724	-.00001803			.00002864
L2.	.00008395	.00007779	.00011656	.00008907	.00011615	.00015283	.00021344	.00013961			9.295e-06
gdp_cap~2005											
--.											
L1.											
z_M_Denmark											
--.	4.437e-06	4.178e-06	.00001532	-5.878e-07	-.00025125	-.00026912	-.00030386	-.00019828	-.00019293	-.00025901	
L1.					-.00034539	-.00029577	-.00022426	-.0003133	-.00032824	-.0002527	
L2.					.00085288**	.00084288**	.00090412*	.00077794**	.00077983**	.0007839**	
z_fdi_prc_~P	.00158681	.00158445	.00134301	.00129477	-.00036658	-.00027652	-.00035105	-.0001311	-.00010955	-.00007574	.00197661
z_nat_res_~p	-.0000655	-.00006613	-.00006081	-.00007832	-.00008259	-.00006567	-.00005889	-.00001951	-.00002023	-.00001905	-.00001645
z_energy_u~P	.00032509	.000323	.00030633	.00034806	.00025206	.00050552	.00073273	-.00035251	-.00038882	.00006286	.00057608
eu											
--.	.0001482	.00014301	.00020546	.00021027	.00033719	.00034259	.00030381	-.00012617	-.00010452	-.00007228	-.00052565
L1.	.00094156*	.00094386*	.00096297	.00092409*	.00058725	.00056707	.00051088	.00066235	.00066676	.00063333	.00120431
L2.											
greenparty											
--.	-.00153786*	-.00151486*	-.00135272**	-.00130467*	-.0013378*	-.00123937*	-.00108322	-.00088987	-.00091977	-.00083645	-.00057232
L1.											
sign_kyoto	.00039185*	.00038787*	.00036532*	.00042303	.000318	.00030776	.00023857	.00017939	.0001804	.00017337	.00015802

Fig. B.3 All models for the Introduction Phase in the ILC Model

Variable	m116	m115	m117	m118	m119	m1	m12	m13	m14	m15	m16
wind_prc											
L1.	1.1824067***	1.1928226***	1.1841836***	1.1981724***	1.1892744***	1.0207984***	1.0803831***	.80371293***	.84620828***	.84983053***	.84421851***
L2.						-.01162402	-.0544713	.359783*	.3256221*	.32256326*	.32767731*
L3.						.04155791	.08563576				
fits											
--.	.00048896	.00074706*	.00046909	.00065302	.00065117	.00012899	-.00002826	-.0000445	-.00009881	-.00011625	-.00010953
L1.	-.00078701*	-.00092822**	-.00082607	-.00068239	-.00093349*						
L2.	.00046473	.00027195	.00054117	.00041716	.00046323						
gdp_cap~2005											
--.	2.828e-07	2.584e-07	2.482e-07	3.627e-07	2.784e-07						
L1.	-2.691e-07	-2.397e-07	-2.354e-07	-3.493e-07	-2.575e-07						
z_M_Denmark											
--.	-2.816e-06	-.00016319	.00007951	.00011149	-.00038151	.00061269	.00032392	.00013678	.00003756	.0000145	.00002637
L1.	-.00020303	-.00004542	-.00034032	-.00040132	.0001313						
L2.											
z_fdi_prc_~P	-.00094578***	-.00094669***	-.00095172***	-.00097626***	-.00096719***	.00019312	-.00018499	-.00050994	.00129069	.00135679	.00145115
z_nat_res_~p	-.00010115	-.00015862	-.0001081	-.00005607	-.00013147	-.00008518	-.00006059	-.00007546	-.00006039	-.00006448	-.00006908
z_energy_u~P	.00008741	.0001917	.00008882	.00006674	.00014373	.00016995	.00019744	.00028646	.00031434	.00031392	.00030771
eu											
--.	-.00024051	-.00020419	-.00009949	-.00028684	-.00010931	.00021609	.00065622	.00091673	.0009464	.00092278*	.00089751
L1.	-.00009496	-.00065705	-.00013222	-.00044574	-.00073493						
L2.	.00115647	.00178503	.00118236	.00161345	.00194306**						
greenparty											
--.	.00278387	.00536124	.00432662	.00462307	.0028743	-.00042081	-.000994*	-.00161588*	-.00175379**	-.0017799**	-.00170635*
L1.	-.003112	-.00607331	-.00460016	-.00512368	-.00375885						
sign_kyoto	.00005657	.0000737	.0000972	.00010626	.00019457	-.0000134	.00003168	.00018057	.00017246	.00019408	.00041533*

Fig. B.4 All models for the Introduction Phase in the ILC Model

Appendix C

C.1 Two Letter Country Codes

Table C.1 2 Letter Country Codes

Country	**ISO-3166-2** (2 Letter Country Code)
Austria	AT
Belgium	BE
Bulgaria	BG
Croatia	HR
Cyprus	CY
Czech Republic	CZ
Denmark	DK
Estonia	EE
Finland	FI
France	FR
Germany	DE
Greece	GR
Hungary	HU
Ireland	IE
Italy	IT
Latvia	LV
Lithuania	LT
Luxembourg	LU
Malta	MT
Netherlands	NL
Norway	NO
Portugal	PT
Romania	RO
Slovakia	SK
Slovenia	SI
Spain	ES
Sweden	SE
Switzerland	CH
United Kingdom	GB

C.2 Composite Indicator (Solar)

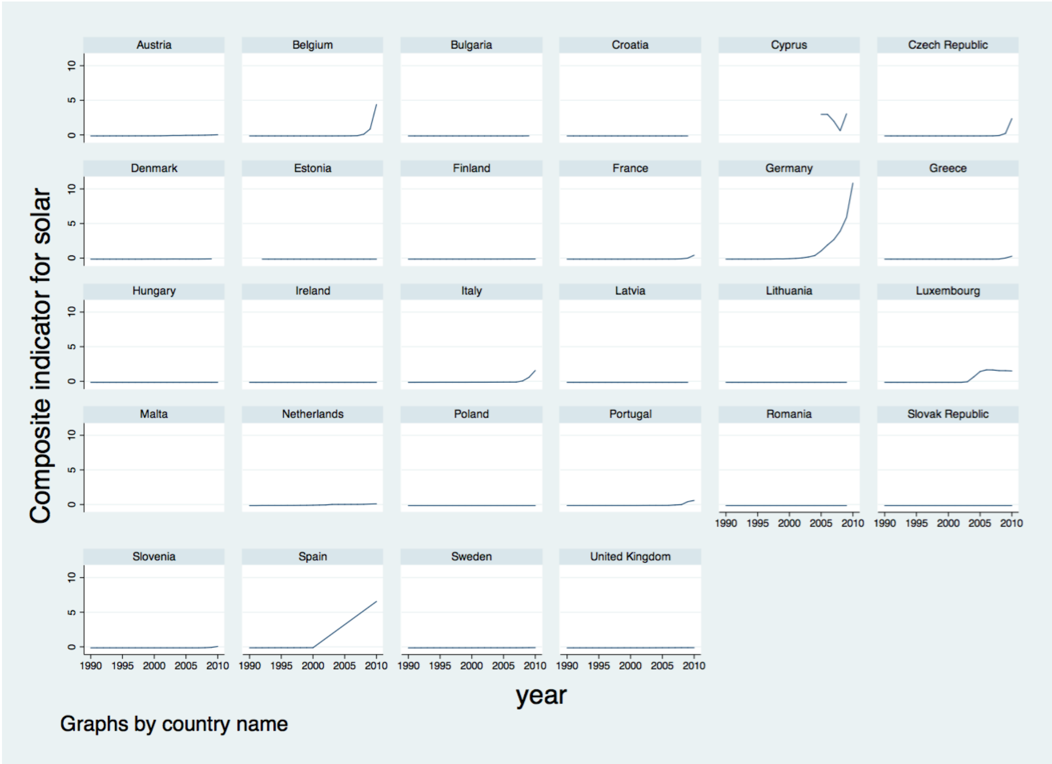


Fig. C.1 Composite Indicator for Solar PV by Country

C.3 Composite Indicator (Wind)

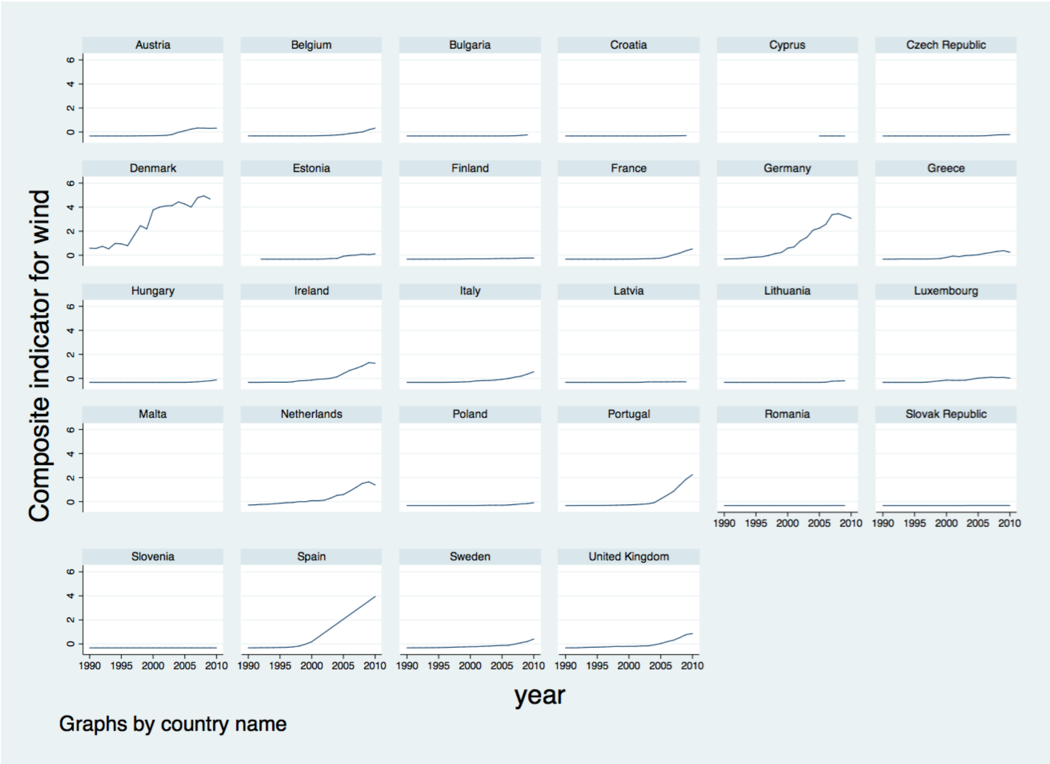


Fig. C.2 Composite Indicator for Wind by Country

C.4 Growth Rate (Solar)

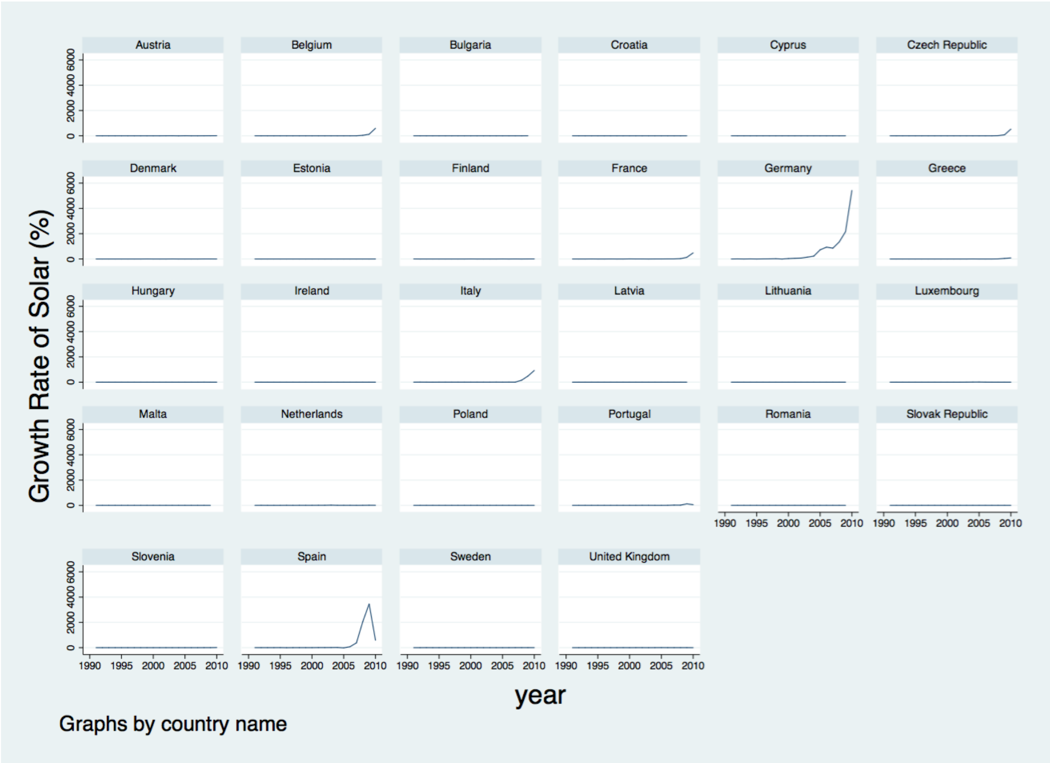


Fig. C.3 Growth Rates for Solar PV by Country

C.5 Growth Rate (Wind)

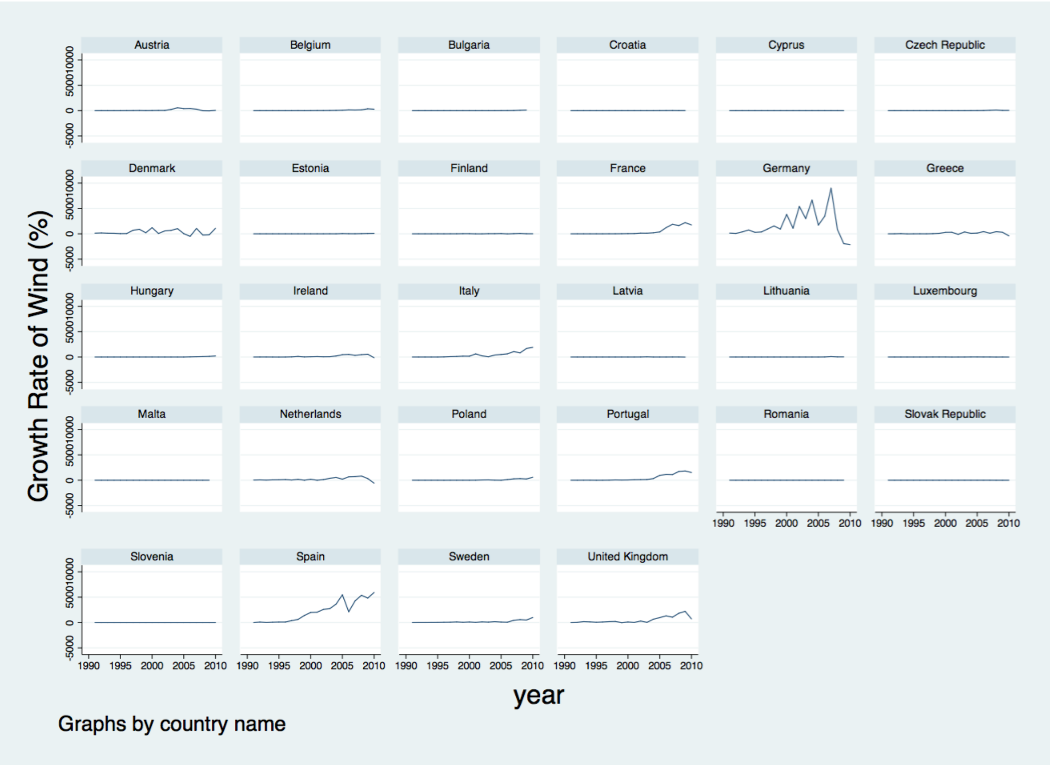


Fig. C.4 Growth Rates for Wind by Country

C.6 Truth Data Table (Solar)

Table C.2 Solar (mean)

f1	f2	f3	f4	f5	f6	number	o1
1	0	1	0	1	0	1	1
1	1	1	1	1	1	5	1
0	0	0	0	0	1	1	1
0	1	0	1	0	1	1	1
0	0	0	0	0	0	6	0
1	0	0	0	0	0	1	0
1	0	0	1	0	0	1	0
1	0	0	1	1	0	1	0
1	0	1	0	0	1	1	0
0	1	1	0	1	1	1	0
1	1	1	0	1	1	1	0

Table C.3 Solar (mean)

f1	f2	f3	f4	f5	f6	number	o2
0	1	1	0	1	1	1	1
1	0	1	0	1	0	1	1
0	0	0	0	0	1	1	1
1	1	1	1	1	1	5	0
0	0	0	0	0	0	6	0
1	0	0	0	0	0	1	0
1	0	0	1	0	0	1	0
1	0	0	1	1	0	1	0
1	0	1	0	0	1	1	0
0	1	0	1	0	1	1	0
1	1	1	0	1	1	1	0

Table C.4 Solar (mean)

f1	f2	f3	f4	f5	f6	number	o3
1	0	1	0	1	0	1	1
1	1	1	1	1	1	5	1
0	0	0	0	0	1	1	1
0	1	0	1	0	1	1	1
0	1	1	0	1	1	1	1
1	0	0	1	0	0	1	1
1	0	0	1	1	0	1	1
0	0	0	0	0	0	6	0
1	0	0	0	0	0	1	0
1	0	1	0	0	1	1	0
1	1	1	0	1	1	1	0

Table C.5 Solar (mean)

f1	f2	f3	f4	f5	f6	number	o4
0	1	1	0	1	1	1	1
1	0	1	0	1	0	1	1
1	1	1	1	1	1	5	0
0	1	0	1	0	1	1	0
0	0	0	0	0	0	6	0
1	0	0	0	0	0	1	0
1	0	0	1	0	0	1	0
1	0	0	1	1	0	1	0
1	0	1	0	0	1	1	0
0	0	0	0	0	1	1	0
1	1	1	0	1	1	1	0

Table C.6 Solar (mean)

f1	f2	f3	f4	f5	f6	number	o5
0	1	0	1	0	1	1	1
1	0	1	0	1	0	1	1
1	1	1	1	1	1	5	0
0	0	0	0	0	0	6	0
0	1	1	0	1	1	1	0
1	0	0	0	0	0	1	0
1	0	0	1	0	0	1	0
1	0	0	1	1	0	1	0
1	0	1	0	0	1	1	0
0	0	0	0	0	1	1	0
1	1	1	0	1	1	1	0

Table C.7 Solar (mean)

f1	f2	f3	f4	f5	f6	number	o6
0	1	1	0	1	1	1	1
1	0	1	0	1	0	1	1
1	1	1	1	1	1	5	0
0	1	0	1	0	1	1	0
0	0	0	0	0	0	6	0
1	0	0	0	0	0	1	0
1	0	0	1	0	0	1	0
1	0	0	1	1	0	1	0
1	0	1	0	0	1	1	0
0	0	0	0	0	1	1	0
1	1	1	0	1	1	1	0

Table C.8 Solar (median)

f1	f2	f3	f4	f5	f6	number	o1
1	1	1	1	1	0	1	1
1	1	1	1	1	1	5	1
0	1	1	1	0	1	1	1
0	1	0	1	0	1	1	1
0	1	1	0	1	0	1	0
0	1	1	0	1	1	1	0
1	0	0	1	1	0	2	0
1	0	0	0	0	0	1	0
1	0	1	1	0	1	1	0
1	1	1	0	1	1	1	0
0	0	0	0	0	0	5	0

Table C.9 Solar (median)

f1	f2	f3	f4	f5	f6	number	o2
1	1	1	1	1	0	1	1
0	1	1	0	1	1	1	1
0	1	0	1	0	1	1	1
1	1	1	1	1	1	5	0
1	0	0	1	1	0	2	0
0	1	1	0	1	0	1	0
0	1	1	1	0	1	1	0
1	0	0	0	0	0	1	0
1	0	1	1	0	1	1	0
1	1	1	0	1	1	1	0
0	0	0	0	0	0	5	0

Table C.10 Solar (median)

f1	f2	f3	f4	f5	f6	number	o3
1	1	1	1	1	0	1	1
1	1	1	1	1	1	5	1
1	0	0	1	1	0	2	1
0	1	0	1	0	1	1	1
0	1	1	0	1	0	1	1
0	1	1	0	1	1	1	1
0	1	1	1	0	1	1	1
1	0	0	0	0	0	1	0
1	0	1	1	0	1	1	0
1	1	1	0	1	1	1	0
0	0	0	0	0	0	5	0

Table C.11 Solar (median)

f1	f2	f3	f4	f5	f6	number	o4
1	1	1	1	1	0	1	1
0	1	1	0	1	1	1	1
1	1	1	1	1	1	5	0
1	0	0	1	1	0	2	0
0	1	1	0	1	0	1	0
0	1	0	1	0	1	1	0
0	1	1	1	0	1	1	0
1	0	0	0	0	0	1	0
1	0	1	1	0	1	1	0
1	1	1	0	1	1	1	0
0	0	0	0	0	0	5	0

Table C.12 Solar (median)

f1	f2	f3	f4	f5	f6	number	o5
1	1	1	1	1	0	1	1
0	1	1	1	0	1	1	1
1	1	1	1	1	1	5	0
0	1	0	1	0	1	1	0
0	1	1	0	1	0	1	0
1	0	0	1	1	0	2	0
0	1	1	0	1	1	1	0
1	0	0	0	0	0	1	0
1	0	1	1	0	1	1	0
1	1	1	0	1	1	1	0
0	0	0	0	0	0	5	0

Table C.13 Solar (median)

f1	f2	f3	f4	f5	f6	number	o6
1	1	1	1	1	0	1	1
0	1	1	0	1	1	1	1
1	1	1	1	1	1	5	0
1	0	0	1	1	0	2	0
0	1	1	0	1	0	1	0
0	1	0	1	0	1	1	0
0	1	1	1	0	1	1	0
1	0	0	0	0	0	1	0
1	0	1	1	0	1	1	0
1	1	1	0	1	1	1	0
0	0	0	0	0	0	5	0

C.7 Truth Data Table (Wind)

Table C.14 Wind (mean)

f1	f2	f3	f4	f5	number	f6	raw consist.
1	1	1	1	0	1	1	1
1	0	1	0	1	1	1	1
1	0	1	1	1	2	1	1
0	1	1	0	0	1	1	1
1	1	1	1	1	4	0	0.75
0	1	1	0	1	1	0	0
1	0	0	1	1	1	0	0
0	0	0	0	0	8	0	0

Table C.15 Wind (mean)

f1	f2	f3	f4	f5	f6	number	o2
1	0	0	1	1	0	1	1
1	1	1	1	1	1	3	1
1	0	1	0	1	1	1	1
0	1	1	0	0	1	1	1
1	0	1	1	1	1	2	0
0	0	0	0	0	0	8	0
0	1	1	0	1	0	1	0
1	1	1	1	0	1	1	0
1	1	1	1	1	0	1	0

Table C.16 Wind (mean)

f1	f2	f3	f4	f5	f6	number	o3
1	1	1	1	1	0	1	1
1	1	1	1	1	1	3	1
1	0	1	1	1	1	2	1
0	1	1	0	0	1	1	1
0	1	1	0	1	0	1	1
1	0	0	1	1	0	1	1
1	0	1	0	1	1	1	1
1	1	1	1	0	1	1	1
0	0	0	0	0	0	8	0

Table C.17 Wind (mean)

f1	f2	f3	f4	f5	f6	number	o4
1	0	0	1	1	0	1	1
1	1	1	1	1	1	3	1
1	0	1	0	1	1	1	1
0	1	1	0	0	1	1	1
1	0	1	1	1	1	2	0
0	0	0	0	0	0	8	0
0	1	1	0	1	0	1	0
1	1	1	1	0	1	1	0
1	1	1	1	1	0	1	0

Table C.18 Wind (mean)

f1	f2	f3	f4	f5	f6	number	o5
1	1	1	1	0	1	1	1
1	1	1	1	1	1	3	1
0	1	1	0	1	0	1	1
1	0	1	0	1	1	1	1
0	0	0	0	0	0	8	0
0	1	1	0	0	1	1	0
1	0	0	1	1	0	1	0
1	0	1	1	1	1	2	0
1	1	1	1	1	0	1	0

Table C.19 Wind (mean)

f1	f2	f3	f4	f5	f6	number	o6
1	0	1	0	1	1	1	1
1	1	1	1	1	1	3	1
0	1	1	0	0	1	1	1
1	0	1	1	1	1	2	0
0	0	0	0	0	0	8	0
1	0	0	1	1	0	1	0
0	1	1	0	1	0	1	0
1	1	1	1	0	1	1	0
1	1	1	1	1	0	1	0

Table C.20 Wind (median)

f1	f2	f3	f4	f5	f6	number	o1
1	1	1	1	1	1	6	1
1	1	1	0	1	1	1	1
0	1	1	0	1	1	2	1
1	1	1	1	0	1	1	1
0	1	0	1	0	0	1	1
0	0	0	0	0	0	4	0
1	0	0	1	0	0	1	0
1	1	0	1	1	0	1	0
0	0	0	1	0	0	1	0
0	0	0	0	1	0	1	0

Table C.21 Wind (median)

f1	f2	f3	f4	f5	f6	number	o2
1	1	0	1	1	0	1	1
1	1	1	0	1	1	1	1
0	1	1	0	1	1	2	0
1	1	1	1	1	1	6	0
0	0	0	0	0	0	4	0
0	1	0	1	0	0	1	0
1	0	0	1	0	0	1	0
0	0	0	1	0	0	1	0
0	0	0	0	1	0	1	0
1	1	1	1	0	1	1	0

Table C.22 Wind (median)

f1	f2	f3	f4	f5	f6	number	o2
1	1	0	1	1	0	1	1
1	1	1	0	1	1	1	1
0	1	1	0	1	1	2	0
1	1	1	1	1	1	6	0
0	0	0	0	0	0	4	0
0	1	0	1	0	0	1	0
1	0	0	1	0	0	1	0
0	0	0	1	0	0	1	0
0	0	0	0	1	0	1	0
1	1	1	1	0	1	1	0

Table C.23 Wind (median)

f1	f2	f3	f4	f5	f6	number	o3
1	1	1	1	1	1	6	1
1	1	1	1	0	1	1	1
0	1	1	0	1	1	2	1
1	1	1	0	1	1	1	1
1	1	0	1	1	0	1	1
0	1	0	1	0	0	1	1
1	0	0	1	0	0	1	1
0	0	0	1	0	0	1	0
0	0	0	0	1	0	1	0
0	0	0	0	0	0	4	0

Table C.24 Wind (median)

f1	f2	f3	f4	f5	f6	number	o4
1	1	0	1	1	0	1	1
1	1	1	0	1	1	1	1
0	1	1	0	1	1	2	0
1	1	1	1	1	1	6	0
0	0	0	0	0	0	4	0
0	1	0	1	0	0	1	0
1	0	0	1	0	0	1	0
0	0	0	1	0	0	1	0
0	0	0	0	1	0	1	0
1	1	1	1	0	1	1	0

Table C.25 Wind (median)

f1	f2	f3	f4	f5	f6	number	o5
1	1	1	1	0	1	1	1
1	1	1	0	1	1	1	1
0	0	0	1	0	0	1	1
1	1	1	1	1	1	6	0
0	1	1	0	1	1	2	0
0	1	0	1	0	0	1	0
1	0	0	1	0	0	1	0
1	1	0	1	1	0	1	0
0	0	0	0	0	0	4	0
0	0	0	0	1	0	1	0

Table C.26 Wind (median)

f1	f2	f3	f4	f5	f6	number	o6
1	1	1	0	1	1	1	1
0	1	1	0	1	1	2	0
1	1	1	1	1	1	6	0
0	0	0	0	0	0	4	0
0	0	0	1	0	0	1	0
0	1	0	1	0	0	1	0
1	0	0	1	0	0	1	0
1	1	0	1	1	0	1	0
0	0	0	0	1	0	1	0
1	1	1	1	0	1	1	0

Table C.27 Assessing the Performance of the system in each function (a)

Activity	Score	Strength	Interpretation
Knowledge Development	0-0.1	Very Weak	• No academic papers produced and no indication of knowledge activities
	0.2-0.4	Weak	• Some papers produced, some patents, but no other activities.
	0.5-0.7	Strong	• A significant number of papers generated, but no signs of commercially viable innovations.
	0.8-1	Very Strong	• Continuous Development of the number of papers produced, as well as establishment of various knowledge institutions. Some evidence of the generation of innovations.

C.8 Coding Criteria

Table C.28 Assessing the Performance of the system in each function (b)

Entrepreneurial Experimentation	0-0.1	Very Weak	• No companies entering the market and no testing of new technologies.
	0.2-0.4	Weak	• Very limited number of new entrants in the market and no testing of new technologies.
	0.5-0.7	Strong	• The creation of limited market niches, some new entrants, and limited testing of new technologies. The size of the companies involved is predominantly small.
	0.8-1	Very Strong	• Large number of entrants and exits from the industry, combined with demonstration projects and other testing mechanisms of new technologies, and the establishment of numerous market niches. There are big players testing the market.

Table C.29 Assessing the Performance of the system in each function (c)

Activity	Score	Strength	Interpretation
Legitimation	0-0.1	Very Weak	• There is either a lack of interest for the technology, or adverse reaction and strong resistance to change. Examples of this include protests against the technology or some demonstrations.
	0.2-0.4	Weak	• The establishment of some NGOs or other informal support groups for this technology. On the contrary, there is some opposition to the establishment of the system, but this is relatively limited.
	0.5-0.7	Strong	• Numerous NGOs and other organisations, some support by the media, and some weak form of political representation in favour of the technology. Also, the establishment of any favourable legislation for similar/supporting technologies can be seen as a characteristic of this level of strength.
	0.8-1	Very Strong	• Strong support groups, with strong influence on government. This can be manifested by the establishment of a green party which has significant control over the country, or a green faction within the ruling party. Also, the creation of ministries or other government institutions dedicated to the system under consideration is also evidence of strengthening legitimation.

Table C.30 Assessing the Performance of the system in each function (d)

Activity	Score	Strength	Interpretation
Guidance of Search	0-0.1	Very Weak	• Complete absence of institutions favouring the system.
	0.2-0.4	Weak	• Limited support by the government, either in the form of official documents, such as Roadmaps, etc. that are not specific to the particular technology but generally favour the broader industry of the technology in question.
	0.5-0.7	Strong	• Strong support by the government either in the form of commitments for future support policies, and strong expression of belief in the growth potential of the technology. Some funding of demonstration projects is also to be expected.
	0.8-1	Very Strong	• Very strong support in favour of the system, expressed by favourable policies, legislation, etc.

Table C.31 Assessing the Performance of the system in each function (e)

Activity	Score	Strength	Interpretation
Resource Mobilisation	0-0.1	Very Weak	• No resources available to the technology.
	0.2-0.4	Weak	• Some financial resources available and/or some human capital ones.
	0.5-0.7	Strong	• Significant financial resources available and/or significant human capital ones.
	0.8-1	Very Strong	• Dedicated financing institutions for the particular technology, as well as dedicated educational institutions and programmes for the promotion of the technology. In addition, any subsidies or grants that are given to support the technology can also be seen as strengthening the function.
Market Formation	0-0.1	Very Weak	• Absence of any relevant market institutions.
	0.2-0.4	Weak	• Some elements of a market, but with the existence of various rigidities and the absence of a regulatory framework.
	0.5-0.7	Strong	• Creation of standards, and complete access of the technology to the market.
	0.8-1	Very Strong	• A complete institutionalisation of the market for the technology in question, with clearly articulated demand and supply.

Table C.32 Assessing the Performance of the system in each function (f)

Activity	Score	Strength	Interpretation
Potential for Technology Diffusion	0-0.1	Very Weak	• No indication that the technology has been adopted.
	0.2-0.4	Weak	• Some adoption of the technology is observed, but there is no potential for further adoption.
	0.5-0.7	Strong	• Some adoption of the technology is observed, and there is significant potential for further adoption.
	0.8-1	Very Strong	• Cost competitiveness of the technology in relation to substitute technology, a significant market potential, and a significant market penetration.

C.9 Functions, Sub-Functions, and Indicators

	Knowledge development and diffusion	Influence on the direction of search	Entrepreneurial experimentation	Market formation	Resource mobilization	Development of positive externalities	Legitimation
Dewald, U. & Truffer, B., 2011				Market growth in Germany and Spain (annual installed capacity in MW, logarithmic scale)			

	Knowledge development and diffusion	Influence on the direction of search	Entrepreneurial experimentation	Market formation	Resource mobilization	Development of positive externalities	Legitimation
Marinova, D. & Balaguer, A., 2009	some description of the role of research funding to universities			description of some policy developments			very briefly discusses/desrib es the existence of coalition in favour of solar
	Number (left) and relative % share (right) of foreign solar energy patents registered in the USA by the top twelve patenting countries, 1975-2003.						

Fig. C.5 Indicators used in Case Studies (a)

	Knowledge development and diffusion	Influence on the direction of search	Entrepreneurial experimentation	Market formation	Resource mobilization	Development of positive externalities	Legitimation
Praetorius et al 2010	R&D projects, activities of industry associations, websites, conferences, linkages among key stakeholders	Visions and beliefs in growth potential	New entrants	Number, type and size of markets	Capital	Knowledge flows	Public interest/acceptance
	Energy RD&D spending in the UK	press coverage	diversification of activities of incumbents	customer base	skills	political power	governmental statements
		regulatory pressures and policy targets	number of different types of applications	actors' strategies		legitimacy/resolution of uncertainties	activities to align institutional setting
		Opinion polls		other drivers such as institutional stimuli, purchasing processes etc.			
				FITs			

Fig. C.6 Indicators used in Case Studies (b)

	Knowledge development and diffusion	Influence on the direction of search	Entrepreneurial experimentation	Market formation	Resource mobilization	Development of positive externalities	Legitimation
van Alphen, K., Noothout, P.M., Hekkert, M.P. & Turkenburg, W.C., 2010	The type of knowledge (scientific, applied, patents) that is created and by whom?	Amount and type of visions and expectations about the technology?	The number and the degree of variety in entrepreneurial experiments?	What phase is the market in and what is its (domestic and export) potential?	Availability of human capital (through education, entrepreneurship or management)?		Public opinion towards the technology and how is the technology depicted in the media?
	The competitive edge of the knowledge base?	Belief in growth potential?	The number of different types of applications?	Who are the users of the technology how is their demand articulated?	Availability of financial capital (seed and venture capital, government funds for RD&D)?		What are the main arguments of actors pro or against the deployment the technology?
	The amount and type of (inter) national collaborating between actors in the innovation system? (homo, or heterogeneous set of actors)?	Clarity about the demands of leading users?	The breadth of technologies used and the character of the complementary technologies employed?	Institutional stimuli for market creation?	Availability of complementary assets (complementary products, services, network infrastructure)?		Legitimacy to make investments in the technology?
	The kind of knowledge that is shared within these existing partnerships?	Specific targets or regulations set by the government or industry?	The number of new entrants and diversifying established firms?	Uncertainties faced by potential project developers?	Level of satisfaction with the amount of resources?		Activity of lobby groups active in the innovation system (size and strength)?
	The amount, type and 'weight' of official gatherings (e.g. conferences, platforms) organized? Configuration of actor networks						
	The (mis)match between the supply of technical knowledge by universities and demand by industry?						

Fig. C.7 Indicators used in Case Studies (c)

	Knowledge development and diffusion	Influence on the direction of search	Entrepreneurial experimentation	Market formation	Resource mobilization	Development of positive externalities	Legitimation
Wieczorek, A.J. & Hekkert, M.P., 2012	What is the knowledge base in terms of quality and quantity? Is the knowledge basic or applied? Are there many projects, research, patents and articles? Is there a leading international position, trigger programmess, many cited patents? Which actors are particularly active? Who finances the knowledge development? Does the technology receive attention in national research and technology programs? Are there enough knowledge users? Are there strong partnerships? Is the knowledge development demand-driven? Is there space for knowledge dissemination? Is there strong competition? Does the knowledge correspond with the needs of the innovation system? Have any licenses been issued?	Is there a clearly articulated and shared goal for the system? Is it generic or specific? Is it supported by specific programs, policies, who are the system's frontrunners? Is the objective inducing government activities? What are the technological expectations (negative/positive)? Does the articulated vision fit in the existing legislation?	Are there enough entrepreneurs? What is the quality of entrepreneurship? What types of businesses are involved? What are the products? To what extent do entrepreneurs experiment? What variety of technological options are available? Are any entrepreneurs leaving the system? Are there new entrepreneurs?	What does the market look like? What is its size (niche/developed)? Who are the users (current and potential)? Who takes the lead (public/private parties)? Are there institutional incentives/barriers to market formation? Must a new market be created or an existing one be opened up?	Are there sufficient financial resources for system development? Do they correspond with the system's needs? What are they mainly used for (research/application/pilot projects etc.)? Is there sufficient risk capital? Is there adequate public funding? Can companies easily access the resources?		Is investment in the technology seen as a legitimate decision? Is there much resistance to change? Where is resistance coming from? How does this resistance manifest itself? What is the lobbying power of the actors in the system? Is coalition forming occurring?

Fig. C.8 Indicators used in Case Studies (d)

	Knowledge development and diffusion	Influence on the direction of search	Entrepreneurial experimentation	Market formation	Resource mobilization	Development of positive externalities	Legitimation
Jacobsson, S. & Johnson, A., 2000	the distribution of Government fund for R&D in the energy sector in the OECD countries, 1970}1995. (Source: Elaboration on OECD/IEA, 1997.) some examples of organised user groups and some description of their role in the system	i) the diffusion process was stimulated through subsidies from 1989; (ii) from 1991, a law (the Electricity Feed Law) guaranteed wind turbine owners a "xed and high price for electricity supplied to the grid; (iii) the government ensured that land was allocated for the use of wind turbines.		difficulties of getting planning permission for wind turbines in Netherlands		describing the two fundamental features of the institutional set-up in the energy sector are the current deregulation of the electricity supply industry within the European Union and the future emergence of a joint European electricity marke	the story of the German Electricity Feed-in Law (EFL).

Fig. C.9 Indicators used in Case Studies (e)

	Knowledge development and diffusion	Influence on the direction of search	Entrepreneurial experimentation	Market formation	Resource mobilization	Development of positive externalities	Legitimation
Gallagher, K.S., Grübler, A., Kuhl, L., Nemet, G. & Wilson, C., 2012,			The only available survey of private-sector RD&D specific to the energy sector is a study conducted by the World Energy Council (88) in seven OECD countries, covering the pe-riod 1985-2000	Market formation investments include public and private investments in the early stages of technological diffusion and they include niche market investments. In the energy domain, these investments include government subsi-dies for certain technologies (e.g., feed-in tariffs or production tax credits) and public procure-ment. They also include private investments to take advantage of markets created by government policies, such as renewable portfolio stan-dards or price instruments like carbon taxes. No systematic numerical estimate of public-sector market formation investments exists, but the numbers are likely to be small compared to private-sector market investments. Private-sector market formation invest-ments can be measured by activity in three main asset classes: venture capital/private eq-uity (VC/PE), both forms of risk-taking private investment, new listings on public markets, and asset finance. Although often used for large and more mature technologies, asset finance invest-ments in new energy technologies are counted here because they are highly dependent on gov-ernmental subsidies and incentives, such as tax equity credits or feed-in tariffs. The technology sector that attracted the most investment for the 2004-2008 period (reviewed in Reference 2) was wind (89, 102). Conversely, market forma-tion investments into energy efficiency are small for unknown reasons. Data on energy supply investments are ex-tremely limited, so the literature typically relies on model estimates or limited surveys	Energy- and technology-specific RD&D data are available for public-sector expenditures in member countries of the International Energy Agency (IEA) also R&D on energy tends to move with oil prices The only available survey of private-sector RD&D specific to the energy sector is a study conducted by the World Energy Council (88) in seven OECD countries, covering the pe-riod 1985-2000		

Fig. C.10 Indicators used in Case Studies (f)

This paper	Johnson (1998), Johnson (2001), and Bergek (2002)	Rickne (2000)	Bergek and Jacobsson (various)	Carlsson et al. (2005)	Edquist (2004)	Galli and Teubal (1997)	Hekkert et al. (2007)
Knowledge development and diffusion	Create knowledge, facilitate information and knowledge exchange	Create human capital	Create new knowledge	Creating a knowledge base	Provision of R&D, competence building	R&D diffusion of information, knowledge and technology	Creation of technological knowledge
Entrepreneurial experimentation	Create knowledge		Create knowledge	Promoting entrepreneurial experiments	Creating and changing organizations needed (e.g. enhancing entrepreneurship)		
Influence on the direction of search	Identify problems. Guide the direction of search. Provide incentives for entry. Recognise the potential for growth	Direct technology, market and partner search. Create and diffuse technological opportunities	Guide the direction of the search process	Creating incentives	Articulation of quality requirements (demand side). Creating/changing institutions that provide incentives or obstacles to innovation		Articulation of demand. Prioritizing of public and private sources (the process of selection)
Market formation	Stimulate market formation	Create market/diffuse market knowledge. Facilitate regulation (may enlarge market and enhance market access)	Facilitate the formation of markets	Creating markets or appropriate market conditions	Formation of new product markets. Articulation of quality requirements (demand side)		Regulation and formation of markets. Articulation of demand
Development of positive external economies	Facilitate information and knowledge exchange	Enhance networking	Facilitate the creation of positive external economies	Promoting positive externalities, or 'free utilities'	Networking	Diffusion of information, knowledge and technology. Professional coordination	Exchange of information through networks
Legitimation	Counteract resistance to change	Legitimize technology and firms			Creating/changing institutions that provide incentives or obstacles to innovation	Design and implementation of institutions. Diffusion of scientific culture	Development of advocacy coalitions for processes of change
Resource mobilization	Supply resources	Facilitate financing. Create a labour market. Incubate to provide facilities, etc. Create and diffuse products (materials, parts, compl. products)	Supply resources	Creating resources (financial and human capital)	Financing of innovation processes, etc. Provision of consultancy services. Incubation activities	Supply of scientific and technical services	Supply of resources for innovation

Fig. C.11 Indicators used in Case Studies (g), (Berget et al. 2008)

Authors	Knowedge development
Suurs et al 2009	Studies
Harborne 2012	Govt funded RnD
Alphen 2009	The competitive edge of the knowledge base? - based on expert opinion
Alphen 2009	The (mis)match between the supply of technical knowledge by universities and demand by industry?
Harborne 2012	workshops and conferences
Alphen 2009	The type of knowledge (scientific, applied, patents) that is created and by whom?
Vasseur 2013	market size (Learning by doing and learning by using)
Alphen 2009	patents
Suurs and Hekkert 2009	Assessment research (studies) with no direct commercial orientation (learning by exploring)
Suurs and Hekkert 2009	Practical research with no direct commercial orientation. (learning by doing)
Vasseur 2013	Research and technological projects
Vasseur 2013	Demonstration and pilot projects
Suurs et al 2009	laboratory trials
Suurs et al 2009	pilots
Negro et al. 2007	number of RnD projects per year
Harborne 2012	technical & economic government-funded demonstrations and field trials (DTs)
Harborne 2012	collaborative development and testing
Alphen 2009	The number and degree of variety in R&D projects
Suurs and Hekkert 2009	Actors' critical notes on institutions and/or past developments (opinion)

Fig. C.12 Indicators used in Event History Papers (Knowledge Development)

Authors	Entrepreneurial Experimentation
Suurs et al 2009	Projects with a commercial aim
Suurs et al 2010	portfolio expansions
Alphen 2009	The number and the degree of variety in entrepreneurial experiments?
Alphen 2009	The number of new entrants and diversifying established firms?
Suurs and Hekkert 2009	a (vested) actor explores activities without any previous experience (Portfolio expansion)
Negro et al. 2007	the number of new entrants
Negro et al. 2007	the number of diversification activities of incumbents
Vasseur 2013	Organisations or companies entering/leaving the market
Vasseur 2013	Export activities
Vasseur 2013	Size of companies
Suurs et al 2009	demonstrations
Harborne 2012	Govt funded technical & commercial DTs investment in start-ups diversification by incumbents
Alphen 2009	The number of different types of applications?
Alphen 2009	The breadth of technologies used and the character of the complementary technologies employed?
Suurs and Hekkert 2009	technology is explored within a societal context and/or with a commercial goal (Project entry/Start)
Suurs and Hekkert 2009	Exploration activities are cancelled (Project exit/Failure)
Negro et al. 2007	the number of experiments with the new technology

Fig. C.13 Indicators used in Event History Papers (Entrepreneurial Experimentation)

Authors	Market Formation
Negro et al 2007	the number of niche market initiatives
Suurs and Hekkert 2009	Niche markets
Harborne 2012	Govt protected nursing markets
Suurs and Hekkert 2009	Protected spaces where practical experiments can be conducted in a market environment
Alphen 2009	What phase is the market in and
Vasseur 2013	Market size
Alphen 2009	what is its (domestic and export) potential?
Vasseur 2013	Import share
Suurs et al 2009	Market regulations
Suurs et al 2009	tax exemptions
Suurs and Hekkert 2009	Tax exemption starts
Suurs and Hekkert 2009	Tax exemption stops
Negro et al 2007	specific tax regimes for new technologies
Suurs et al 2010	Market regulations
Suurs et al 2010	tax exemptions
Harborne 2012	Subsidies & tax benefits
Vasseur 2013	Regulations/tax regimes
Vasseur 2013	Financial market incentives (regulation/stimulation programmes)
Harborne 2012	Proactive standards setting
Negro et al 2007	environmental standards
Alphen 2009	Who are the users of the technology
Alphen 2009	how is their demand articulated?
Alphen 2009	Uncertainties faced by potential project developers?

Fig. C.14 Indicators used in Event History Papers (Market Formation)

Authors	Resource Mobilisation
Alphen 2009	financial capital (seed and venture capital, government funds for RD\&D)?
Vasseur 2013	Financial resources (e.g. subsidies for and investments in the technology)
Suurs and Hekkert 2009	Subsidies
Negro et al 2007	Subsidies
Suurs et al 2009	Subsidies
Harborne 2012	Subsidies
Suurs et al 2010	Subsidies
Harborne 2012	venture capital collaboration
Vasseur 2013	Foreign direct investment
Alphen 2009	human capital (through education, entrepreneurship or management)?
Vasseur 2013	Human resources
Vasseur 2013	Physical resources
Alphen 2009	complementary assets (complementary products, services, network infrastructure)?
Suurs et al 2009	investments
Suurs et al 2010	investments
Negro et al 2007	investments

Fig. C.15 Indicators used in Event History Papers (Resource Mobilisation)

Authors	Influence on the direction of research
Negro et al 2008	Positive expectations on tech
Alphen 2009	Amount and type of visions and expectations about the technology?
Alphen 2009	Belief in growth potential?
Suurs et al 2009	Expectations
Suurs and Hekkert 2009	Doubt, Uncertainty – Expression of the technology's uncertain circumstances.
Suurs and Hekkert 2009	Expectations positive – Expression of the technology's future expectations.
Suurs and Hekkert 2009	Expectations negative – Negative expressions of the technology's future expectations -
Suurs and Hekkert 2009	Promises or targets positive – Promises by actors with the power to change institutions, complementing the technology.
Suurs and Hekkert 2009	Promises or targets negative – Promises by actors with the power to change institutions, hampering the technology.
Suurs et al 2010	Expectations
Vasseur 2013	Expectations and opinion of experts (positive/negative)
Negro et al 2008	regulations by government
Negro et al 2007	announcement of government goal to reach a particular goal
Alphen 2009	Clarity about the demands of leading users?
Alphen 2009	Specific targets or regulations set by the government or industry?
Suurs et al 2009	policy targets
Suurs et al 2009	standards
Suurs and Hekkert 2009	Standard setting
Suurs et al 2010	policy targets
Suurs et al 2010	standards
Harborne 2012	Govt strategy & policy
Vasseur 2013	Targets set by the government of industry
Negro et al 2007	the positive and negative publications wrt the developments of the particular technology
Suurs et al 2009	research outcomes
Suurs and Hekkert 2009	results of research and trials, often mentioned when reports are published.
Suurs et al 2010	research outcomes
Harborne 2012	Govt publications on R&D outcomes proactive standards setting
Suurs and Hekkert 2009	Classification
Suurs and Hekkert 2009	Technological guide, Manual – Aid to support entrepreneurs
Harborne 2012	Govt funding for R&D and DTs

Fig. C.16 Indicators used in Event History Papers (Influence on the direction of research)

Authors	Legitimation
Suurs and Hekkert 2009	Lobby or advice contra – Pressure on actors in power to change institutions, hampering the technology.
Alphen 2009	What are the main arguments of actors pro or against the deployment the technology?
Alphen 2009	Activity of lobby groups active in the innovation system (size and strength)?
Suurs and Hekkert 2009	Dissent – Conflicting interests around the technology.
Vasseur 2013	Extent to which the technology is promoted by organisations, government (awards, brochures, com- petitions)
Suurs et al 2009	lobbies
Suurs et al 2010	lobbies
Vasseur 2013	Lobby activities for/against the technology
Suurs and Hekkert 2009	Lobby or advice pro – Pressure on actors in power to change institutions, complementing the technology.
Harborne 2012	Positive advocacy coalitions;
Negro et al 2008	Support by government/industry that legitimizes the use of the technology
Harborne 2012	subsidies
Harborne 2012	Positive market regulations,
Harborne 2012	tax benefits
Alphen 2009	Public opinion towards the technology and how is the technology depicted in the media?

Fig. C.17 Indicators used in Event History Papers (Legitimation)

Activity	Sub-Activity	Indicator	Source	Coding	Notes
Development of Knowledge	Downstream	Patents	PATSTAT	Median	
			WIPO - PATENTSCOPE	Median	
	Upstream	Number Of Academic Papers on the technology	Scopus	Median	Keywords used: solar, wind, solar PV
Resource Mobilisation	Quality and Availability of Financal Capital	Total RD&D in Million USD (2011 prices-Current Exchange rates/PPP)	OECD Main Science and Technology Indicators	Median	
		Govt R&D in Million NC (nominal)	OECD Main Science and Technology Indicators	Median	
		Govt demonstration in Million NC (nominal)	OECD Main Science and Technology Indicators	Median	
		RD&D per thousand units of GDP	OECD Main Science and Technology Indicators	Median	
		Solar/Wind RnD as a % of total energy RnD	OECD Main Science and Technology Indicators	Median	
		Business Enterprise Research and Development (BERD)	OECD Main Science and Technology Indicators	Median	
		Business Enterprise Expenditure on R&D	OECD Main Science and Technology Indicators	Median	
		Gross domestic expenditure on research and development (GERD)	OECD Main Science and Technology Indicators	Median	
		Government Expenditure on R&D (GOVERD)	OECD Main Science and Technology Indicators	Median	
	Quality and Availability of human capital	Years of Schooling	Barro-Lee database	Median	
		Total Business Enterprise R&D personnel (FTE)	OECD Main Science and Technology Indicators	Median	
		Total R&D personnel (FTE)	OECD Main Science and Technology Indicators	Median	
		Total researchers (FTE)	OECD Main Science and Technology Indicators	Median	
Legitimation	Social	TIS References In The Media	Google Trends	Median	Keywords used: solar, wind, solar PV
	Lobbying	Number of the NGOs that received funding from the EC	European Commission	Median	
		Member in the European Environmental Bureau	European Environmental Bureau	Binary	Whether the country is a member in the EEB
	Political	Green Parties	online data	Binary	Whether there is a Green Party in the country
	Geopolitical	Energy Dependence, as it is measured by Energy Imports (% of energy use)	World Bank Development Indicators	Median	
Direction of Research	Market Growth Expectation	Electricity consumption (GWh)	International Energy Agency - Energy Balances of OECD countries	Median	
		Electricity Supplied (GWh)	International Energy Agency - Energy Balances of OECD countries	Median	
		Electricity output (GWh) from the specific RET	International Energy Agency - Renewables Information	Median	
	Technological Expectations	Prices of electricity (MWh) (Household)	International Energy Agency - Energy Balances of OECD countries	Median	
		Prices of Competing Sources (e.g. Natural gas, Oil, Coal, etc.)	International Energy Agency - Energy Balances of OECD countries	Median	
		Number of papers on the technology as a % of total number of papers on energy	Scopus Database	Median	
	Government Expectations	Belief In Growth Potential	National Ministries	Binary	Whether the country has established a roadmap for solar/wind before the EU 20-20-20
Market formation	Demand	Number Of Current Adopters	International Energy Agency - Renewables Information	Median	
		Electricity output (GWh) from the specific RET	International Energy Agency - Renewables Information	Median	
		Electricity Capacity from the specific RET	International Energy Agency - Renewables Information	Median	
	Supply	ISO for the specific RET	ISO (International Organization for Standardization)	Binary	Whether the country is participating in the ISO classification of the particular technology
	Institutionalisation Of The Market	Subsidies	National Ministries	Binary	Whether the country has introduced support mechanisms for the particular technology
		Ease of Grid access	IEA Country Reports	Binary	Whether there are any mentions in the IEA country reports of grid access issues
		Availability of regulatory barriers	IEA Country Reports	Binary	Whether there are any mentions in the IEA country reports of the existence of regulator barriers
Enterpreneurial Experimentation	Entrants And Incumbents	Number of Companies	Amadeus Database	Median	
	Available Technologies	Number of Patents in a county, as a proportion of the total patents for the technology in the world	PATSTAT, WIPO - PATENTSCOPE	Median	
Potential for Technology diffusion	Cost Relative To Substitute Technologies	Subsidies	National Ministries	Binary	Whether the country has introduced support mechanisms for the particular technology?
		Taxes	National Ministries	Binary	Whether the country has increased taxes for competing technologies?
	Market Potential	Total Available Resources (Full load wind hours, Solar Radiation)	EU Commission	Median	
		Number Of Potential Adopters - Total gross production of Electricity (GWh)	International Energy Agency - Renewables Information	Median	

Building the QCA Database

Table C.33 summarises the indicators, the sources and how they were coded in this dataset. The first two columns represent the theoretical underpinnings of the indicators. Column three illustrates the actual indicator used to capture the effect of the activity, Column four gives the data source, and Columns 5 and 6 give an explanation of the treatment of the data.

To be more precise, column E presents the type of coding. This can be explained in the following way:
Median Approach:
• The fist step was to calculate the median value for the particular indicator, on the particular point in time. Then, each country was assigned a value of 0 or 1, based on whether the value of the indicator is above or below the median, with 0 implying below and 1 above.
Binary
• In this case, the indicator could take either value 0 or 1, depending on the answer to the question that is illustrated in Column six. If the answer was positive, the value of 1 was given, while if the answer was negative, the value of 0 was given.

After converting all indicators for all functions into 0 and 1, the next step was to create a composite indicator, which was simply the average of all the indicators for each function at a point in time, yielding a value for the indicator for the country within the interval [0, 1].
The next step was to round the numbers to either 0 or 1; if the value was below 0.499, then the value of the function would be equal to 0. If the value was 0.5 or higher, then the value of the function would equal to 1.

A note on Resource Mobilisation

For resource mobilisation, it is evident that there are many indicators used, many of which are highly similar. A characteristic example is overall government-funded R&D AND government-performed R&D. The difference between those two indicators is subtle, and consequently their difference is not significant enough to influence our results for the performance of the resource mobilisation function. Therefore, our choice to include both bears no adverse impact on our results

Fig. C.18 Functions, Sub-Functions, and Indicators

C.10 Correlation Matrices for the Data used for QCA in Solar PV

Tables C.33 and C.34 illustrate the correlation coefficients between the functions and the outcome variables in the case of solar. For all of the tables, we have tabulated the coefficients between all of the different outcomes ($o1 \ldots o6$), and all of the different configurations for the functions.

Table C.33 Correlation Matrix Between Functions and Outcomes (Solar-Mean)

	o1	o2	o3	o4	o5	o6
f1	0.4177	0.4893*	0.6445*	0.4893*	0.368	0.3906
f2	0.5189*	0.42	0.5189*	0.42	0.5476*	0.5347*
f3	0.7161*	0.4177	0.7161*	0.4177	0.5060*	0.5669*
f4	0.35	0.338	0.5794*	0.338	0.2326	0.2166
f5	0.4177	0.4893*	0.6445*	0.4893*	0.368	0.3906
f6	0.5794*	0.5673*	0.5794*	0.5673*	0.4536	0.7008*

* significant at the 95% level

Table C.34 Correlation Matrix Between Functions and Outcomes (Solar-Median)

	o1	o2	o3	o4	o5	o6
f1	0.2626	0.4177	0.7161*	0.4177	0.2875	0.3276
f2	0.6548*	0.5189*	0.8895*	0.5189*	0.3571	0.4564*
f3	0.7161*	0.4177	0.7161*	0.4177	0.5060*	0.5669*
f4	0.1086	0.1207	0.5673*	0.1207	0.2094	0.0255
f5	0.338	0.5794*	0.5673*	0.5794*	0.2094	0.5096*
f6	0.7161*	0.4177	0.7161*	0.4177	0.5060*	0.5669*

* significant at the 95% level

C.11 Correlation Matrices for the Data used for QCA in Wind

Tables C.35 and C.36 represent the findings for wind. For all of the tables, we have tabulated the coefficients between all of the different outcomes ($o1 \ldots o6$), and all of the different configurations for the functions.

Table C.35 Correlation Matrix Between Functions and Outcomes (Wind-Mean)

	o1	o2	o3	o4	o5	o6
f1	0.4177	0.4893*	0.6445*	0.4893*	0.368	0.3906
f2	0.5189*	0.42	0.5189*	0.42	0.5476*	0.5347*
f3	0.7161*	0.4177	0.7161*	0.4177	0.5060*	0.5669*
f4	0.35	0.338	0.5794*	0.338	0.2326	0.2166
f5	0.4177	0.4893*	0.6445*	0.4893*	0.368	0.3906
f6	0.5794*	0.5673*	0.5794*	0.5673*	0.4536	0.7008*

* significant at the 95% level

Table C.36 Correlation Matrix Between Functions and Outcomes (Wind-Median)

	o1	o2	o3	o4	o5	o6
f1	0.2626	0.4177	0.7161*	0.4177	0.2875	0.3276
f2	0.6548*	0.5189*	0.8895*	0.5189*	0.3571	0.4564*
f3	0.7161*	0.4177	0.7161*	0.4177	0.5060*	0.5669*
f4	0.1086	0.1207	0.5673*	0.1207	0.2094	0.0255
f5	0.338	0.5794*	0.5673*	0.5794*	0.2094	0.5096*
f6	0.7161*	0.4177	0.7161*	0.4177	0.5060*	0.5669*

* significant at the 95% level

C.12 Results for Solar PV from QCA

Please note that in the following tables the **Conversion Factor** denotes whether the mean or the median was used as a threshold to convert the data from continuous to categorical.

In terms of the Functions:
f1: Knowledge Development
f2: Legitimation
f3: Guidance of Search
f4: Enterpreneurial Experimentation
f5: Resource Mobilisation
f6: Market Formation

In terms of the outcome variables:
o1: Outcomes were defined based on empirical observations.
o2: Outcomes were defined based on the composite indicator with mean as the threshold level.
o3: Outcomes were defined based on the composite indicator with median as the threshold level.
o4: Outcomes were defined based on the composite indicator with a visual inspection helping to find the threshold level.
o5: Outcomes were defined based on the growth rate.
o6: Outcomes were defined based on combination of all the above indicators.

Model	1		
TIS	Solar		
Outcome Variable	o1		
Conversion Factor	Mean		
Complex Solution			
	raw coverage	unique coverage	consistency
~f1*~f2*~f3*~f4*~f5*f6	0.125	0.125	1
f1*~f2*f3*~f4*f5*~f6	0.125	0.125	1
~f1*f2*~f3*f4*~f5*f6	0.125	0.125	1
f1*f2*f3*f4*f5*f6	0.625	0.625	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f3*~f6	0.125	0.125	1
~f3*f6	0.25	0.125	1
f2*f4	0.75	0.625	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*~f3	0.25	0.125	1
f6*f4*f2	0.75	0.625	1
~f6*f5*f3*f1	0.125	0.125	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		

Model	5		
TIS	Solar		
Outcome Variable	o2		
Conversion Factor	Mean		
Complex Solution			
	raw coverage	unique coverage	consistency
~f1*~f2*~f3*~f4*~f5*f6	0.166667	0.166667	1
f1*~f2*f3*~f4*f5*~f6	0.166667	0.166667	1
~f1*f2*f3*~f4*f5*f6	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.5		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
~f1*~f4*f6	0.333333	0.333333	1
f3*~f6	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.5		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*~f4*~f1	0.333333	0.333333	1
~f6*f5*f3*f1	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.5		
solution consistency:	1		

Model	2		
TIS	Solar		
Outcome Variable	o3		
Conversion Factor	Mean		
Complex Solution			
	raw coverage	unique coverage	consistency
f1*∼f2*∼f3*f4*∼f6	0.166667	0.166667	1
∼f1*∼f2*∼f3*∼f4*∼f5*f6	0.083333	0.083333	1
f1*∼f2*f3*∼f4*f5*∼f6	0.083333	0.083333	1
∼f1*f2*∼f3*f4*∼f5*f6	0.083333	0.083333	1
∼f1*f2*f3*∼f4*f5*f6	0.083333	0.083333	1
f1*f2*f3*f4*f5*f6	0.416667	0.416667	1
Diagnostics			
solution coverage:	0.916667		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f4	0.666667	0.583333	1
∼f1*f6	0.25	0.166667	1
f3*∼f6	0.083333	0.083333	1
Diagnostics			
solution coverage:	0.916667		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*∼f1	0.25	0.25	1
f4*f1	0.583333	0.583333	1
∼f6*f5*f3*f1	0.083333	0.083333	1
Diagnostics			
solution coverage:	0.916667		
solution consistency:	1		

Model	7		
TIS	Solar		
Outcome Variable	o4		
Conversion Factor	Mean		
Complex Solution			
	raw coverage	unique coverage	consistency
f1*∼f2*f3*∼f4*f5*∼f6	0.2	0.2	1
∼f1*f2*f3*∼f4*f5*f6	0.2	0.2	1
Diagnostics			
solution coverage:	0.4		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f3*∼f6	0.2	0.2	1
∼f1*f3	0.2	0.2	1
Diagnostics			
solution coverage:	0.4		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
∼f6*f5*f3*f1	0.2	0.2	1
f6*f5*f3*f2*∼f1	0.2	0.2	1
Diagnostics			
solution coverage:	0.4		
solution consistency:	1		

Model	9		
TIS	Solar		
Outcome Variable	o5		
Conversion Factor	Mean		
Complex Solution			
	raw coverage	unique coverage	consistency
f1*∼f2*f3*∼f4*f5*∼f6	0.166667	0.166667	1
∼f1*f2*∼f3*f4*∼f5*f6	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.333333		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f2*∼f5	0.166667	0.166667	1
f3*∼f6	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.333333		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*∼f5*f4*f2	0.166667	0.166667	1
∼f6*f5*f3*f1	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.333333		
solution consistency:	1		

Model	10		
TIS	Solar		
Outcome Variable	o6		
Conversion Factor	Mean		
Complex Solution			
	raw coverage	unique coverage	consistency
f1*∼f2*f3*∼f4*f5*∼f6	0.2	0.2	1
∼f1*f2*f3*∼f4*f5*f6	0.2	0.2	1
Diagnostics			
solution coverage:	0.4		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f3*∼f6	0.2	0.2	1
∼f1*f3	0.2	0.2	1
Diagnostics			
solution coverage:	0.4		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
∼f6*f5*f3*f1	0.2	0.2	1
f6*f5*f3*f2*∼f1	0.2	0.2	1
Diagnostics			
solution coverage:	0.4		
solution consistency:	1		

Model	3		
TIS	Solar		
Outcome Variable	o1		
Conversion Factor	Median		
Complex Solution			
	raw coverage	unique coverage	consistency
∼f1*f2*f4*∼f5*f6	0.25	0.25	1
f1*f2*f3*f4*f5	0.75	0.75	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f2*f4	1	1	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*f4*f2	0.875	0.25	1
f5*f4*f3*f2*f1	0.75	0.125	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		

Model	6		
TIS	Solar		
Outcome Variable	o2		
Conversion Factor	Median		
Complex Solution			
	raw coverage	unique coverage	consistency
∼f1*f2*∼f3*f4*∼f5*f6	0.166667	0.166667	1
∼f1*f2*f3*∼f4*f5*f6	0.166667	0.166667	1
f1*f2*f3*f4*f5*∼f6	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.5		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f2*∼f3	0.166667	0.166667	1
∼f1*∼f4*f6	0.166667	0.166667	1
f1*f2*∼f6	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.5		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*f4*∼f3*f2	0.166667	0.166667	1
f6*f5*∼f4*f3*f2*∼f1	0.166667	0.166667	1
∼f6*f5*f4*f3*f2*f1	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.5		
solution consistency:	1		

Model	4		
TIS	Solar		
Outcome Variable	o3		
Conversion Factor	Median		
Complex Solution			
	raw coverage	unique coverage	consistency
~f1*f2*f3*~f4*f5	0.166667	0.166667	1
~f1*f2*f4*~f5*f6	0.166667	0.166667	1
f1*f2*f3*f4*f5	0.5	0.5	1
f1*~f2*~f3*f4*f5*~f6	0.166667	0.166667	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
~f1*f2	0.333333	0.333333	1
f4*f5	0.666667	0.666667	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f5*f4*f1	0.666667	0.666667	1
f6*f4*f2*~f1	0.166667	0.166667	1
f5*f3*f2*~f1	0.166667	0.166667	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		

Model	8		
TIS	Solar		
Outcome Variable	o4		
Conversion Factor	Median		
Complex Solution			
	raw coverage	unique coverage	consistency
∼f1*f2*f3*∼f4*f5*f6	0.2	0.2	1
f1*f2*f3*f4*f5*∼f6	0.2	0.2	1
Diagnostics			
solution coverage:	0.4		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
∼f1*∼f4*f6	0.2	0.2	1
f1*f2*∼f6	0.2	0.2	1
Diagnostics			
solution coverage:	0.4		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*f5*∼f4*f3*f2*∼f1	0.2	0.2	1
∼f6*f5*f4*f3*f2*f1	0.2	0.2	1
Diagnostics			
solution coverage:	0.4		
solution consistency:	1		

Model	12		
TIS	Solar		
Outcome Variable	o5		
Conversion Factor	Median		
Complex Solution			
	raw coverage	unique coverage	consistency
∼f1*f2*f3*f4*∼f5*f6	0.166667	0.166667	1
f1*f2*f3*f4*f5*∼f6	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.333333		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
∼f1*f3*∼f5	0.166667	0.166667	1
f1*f2*∼f6	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.333333		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*∼f5*f4*f3*f2*∼f1	0.166667	0.166667	1
∼f6*f5*f4*f3*f2*f1	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.333333		
solution consistency:	1		

Model	11		
TIS	Solar		
Outcome Variable	o6		
Conversion Factor	Median		
Complex Solution			
	raw coverage	unique coverage	consistency
~f1*f2*f3*~f4*f5*f6	0.2	0.2	1
f1*f2*f3*f4*f5*~f6	0.2	0.2	1
Diagnostics			
solution coverage:	0.4		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
~f1*~f4*f6	0.2	0.2	1
f1*f2*~f6	0.2	0.2	1
Diagnostics			
solution coverage:	0.4		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*f5*~f4*f3*f2*~f1	0.2	0.2	1
~f6*f5*f4*f3*f2*f1	0.2	0.2	1
Diagnostics			
solution coverage:	0.4		
solution consistency:	1		

C.13 Results for Wind from QCA

Please note that in the following tables the **Conversion Factor** denotes whether the mean or the median was used as a threshold to convert the data from continuous to categorical.

In terms of the Functions:
f1 Knowledge Development
f2: Legitimation
f3: Guidance of Search
f4: Enterpreneurial Experimentation
f5: Resource Mobilisation
f6: Market Formation

In terms of the outcome variables:
o1: Outcomes were defined based on empirical observations.
o2: Outcomes were defined based on the composite indicator with mean as the threshold level.
o3: Outcomes were defined based on the composite indicator with median as the threshold level.
o4: Outcomes were defined based on the composite indicator with a visual inspection helping to find the threshold level.
o5: Outcomes were defined based on the growth rate.
o6: Outcomes were defined based on combination of all the above indicators.

Model	3		
TIS	Wind		
Outcome Variable	o1		
Conversion Factor	Mean		
Complex Solution			
	raw coverage	unique coverage	consistency
f1*∼f2*f3*f5*f6	0.230769	0.230769	1
f1*f2*f3*f4*f5	0.307692	0.076923	1
f1*f2*f3*f4*f6	0.307692	0.076923	1
∼f1*f2*f3*∼f4*f5*∼f6	0.076923	0.076923	1
∼f1*f2*f3*∼f4*∼f5*f6	0.076923	0.076923	1
Diagnostics			
solution coverage:	0.769231		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f3	0.769231	0.769231	1
Diagnostics			
solution coverage:	0.769231		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*f3*f2	0.384615	0.153846	1
f5*f3*f2	0.384615	0.153846	1
f6*f5*f3*f1	0.461538	0.230769	1
Diagnostics			
solution coverage:	0.769231		
solution consistency:	1		

Model	6		
TIS	Wind		
Outcome Variable	o2		
Conversion Factor	Mean		
Complex Solution			
	raw coverage	unique coverage	consistency
f1*∼f2*∼f3*f4*f5*∼f6	0.166667	0.166667	1
∼f1*f2*f3*∼f4*∼f5*f6	0.166667	0.166667	1
f1*∼f2*f3*∼f4*f5*f6	0.166667	0.166667	1
f1*f2*f3*f4*f5*f6	0.5	0.5	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
∼f4*f6	0.333333	0.333333	1
f2*f5*f6	0.5	0.5	1
f1*∼f3	0.166667	0.166667	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*∼f4*f3*f2	0.166667	0.166667	1
f5*f4*∼f3*f1	0.166667	0.166667	1
f6*f5*∼f4*f3*f1	0.166667	0.166667	1
f6*f5*f4*f2*f1	0.5	0.5	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		

Model	2		
TIS	Wind		
Outcome Variable	o3		
Conversion Factor	Mean		
Complex Solution			
	raw coverage	unique coverage	consistency
f1*∼f2*f3*f5*f6	0.230769	0.230769	1
f1*f2*f3*f4*f5	0.307692	0.076923	1
f1*f2*f3*f4*f6	0.307692	0.076923	1
∼f1*f2*f3*∼f4*f5*∼f6	0.076923	0.076923	1
f1*∼f2*∼f3*f4*f5*∼f6	0.076923	0.076923	1
∼f1*f2*f3*∼f4*∼f5*f6	0.076923	0.076923	1
Diagnostics			
solution coverage:	0.846154		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f3	0.769231	0.153846	1
f5	0.692308	0.076923	1
Diagnostics			
solution coverage:	0.846154		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*f3*f2	0.384615	0.153846	1
f5*f3*f2	0.384615	0.076923	1
f5*f4*f1	0.538462	0.076923	1
f6*f5*f3*f1	0.461538	0.076923	1
Diagnostics			
solution coverage:	0.846154		
solution consistency:	1		

Conversion Factor	Mean		
Complex Solution			
	raw coverage	unique coverage	consistency
f1*∼f2*∼f3*f4*f5*∼f6	0.166667	0.166667	1
∼f1*f2*f3*∼f4*∼f5*f6	0.166667	0.166667	1
f1*∼f2*f3*∼f4*f5*f6	0.166667	0.166667	1
f1*f2*f3*f4*f5*f6	0.5	0.5	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
∼f4*f6	0.333333	0.333333	1
f2*f5*f6	0.5	0.5	1
f1*∼f3	0.166667	0.166667	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*∼f4*f3*f2	0.166667	0.166667	1
f5*f4*∼f3*f1	0.166667	0.166667	1
f6*f5*∼f4*f3*f1	0.166667	0.166667	1
f6*f5*f4*f2*f1	0.5	0.5	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		

Conversion Factor	Mean		
Complex Solution			
	raw coverage	unique coverage	consistency
f1*f2*f3*f4*f6	0.571429	0.571429	1
∼f1*f2*f3*∼f4*f5*∼f6	0.142857	0.142857	1
f1*∼f2*f3*∼f4*f5*f6	0.142857	0.142857	1
Diagnostics			
solution coverage:	0.857143		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
∼f4*f5	0.285714	0.285714	1
f1*f2*f6	0.571429	0.571429	1
Diagnostics			
solution coverage:	0.857143		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f5*∼f4*f3*f2	0.142857	0.142857	1
f6*f5*∼f4*f3*f1	0.142857	0.142857	1
f6*f4*f3*f2*f1	0.571429	0.571429	1
Diagnostics			
solution coverage:	0.857143		
solution consistency:	1		

Conversion Factor	Mean		
Complex Solution			
	raw coverage	unique coverage	consistency
~f1*f2*f3*~f4*~f5*f6	0.2	0.2	1
f1*~f2*f3*~f4*f5*f6	0.2	0.2	1
f1*f2*f3*f4*f5*f6	0.6	0.6	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
~f4*f6	0.4	0.4	1
f2*f5*f6	0.6	0.6	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*~f4*f3*f2	0.2	0.2	1
f6*f5*~f4*f3*f1	0.2	0.2	1
f6*f5*f3*f2*f1	0.6	0.6	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		

Model	12		
TIS	Wind		
Outcome Variable	o6		
Conversion Factor	Median		
Complex Solution			
	raw coverage	unique coverage	consistency
f1*f2*f3*∼f4*f5*f6	0.2	0.2	1
Diagnostics			
solution coverage:	0.2		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f1*∼f4	0.2	0.2	1
Diagnostics			
solution coverage:	0.2		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f6*f5*∼f4*f3*f2*f1	0.2	0.2	1
Diagnostics			
solution coverage:	0.2		
solution consistency:	1		

Model	11		
TIS	Wind		
Outcome Variable	o5		
Conversion Factor	Median		
Complex Solution			
	raw coverage	unique coverage	consistency
~f1*~f2*~f3*f4*~f5*~f6	0.142857	0.142857	1
f1*f2*f3*f4*~f5*f6	0.142857	0.142857	1
f1*f2*f3*~f4*f5*f6	0.142857	0.142857	1
Diagnostics			
solution coverage:	0.428571		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f1*~f4	0.142857	0.142857	1
~f1*~f2*f4	0.142857	0.142857	1
f3*~f5	0.142857	0.142857	1
Diagnostics			
solution coverage:	0.428571		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f4*~f2*~f1	0.142857	0.142857	1
f6*f5*~f4*f3*f2*f1	0.142857	0.142857	1
f6*~f5*f4*f3*f2*f1	0.142857	0.142857	1
Diagnostics			
solution coverage:	0.428571		
solution consistency:	1		

Model	10		
TIS	Wind		
Outcome Variable	o4		
Conversion Factor	Median		
Complex Solution			
	raw coverage	unique coverage	consistency
f1*f2*∼f3*f4*f5*∼f6	0.166667	0.166667	1
f1*f2*f3*∼f4*f5*f6	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.333333		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
1*∼f4	0.166667	0.166667	1
f1*f2*∼f6	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.333333		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
∼f6*f5*f4*f2*f1	0.166667	0.166667	1
f6*f5*∼f4*f3*f2*f1	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.333333		
solution consistency:	1		

Model	5		
TIS	Wind		
Outcome Variable	o3		
Conversion Factor	Median		
Complex Solution			
	raw coverage	unique coverage	consistency
f2*f3*∼f4*f5*f6	0.230769	0.230769	1
f1*f2*f3*f4*f6	0.538462	0.538462	1
f1*∼f2*∼f3*f4*∼f5*∼f6	0.076923	0.076923	1
∼f1*f2*∼f3*f4*∼f5*∼f6	0.076923	0.076923	1
f1*f2*∼f3*f4*f5*∼f6	0.076923	0.076923	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f1	0.769231	0.076923	1
f2	0.923077	0.230769	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
f4*f2	0.692308	0.076923	1
f4*f1	0.692308	0.076923	1
f6*f5*f3*f2	0.692308	0.230769	1
Diagnostics			
solution coverage:	1		
solution consistency:	1		

Model	8		
TIS	Wind		
Outcome Variable	o2		
Conversion Factor	Median		
Complex Solution			
	raw coverage	unique coverage	consistency
f1*f2*∼f3*f4*f5*∼f6	0.166667	0.166667	1
f1*f2*f3*∼f4*f5*f6	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.333333		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f1*∼f4	0.166667	0.166667	1
f1*f2*∼f6	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.333333		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
∼f6*f5*f4*f2*f1	0.166667	0.166667	1
f6*f5*∼f4*f3*f2*f1	0.166667	0.166667	1
Diagnostics			
solution coverage:	0.333333		
solution consistency:	1		

Model	4		
TIS	Wind		
Outcome Variable	o1		
Conversion Factor	Median		
Complex Solution			
	raw coverage	unique coverage	consistency
f2*f3*∼f4*f5*f6	0.230769	0.230769	1
f1*f2*f3*f4*f6	0.538462	0.538462	1
∼f1*f2*∼f3*f4*∼f5*∼f6	0.076923	0.076923	1
Diagnostics			
solution coverage:	0.846154		
solution consistency:	1		
Parsimonious Solution			
	raw coverage	unique coverage	consistency
f3	0.769231	0.692308	1
f2*∼f5	0.153846	0.076923	1
Diagnostics			
solution coverage:	0.846154		
solution consistency:	1		
Intermediate Solution			
	raw coverage	unique coverage	consistency
∼f5*f4*f2	0.153846	0.153846	1
f6*f5*f3*f2	0.692308	0.692308	1
Diagnostics			
solution coverage:	0.846154		
solution consistency:	1		

Appendix D

D.1 Oil Prices (1946-2013) (Nominal and Inflation Adjusted)

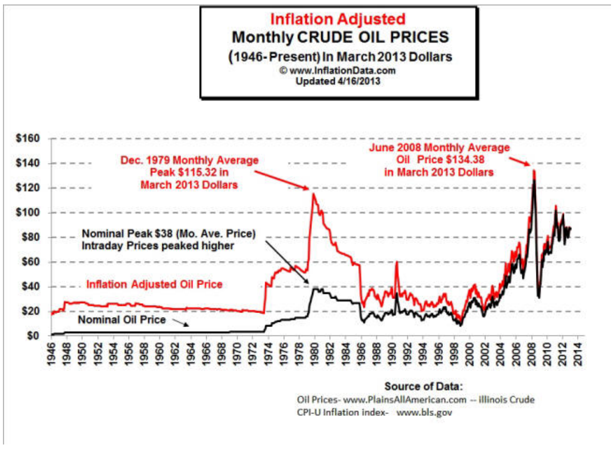


Fig. D.1 World Oil Prices

Source: InflationData.com

D.2 The Evolution of Functions Across Time (Line Charts)

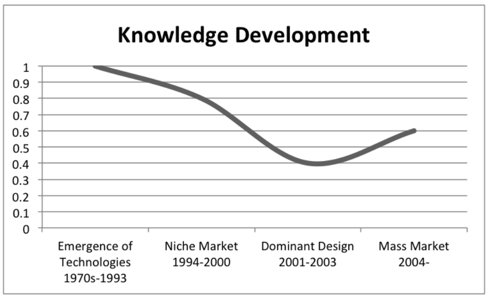


Fig. D.2 Evolution of KD Functions in the Idealised model

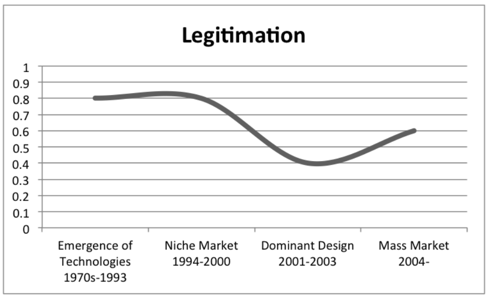


Fig. D.3 Evolution of LE Functions in the Idealised model

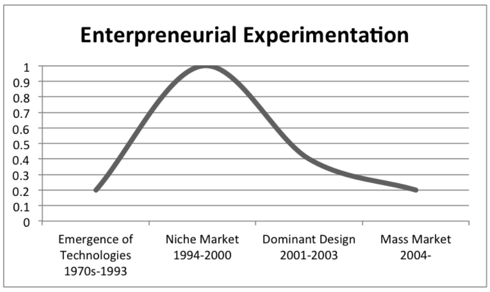


Fig. D.4 Evolution of EE Functions in the Idealised model

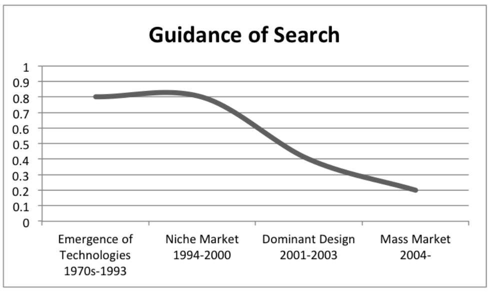


Fig. D.5 Evolution of GS Functions in the Idealised model

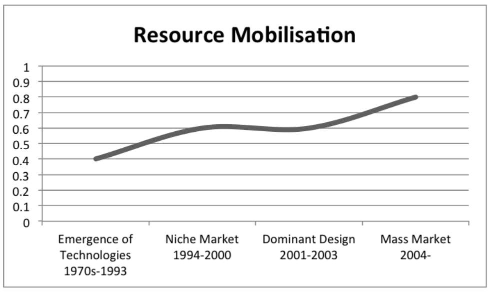


Fig. D.6 Evolution of RM Functions in the Idealised model

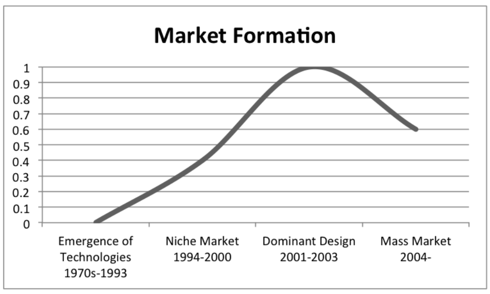


Fig. D.7 Evolution of MF Functions in the Idealised model

D.3 The Functions

The labelling of the functions can be seen in the following table:

Label	Function
(F_1)	Knowledge development
(F_2)	Legitimation
(F_3)	Guidance of search
(F_4)	Entrepreneurial experimentation
(F_5)	Resource mobilisation
(F_6)	Market formation
(F_7)	Potential for Technology diffusion

The values for the strength of the coefficients for the functions and the complementarities can be seen in the following table:

Strength	Implied Range of Values
Very Strong (VS)	0.8 - 1
Strong (S)	0.5 - 0.7
Weak (W)	0.2 - 0.4
Very Weak (VW)	0 - 0.1

D.4 The Stylised Model

Our conceptualisation of the strength of each function in the stylised model is illustrated in the table D.1

Stylised Model

Function	Emergence of technologies	Niche Markets	Dominant Design	Mass Market
F_1	VS	VS	W	VW
F_2	VS	VS	W	W
F_3	S	VS	W	VW
F_4	W	VS	S	VW
F_5	W	VS	S	S
F_6	VW	W	VS	S
F_7	VW	VW	S	VS

Table D.1 Stylised Model: Strength of the Functions

D.5 The Values Of The Complementarities (Numerical)

The following matrices present an example of some randomly generated numbers for our complementarities across time, which are used in our model estimations.

$$J^{(1)} = \begin{pmatrix} 0.1 & 0.5 & 0.6 & 0.1 & 0.6 & 0.2 & 0.9 \\ 0.8 & 0.1 & 1 & 0.4 & 0.1 & 0.1 & 0 \\ 0.3 & 0.5 & 0 & 0.3 & 0.1 & 0.2 & 0.5 \\ 0.9 & 1 & 0.9 & 0.1 & 1 & 0 & 1 \\ 0.4 & 0.8 & 0.7 & 0.3 & 0.1 & 0.2 & 0.1 \\ 0.5 & 0.9 & 1 & 0.9 & 1 & 0.1 & 0.1 \\ 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$J^{(2)} = \begin{pmatrix} 0.1 & 0.8 & 0.7 & 0.8 & 0.6 & 0.5 & 0.3 \\ 0.9 & 0.1 & 0.9 & 0.8 & 0.4 & 1 & 0 \\ 0.8 & 1 & 0.1 & 0.3 & 0.4 & 0.4 & 1 \\ 0.9 & 0.6 & 0.9 & 0.1 & 1 & 0.2 & 0.9 \\ 0.4 & 0.7 & 1 & 0.3 & 0.1 & 0.4 & 0 \\ 0.2 & 0.6 & 0.8 & 0.8 & 1 & 0 & 0 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0 & 0 & 0 \end{pmatrix}$$

$$J^{(3)} = \begin{pmatrix} 0 & 0.9 & 0.9 & 0.1 & 1 & 1 & 0.2 \\ 0.1 & 0.1 & 0.5 & 0.2 & 0.4 & 0.8 & 0.8 \\ 0.8 & 0 & 0 & 0.1 & 0.4 & 0.6 & 0.8 \\ 0.3 & 0.3 & 0 & 0.1 & 0 & 0.1 & 0 \\ 1 & 0.2 & 0.6 & 0.1 & 0.1 & 0.3 & 0.6 \\ 0.5 & 0.3 & 0.6 & 0.1 & 0.7 & 0 & 0 \\ 0 & 0 & 0.1 & 0 & 0.1 & 0.1 & 0.1 \end{pmatrix}$$

D.6 The Results from The Case Studies

The following tables show the results from our case studies.

Greece				
	emergence of technologies	niche markets	dominant design	mass market
F1	0.4	0.6	0.4	0.8
F2	0.4	0.6	0	0.8
F3	0.2	0.6	0.2	0.8
F4	0.2	0.2	0.2	0.8
F5	0.8	0.4	0	0.6
F6	0	0.2	0.4	0.8
F7	0	0	0	0.6

Table D.2 Results from Case Studies: Greece

Czech Republic				
	emergence of technologies	niche markets	dominant design	mass market
F1	0	0	0.4	0.6
F2	0.2	0	0.6	0.8
F3	0	0	0.4	0.6
F4	0.2	0	0	0.8
F5	0	0	0.2	0.8
F6	0	0	0	1
F7	0	0	0	0.8

Table D.3 Results from Case Studies: Czech Republic

UK				
	emergence of technologies	niche markets	dominant design	mass market
F1	1	0.8	0.8	0.6
F2	0.8	0.6	0.6	0.6
F3	0.2	0	0.6	0.6
F4	0.2	0.2	0.2	0
F5	0.4	0.4	0.4	0.8
F6	0	0.2	0.4	0.6
F7	0	0	0.2	0.6

Table D.4 Results from Case Studies: UK

Germany				
	emergence of technologies	niche markets	dominant design	mass market
F1	0.8	0.6	0.8	0.6
F2	0.6	0.6	0.8	0.6
F3	0.6	1	1	0.2
F4	0.2	0.6	1	0.2
F5	0.8	0.6	0.6	0.8
F6	0	0.2	0.8	0.8
F7	0	0.2	0.4	1

Table D.5 Results from Case Studies: Germany

D.7 The Results from The Base Model

The following tables show the results from our base model.

Greece				
	emergence of technologies	niche markets	dominant design	mass market
F1	0.4	0.32	0.32	0.31
F2	0.4	0.35	0.31	0.28
F3	0.2	0.2	0.23	0.24
F4	0.2	0.32	0.3	0.31
F5	0.8	0.59	0.46	0.35
F6	0	0.3	0.33	0.33
F7	0	0.02	0.02	0.05

Table D.6 Results from Base Model: Greece

Czech Republic				
	emergence of technologies	niche markets	dominant design	mass market
F1	0	0.02	0.06	0.06
F2	0.2	0.14	0.08	0.06
F3	0	0.03	0.04	0.04
F4	0.2	0.08	0.06	0.06
F5	0	0.04	0.05	0.05
F6	0	0.06	0.06	0.06
F7	0	0	0	0.01

Table D.7 Results from Base Model: Czech Republic

UK				
	emergence of technologies	niche markets	dominant design	mass market
F1	1	0.6	0.51	0.43
F2	0.8	0.69	0.51	0.41
F3	0.2	0.27	0.35	0.34
F4	0.2	0.4	0.4	0.41
F5	0.4	0.44	0.43	0.4
F6	0	0.36	0.4	0.41
F7	0	0.03	0.04	0.08

Table D.8 Results from Base Model: UK

Germany				
	emergence of technologies	niche markets	dominant design	mass market
F1	0.8	0.57	0.53	0.49
F2	0.6	0.59	0.52	0.45
F3	0.6	0.48	0.43	0.4
F4	0.2	0.47	0.47	0.47
F5	0.8	0.68	0.6	0.5
F6	0	0.43	0.49	0.5
F7	0	0.03	0.05	0.09

Table D.9 Results from Base Model: Germany

D.8 The Results from The Base Model

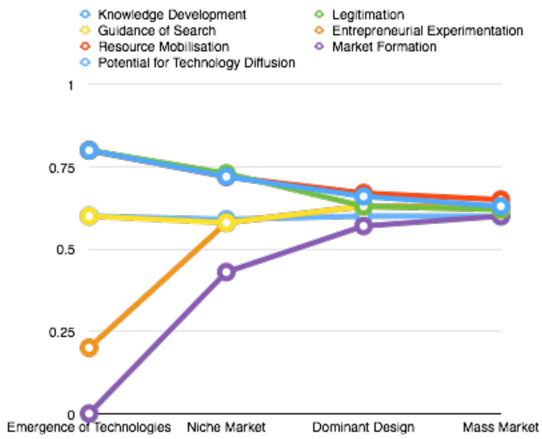


Fig. D.8 The Evolution of Functions in Germany

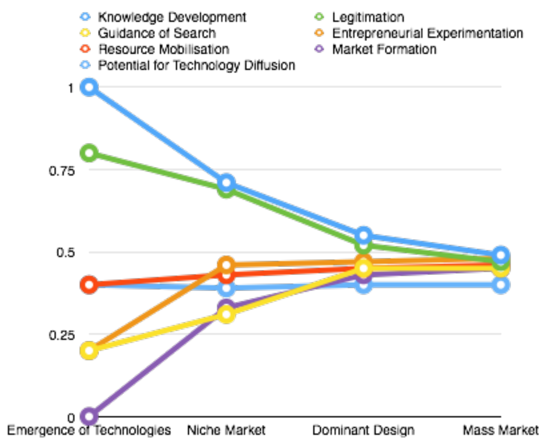


Fig. D.9 The Evolution of Functions in the UK

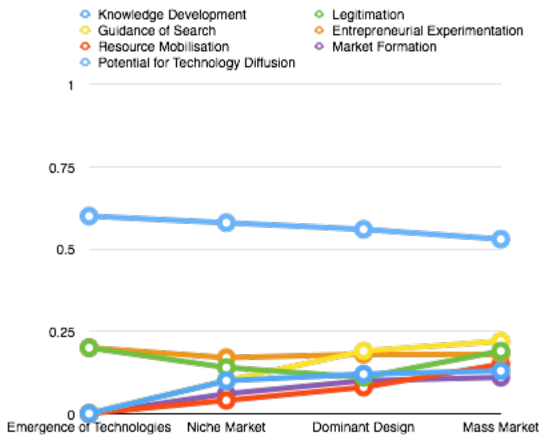


Fig. D.10 The Evolution of Functions in the Czech Republic

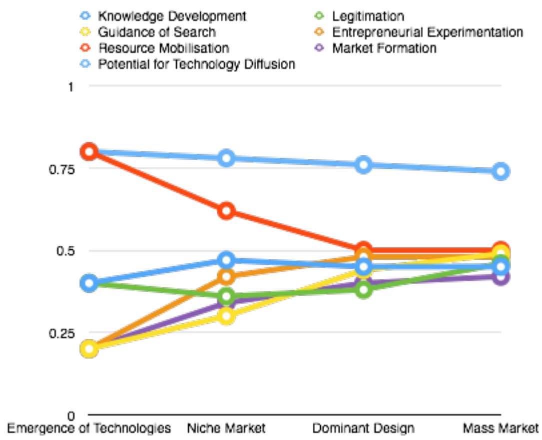


Fig. D.11 The Evolution of Functions in Greece

Appendix E

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