Understanding the dynamics of emerging innovation systems and the transition to the growth phase of renewable energy technologies

Towards a comprehensive model of function dynamics

Master thesis

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Voorwoord

Voor u ligt het resultaat van zes maanden werken aan mijn masterscriptie voor de masteropleiding Science and Innovation Management aan de Universiteit Utrecht. In het kader van mijn afstuderen heb ik ervoor gekozen mijn scriptie extern te schrijven en wel bij Technopolis Group in Amsterdam, onder begeleiding van Jan-Frens van Giessel. Ik wil Jan-Frens en Technopolis hartelijk bedanken voor hun fijne begeleiding en de interesse en hartelijkheid van alle collegae aldaar. Ik heb er behalve het inhoudelijke deel van mijn onderzoek veel geleerd over de dagelijkse praktijk en materie van een adviesbureau voor innovatiebeleid en heb het er erg naar mijn zin gehad.
Simona Negro was mijn begeleidster vanuit de Universiteit Utrecht. Haar kennis van technologische innovatiesystemen is groot en ze heeft me goed geholpen om theoretisch en methodisch mijn onderzoek zo sterk mogelijk te maken. Behalve inhoudelijk was Simona ook een erg gezellige begeleider en ik heb al onze overleggen zeer prettig ervaren en ook haar wil ik hartelijk danken voor de goede begeleiding.
Het was mijn doel om een onderzoek te doen dat zowel wetenschappelijke als praktische waarde heeft. Ik wilde de theorie over functies van technologische innovatiesystemen verder brengen, maar ook maatschappelijke waarde creëren door bruikbare aanbevelingen aan beleidsmakers te doen. Ik denk zelf dat ik aan beide doelen een bijdrage heb kunnen leveren en hoop dat ieder die dit leest meer inzicht krijgt in hoe we innovatieprocessen in de duurzame energie beter kunnen stimuleren.

Nogmaals dank aan ieder die mij heeft geholpen om mijn onderzoek zo succesvol mogelijk af te ronden en veel plezier met lezen,

Marjolein van der Klauw

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Contents

1. Introduction

Technological innovation emerges in a complex system of forces that influences the development, diffusion and use of this innovation (Edquist, 1997). Especially for radical innovations the way to successful implementation can be obstructed with resistance by the present market leaders and a lack of compatibility with the existing infrastructure. Renewable energy technologies are such innovations that may replace large parts of the incumbent energy system and which need adjusted electricity infrastructures (Hekkert *et al.*, 2007). Some renewable energy technologies, like wind turbines and solar panels, have developed towards a phase where installations in some countries are successfully delivering electricity to the net and these technologies contribute in a substantial way to national goals to increase percentages of sustainable energy generation and use.
Other renewable energy technologies are still in very early phases of commercial maturity, or they are installed only in some countries, but not in any others. For further growth of these renewable energy technologies it is useful to understand what important factors are for successful development. Such factors need to be assessed from both a technological point of view and an institutional point of view.

A fruitful framework to analyze the context of renewable energy technologies is the technology specific innovation system (Carlsson and Jacobsson, 1997). This is a multidisciplinary and multi-actor system that influences the development, diffusion and use of technological innovations. Since most renewable energy technologies have not yet reached independence of a supportive (financial and institutional) infrastructure and because many renewable energy technologies are still developing in protected niche markets, this innovation system is regarded as an emerging innovation system for many renewable energy technologies (Alkemade and Hekkert, 2009).

In such emerging innovation systems the technology develops from its earliest phases of fundamental research and experimentation in niches towards products that can be installed for use by energy companies and private customers. The way to this successful implementation of the technology is often characterized by high uncertainties, risks and investments, and late returns on investment (Alkemade *et al.*, 2007). In the process towards successful implementation of these renewable energy technologies such barriers have to be overcome, continuous development and maturing of the technology has to take place and an institutional and physical infrastructure needs to be shaped in which the technologies can be embedded.
The emerging innovation system has similarities with the framework of strategic niche management. In this approach characteristics of the systems of emerging technologies are studied as a niche context. This theory emphasizes the need for protected niches to be able to develop, diffuse and use the innovation (Kemp *et al.*, 1998). Then, according to multi-level theory (Geels, 2002), when the technology is successfully developed in a niche this technology grows into a regime size system. The transition from niche to regime is comparable to the transition of an emerging innovation system to a (regular) technological innovation system, and comparable to a transition from the exploratory phase of a product or industry to the growth phase of that product or industry (Klepper, 1997).
The goal of this study is formulated as follows:

> *"To understand the dynamics of an emerging technological innovation system from beginning to the end of the exploratory phase for renewable energy technology, and to understand the conditions of the transition to the regime system and growth phase of the technology."*

The conditions that the emerging technological innovation system has to comply with in order to reach success are structured in the approach of System Functions (Jacobsson and Johnson, 2000). This approach involves seven functions that have to be fulfilled sufficiently in order to path the way for success for the renewable energy technology. These seven functions, which are explained in detail in the next chapter, develop in different patterns of dynamics over time. Some functions are very important in earliest phases, while others are important for growth in a later phase, and again others need to be continuously present at all times in the emerging innovation system (Hekkert *et al.*, 2007).

Understanding the dynamics of these functions for technological innovation systems from the earliest phase towards successful implementation is important for fruitful policy making to reach ambitious goals for renewable energy use. When insight is gained about the importance of certain functions within certain phases of technological maturity, specific policy can be created to stimulate the fulfilment of these functions and thereby to accelerate the development of the technology towards the next phase. The better these dynamics of function fulfilment are understood, the better policy can be

specified to the phase of the technology and thereby the acceleration of the development of the technology.
The research question is formulated as follows:

"What are the dynamics of functions of innovation systems for renewable energy technologies during the first phases and the transition to the growth phase of its life cycle?"

The last few years several studies are conducted that use the functions approach to study innovation systems of renewable energy technologies. In most cases a qualitative study was conducted in which a qualitative process analysis described the sequence of events that had influenced the development of the renewable energy technology (see section 2.3). Also, some studies are conducted that combine these case study outcomes and that conclude on overall patterns of dynamics and so-called motors between functions (Suurs, 2009: section 2.1).
However, a relation between the phase of commercial maturity in the life cycle of a technological innovation and the fulfilment of functions at that phase is made only at a level of relative high aggregation. Alkemade and Hekkert (2009) have combined fifteen case studies to conclude on dynamics for the exploratory phase, the growth phase and the mature phase of the technology. However, from the perspective of commercial maturity the mature phase has not yet been reached for any renewable energy technology except for hydropower, and the distinction of only two phases to describe the dynamics of the functions is considered too small for thorough understanding of dynamics. When function fulfilment is related to commercial maturity in more separate phases of maturity, better understanding of sequences and dynamics of function fulfilment is created and this may lead to more effective policy, because policy can better be adjusted to the phase and thus the needs of the emerging technology.
For example, a renewable energy technology may need funding for research activities first, while later they need better circumstances for delivering of electricity to the net and again later it needs attractive financial incentives for purchase of the product. These needs all appear in the exploratory phase before the take-off of the technology can happen, but the moments in time differ. Improved understanding of these dynamics is possible by increasing the number of phases within the concept of the exploratory phase.

Paper outline

Chapter 2 elaborates on the theoretical framework that is used for this study and explains the reasoning for the hypotheses and the conceptual model. Chapter 3 gives the operationalisation of the concepts and explains the methods used for the data gathering for and analysis of the case studies. The chapters 4 to 6 each present the data results and a short story line for the functions fulfilment and importance of each of the case studies. Chapter 7 combines of the outcomes of the three case studies and compares these with the hypotheses. Chapter 8 concludes on the overall outcomes of dynamics per phase and presents a comprehensive model of function fulfilment dynamics. Chapter 9 presents the recommendations to policy makers. Chapter 10 discusses the theoretic framework and the system functions approach and gives recommendations for the use of these frameworks.

2. Theory

This chapter focuses on two main theoretical frameworks that guide this study: the framework of technological innovation systems and the functions approach, and life cycle theory, in particular the framework for phases of commercial maturity. The third subsection gives the hypotheses and the conceptual model.

2.1 Technological innovation systems and the functions approach

In this research project the definition of an innovation system from Edquist (1997: 10) is followed, defined as "*consist[ing] of all important economic, social, political, organizational, institutional and other factors that influence the development, diffusion and use of innovation*". The Innovation Systems concept was introduced in 1985 by Lundvall. The first subsystem was the National Innovation Systems concept, introduced by Freeman (1987) and strongly supported by Nelson, Lundvall and Dosi (Dosi, 1988). Then, the Regional Systems of Innovation were introduced by Cooke (1996) and shortly after this Carlsson and Jacobsson (1997) developed the concept of Technological Innovation Systems. In the same year the fourth dimension was introduced: the Sectoral Systems of Innovation by Breschi and Malerba (1997).
For this particular study the Technological Innovation System approach fits best, because the Technological Innovation System is created to discuss trans-national systems of actors, institutions and networks for one specific technology. The single technology as a unit of analysis provides for in-depth understanding of a small industrial area, instead of the more general views, which would be the result when other approaches would be chosen. Choosing the Technological Innovation System also provides the opportunity for effective policy recommendations (Hekkert *et al.*, 2007). The Technological Innovation System is defined as following:

> *"A set of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of varieties of a new technology or product." (Markard and Truffer, 2008: 600)*

To study Technological Innovation Systems the functions approach is chosen, because this method encompasses the totality of important actors and interactions of an innovation system and it is particularly fruitful in providing insight for corporate and public policy making. Jacobsson and Johnson (2000: 632) define these System Functions as "*a contribution of a component or a set of components to a system's performance*". The components are actors, relations between actors and institutions. The performance of the system functions together is seen as the rate of development, diffusion and implementation of the innovation.
The composition of functions has changed over time and for this study the seven functions defined by Hekkert *et al.* (2007: 423) will be used. Hekkert *et al.* have based their set on both literature study on the history and reasoning for former sets of functions and the results of empirical studies on the composition of functions. It is therefore perceived as the state-of-the art in functions of Technological Innovation Systems.
Although the most state-of-the-art set of functions is chosen, interpretations or emphasis of concepts for these functions differ slightly among researchers. A comparative study of several interpretations of the seven functions from previous studies, combined with the aim and characteristics of this specific study, leads to the following description of the seven functions for this study. For each description the most indicative source is given.

F1: Entrepreneurial Activity

Entrepreneurs are essential for a well-functioning innovation system. The task of the entrepreneur is to turn the potential of new knowledge, networks and markets into concrete actions to generate – and take advantage of – new business opportunities. Entrepreneurs are very important in overcoming uncertainties that are present in the early phase of a technology. They can be new entrants in new markets, or incumbent companies who diversify their business strategy to take advantage of new development (Alkemade *et al.*, 2007).
Please note that entrepreneurs can perform these activities, but most important is *that* the activities are performed; and which (type of) organization performs them is of less importance.

F2: Knowledge Development

Learning mechanisms are at the heart of an innovation process. According to Lundvall, *"the most fundamental resource in modern economy is knowledge, and, according the most important process is learning"* (Lundvall, 1992). Therefore, R&D and Knowledge Development are prerequisites for the innovation system. This function encompasses 'learning by searching' and 'learning by doing'. The function includes, besides technological Knowledge Development, also financing knowledge, user experiences and insights in bottlenecks that limit diffusion, for instance by feasibility studies (Hekkert *et al.*, 2007).

F3: Knowledge Diffusion

According to Carlsson and Stankiewicz (1991), the essential function of networks is the exchange of information. This is important in a strict R&D setting, but especially in a heterogeneous context where R&D meets government, competitors and market. Here policy decisions should be consistent with the latest technological insights. At the same time information through networks can lead to changing R&D agendas affected by changing norms and values. With these networks leading to learning at system level, network activity can be regarded as a precondition to 'learning by interacting' (Hekkert and Negro, 2009).

F4: Guidance of the Search

Since resources are almost always limited, it is important that when various different technological options exist, specific priorities are in place for investment decisions. Without this selection there will be insufficient resources left over for the individual options. The function therefore includes expectations, because these can converge on a specific topic and generate momentum for change in a specific direction. Several actors can fulfill this function in the innovation system, such as government, industry and market. It includes also those activities, which can positively affect the visibility and clarity of specific wants among technology users. An example is the announcement of a government goal to achieve a certain percentage of renewable energy in a future year (Negro *et al.*, 2007).

F5: Market Formation

New technologies often have difficulties to compete with embedded technologies. The reason is that new technologies are often badly adapted to many of the ultimate uses to which they will eventually be put. Therefore it is important to create protected spaces for new technology development. One possibility is the formation of temporary niche markets for specific applications of the technology. The government plays a crucial role in creating these niche markets, because they can act as a launching customer: they can articulate the demand by acting as an early user, or by formulating policy targets. Other possibilities are to create a temporary competitive advantage by favourable tax regimes or minimal consumption rates (Alkemade *et al.*, 2007; Negro *et al.*, 2007).

F6: Resource Mobilisation

Financial, human and physical (e.g. in the case of biomass technology) resources are necessary as a basic input to all activities within the Innovation System. For a specific technology the allocation of sufficient resources is necessary to make knowledge production possible. The two major providers of financial resources are the government and the venture capital industry. When venture capitalists invest relatively much this can be seen as a sign that Entrepreneurial Activity is performing well, because they only invest in those enterprises where the business plan is promising enough profitability (Alkemade *et al.*, 2007).

F7: Lobby Activity and Creation of Legitimacy

In order to develop well, a new technology has to become part of an incumbent regime, or it even has to overthrow that regime. Parties with vested interests will often oppose to this force of 'creative destruction'. In that case, advocacy coalitions can function as a catalyst: they can put a new

technology on the agenda or lobby for resources and favourable tax regimes, and by doing so they create legitimacy for a new technological trajectory. If successful, the advocacy coalitions will grow in size and influence and they may become powerful enough to brisk up the spirit of creative destruction (Hekkert *et al.*, 2007a).

Motors between system functions

Suurs (2009) compared the dynamics of functions for five case studies and identified motors between the seven functions. He states that the presence of these motors depends on the phase of the technological innovation system. The four motors he identifies can be placed in a sequence, where the successful dynamics of one motor, lead to the establishment of the next motor. The four motors are explained quoting Suurs (2009):

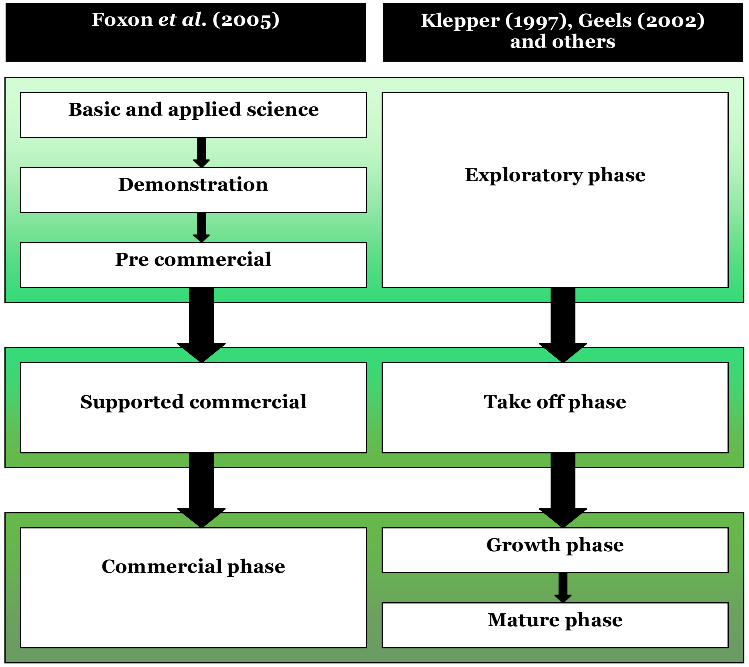
1. **Science and Technology Push Motor**
"The Science and Technology Push Motor is dominated by Knowledge Development (F2), Knowledge Diffusion (F3), Guidance of the Search (F4) and Resource Mobilisation (F6). All the other system functions are either absent or weak." (Suurs, 2009: 265)
2. **Entrepreneurial Motor**
"The Entrepreneurial Motor is partly similar to the STP Motor. Its dynamics are also characterized by a strong fulfilment of Knowledge Development (F2), Knowledge Diffusion (F3), Guidance of the Search (F4) and Resource Mobilisation (F6). What sets this motor apart from the STP Motor is the particularly important role of Support from advocacy coalitions (F7) and Entrepreneurial Activity (F1)." (Suurs, 2009: 265)
3. **System Building Motor**
"In the System Building Motor the set of dominant system functions is similar to those of the Entrepreneurial Motor, but it includes a more important role of Market Formation (F5). The main difference lies in the connection between Support from advocacy coalitions (F7) on the one hand and Market Formation (F5) and Guidance of the Search (F4) on the other hand)." (Suurs, 2009: 266)
4. **Market Motor**
"The Market Motor is characterized by a strong contribution to Entrepreneurial Activity (F1), Knowledge Development (F2), Knowledge Diffusion (F3), Guidance of the Search (F4), Resource Mobilisation (F6) and Market Formation (F5)" (Suurs, 2009: 266)

2.2 The framework for commercial maturity of technology

Various sets to describe phases in life cycles of products or technologies exist. Two relatively old frameworks are the *product* life cycle, which originated in marketing literature and was supported by Dean (1950), Levitt (1965), Vernon (1966) and Cox (1967) amongst others, and the *industry* life cycle (Klepper, 1997). The industry life cycle by Klepper (1997) distinguishes the following three phases: exploratory or formative phase, the intermediate or growth phase, and the mature phase. To emphasize the transition from the exploratory phase to the growth phase, and the specific circumstances the innovation system is in at that moment, motivated Geels (2002) to introduce the take-off phase, which is placed in between the exploratory phase and the growth phase.

The need for more space for detail in the earliest phases is partly addressed by Geels in this way, but as explained in the previous chapter, more separated phases are needed. The specific dynamics that play a role for renewable energy technologies such as the high uncertainties and risks and resistance by the incumbent regime (Alkemade *et al.*, 2007) can be observed better when the exploratory phase is studied by investigating dynamics following the commercial maturity of the technology (Foxon *et al.*, 2005). When the exploratory phase is split into three separate phases of commercial maturity, combining the dynamics of the functions for each of these phases gives better insight in the evolution of the technology during its exploratory phase. This provides better insight in which functions should be stimulated at particular moments in time within the exploratory phase.

Figure 1 Comparison of theory on life cycles



The framework of commercial maturity of technology by Foxon *et al.* (2005) is chosen as the leading framework for the life cycle. Foxon *et al.* studied seven renewable energy technologies in the United Kingdom and their life cycle determination proved "*to best represent and analyze technologies in the early phases of development […] for most new and renewable energy technologies*" (Foxon *et al.*, 2005: 2126). It is for the successfulness of their method in obtaining similar outcomes for several technologies that their operationalisation of life cycle phases is used for this study. The five phases of commercial maturity of a technology are defined as follows (Foxon *et al*., 2005: 2126-2127):

- *Basic and applied R&D* includes both 'blue skies' science and engineering / application focused research. These include both university and industry R&D.
- *Demonstration* includes early prototypes and is intended to refer up to the point where full-scale working devices are installed – but only in single units or small numbers, and still financed largely through R&D related grants. This is often the preserve of small spinouts or research subsidiaries.
- *Pre commercial* is intended to capture a fairly broad phase of development, one where multiple units of previously demonstration-phase technologies are installed for the first time, and/or where the first few multiples of units move to much larger scale installation for the first time. Larger players begin to move in or spinouts must grow rapidly, so investment risks are high at this phase.
- *Supported commercial* is the phase where, given generic renewables support measures such as the UK Renewables Obligation, technologies are rolled out in substantial numbers and by commercially oriented companies.
- *Commercial technologies* can compete unsupported, within the broad regulatory framework.

By comparing the determination and definitions of the phases of Klepper (1997) and Geels (2002) on the one hand and Foxon *et al.* (2005) on the other hand the following scheme of life cycle phases is constructed to give a graphic representation of the overlapping aggregation levels. See Figure 1.

Only the first four phases of Foxon *et al.* are used in this study. The technologies upon which the hypotheses are based and the case study technologies have not yet entered the commercial phase where they are independent of a supportive infrastructure. The start of the commercial phase in the case of renewable energy technologies can be regarded as the moment that grid parity for that technology is reached. This is when the total (long term) price of energy production from a renewable energy source is equal to or lower than the price on conventional energy production of fossil fuels. Since no renewable energy technology – except hydropower, but this technology is neither used for the hypotheses nor in the case studies – has reached this point, this study will investigate dynamics up to the supported commercial phase.

Relating the motors of system functions to the life cycle phases

The phases Suurs (2009) identified for these motors show similarity with Foxon's (2005) phases of commercial maturity. Since Suurs had not clearly defined his phases, it is assumed that his four phases are similar to the first four phases of Foxon *et al.* (2005). This is considered valid because the 'definitions' of the phases show similarities: both authors describe the first phase as one with mainly scientific activity; both characterize the second phase as a phase with experiments and demonstration projects. The third phase is a transition from the second to the fourth phase. The fourth phase is by both authors seen as a phase with an effective (government) supported system. Suurs (2009: 267) explains the motors and their corresponding phases as follows:

> *"It turned out that the immature TIS[1]s were less prone to develop something other than an Science and Technology Push motor. Only when a TIS was developed enough to generate short-term opportunities for firms did the Entrepreneurial motor emerge. A System building motor was observed as being a transformation of the Entrepreneurial motor. And finally, the Market motor was typically developed from structures shaped by the System building motor. In general there was a relation between the motors observed and the maturity of the TIS in terms of actors involved and in terms of technology and institutions."*

The following phases of commercial maturity by Foxon *et al.* (2005) relate thus to these corresponding motors.

- Basic and applied science → Science and Technology Push Motor
- Demonstration phase → Entrepreneurial Motor
- Pre commercial phase → System Building Motor
- Supported commercial phase → Market Motor.
- It is assumed that in the commercial phase the Market Motor continues.

2.3 Hypotheses

This research will be carried out by a comparison of outcomes of case studies with hypotheses based on previous studies of renewable energy where the functions approach was used. The hypotheses are constructed as a combination of the seven functions with the first four phases of commercial maturity. For each phase and the moment of transition to the next phase a proposition is formulated of the level of fulfilment of that function. This level of fulfilment is expressed in one of the three values low, medium or high.
The appointed values are based on previous studies among which the motors of Suurs (2009). Suurs' motors are integrated as follows: for all phases or transitions where Suurs stated that this function was not involved in a motor, the value 'low' is attributed to that phase of the function. For those functions that Suurs considers as part of a motor in a certain phase, either the value medium or high is appointed. It depends on the outcomes of recent studies which of these two values is chosen for the hypothesis.

[1] TIS stands for Technological Innovation System

For each function the hypothesis is explained and presented in the following paragraphs.

F1: Entrepreneurial Activity

Theory on Industrial Life Cycles (Klepper, 1997) explains that the majority of industries undergo the same pattern of industrial change in terms of the amount of corporations in the industry. This theory states that within an industry in the first phase (initial phase) the amount of corporations is relatively low. When the market grows (growth phase) and a lot of uncertainty remains on the market's wishes, there is a high entry rate of new players. However, once a more stable and less uncertain industry is shaped and winners and losers become clear, a shakeout in the amount of players occurs, where only the winners stay in place (mature phase). Also, in this last phase new players enter who comply with the dominant systems' characteristics.
This theory is applicable to formulate the hypothesis, because the 'industry' aggregation level has similarities with the level of 'technological innovation system': they both contain a variety of actors who play an entrepreneurial role in the development of a technology. Transferring these three phases of Klepper (initial, growth and mature phase) into the four phases of the conceptual model, results in the assumption that the moment when a shake-out occurs in the industrial life cycle, can be compared with the beginning of the commercial phase, when entrepreneurs encounter the first tough competition in an attractive market. It is therefore that importance of Entrepreneurial Activity grows from low to medium to high within our time boundaries, because the commercial phase is not included in our analysis.

This notion of low activity in the earliest phases is also recognized by Suurs' (2009) analysis of motors. In the Science and Technology push motor this function is not in place. Only from the demonstration phase on Entrepreneurial Activity becomes and stays important.

Besides Klepper also Negro and Hekkert (2009) conclude on the rather linear dynamics of this function. In their comparative study (2009: 21) they conclude that "*entrepreneurial activities proved to be a prime indicator whether an innovation system progresses or not*". Implicitly they state that continuous growth of the function Entrepreneurial Activity is visible during the life cycle of a technology. This implies that the function develops from relatively small to medium to high value for the emergence of the full innovation system. Also, they claim that Entrepreneurial Activity grows after the function Knowledge Development has started to develop. Therefore, Entrepreneurial Activity can only become of medium importance (second phase) after Knowledge Development has occurred (first phase).

In the case of biomass gasification (Negro *et al.*, 2008) it becomes clear that the first demonstration projects of entrepreneurs took place four years after the first guidance activities had taken place. This shows a clear lag in time with the first signs of an emerging technological innovation system. However, it is wrong to claim that no Entrepreneurial Activity takes place in the first phase. In a study on biomass digestion (Negro *et al.*, 2007) Entrepreneurial Activity takes place already before government guidance takes place, although on a very small scale. Also in a study on the Californian wind energy innovation system (Alkemade *et al.*, 2007) it appeared that incumbent players were involved in experiments in a very early phase. However, substantial impact of entrepreneurs on the emerging innovation system develops over time (Negro *et al.* (2007).

The function entrepreneurship is involved in a virtuous cycle with the function 'lobby activities' and 'Guidance of the Search' according to Hekkert and Negro (2009). They state that entrepreneurs will have to engage in lobby activities to strengthen their position by persuading the government and other system guiding actors to create favourable institutional conditions for their renewable technology. As long as these lobby activities are successful, the innovation system will have a positive development. This is why the values for lobby activities in the conceptual model evolve similarly in all phases. For other reasons (see the paragraph 4 on guidance) Guidance of the Search is always of high importance in the first three phases, but co-evolves with Entrepreneurial Activity and lobby activities during the supported because of the virtuous cycle.

Summary and hypothesis:

Thus, according to industry life cycle theory (Klepper, 1997) and Negro and Hekkert (2009) the dynamics of this function can be regarded as rather linear, starting at a relative low level of fulfilment in the first phase and growing towards high fulfilment in the supported commercial phase. The medium level of fulfilment starts in de demonstration phase according to Suurs (2009). Since Entrepreneurial Activity co-evolves with lobby activity its continuous growth is sustained by increased lobby activities.

The hypothesis for the dynamics of fulfilment of the function Entrepreneurial Activity is therefore formulated as follows:

H1: fulfilment of the function Entrepreneurship for the creation of a successful technological innovation system is of relative low level in the basic and applied science phase and the first transition, of medium level in the demonstration phase and the second transition and of relatively high level in the pre commercial and supported commercial phase.

F2: Knowledge Development

From the definition of the basic and applied science phase it is obvious and necessary that Knowledge Development takes place in the first phase. Logically, without sufficient creation of knowledge, the second phase cannot be reached. This phase is characterized by both fundamental and applied knowledge creation. In the demonstration and pre commercial phase, the type of Knowledge Development becomes more applied, because by conducting demonstration projects and the usage of small-scale applications, learning by doing and learning by using takes place.

For example, in the case of wind energy in California, characteristics of the first two phases were in place at the same time: fundamental research was performed on national level by NASA, while Knowledge Development from learning by doing took place at the manufacturers side from the construction and evaluation of prototypes (Alkemade *et al.*, 2007: 150). In general it can be stated, that with the rise of entrepreneurial activities, also a rise in Knowledge Development takes place, which is often seen as a shift from fundamental to applied Knowledge Development (Hekkert and Negro, 2009).

Also Suurs (2009) confirms continuous importance of this function. In all four motors and thus in all phases of this study he states that Knowledge Development accelerates the development of the technology.

All phases are appointed the value 'high' for Knowledge Development for two reasons. First, continuous Knowledge Development is necessary for a technology to develop during the first three phases towards each next phase. According to Hekkert and Negro (2009: 21), *"[for] complex technologies in early phases of emergence uncertainty about technological performance is high. It is only natural that much R&D is necessary to solve technological problems and create technology with acceptable specifications*."
Furthermore, Knowledge Development is part of a virtuous cycle with the functions Guidance of the Search and Resource Mobilisation. According to Negro and Hekkert (2009), previous studies of biomass technologies show that for a technology to develop successfully a continuous reinforcing cycle between these three functions is needed. For biomass gasification this virtuous cycle was clearly visible and described as follows: *"positive results from research (F2) result in high expectations of biomass gasification (F4), which, in turn, result in the set up of research programs in the context of which demonstration projects are set up (F2, F6)"* (Negro *et al.*, 2008: 66).

However, despite evidence from empirical studies and theoretical argumentations, not for all renewable energy technologies continuous high values for Knowledge Development were observed. In the case of biomass digestion (Negro *et al.*, 2007), only little Knowledge Development took place in the first period. It took about 14 years before a rise in Knowledge Development would take place. However, the whole development of the innovation system around biomass digestion took a long time, and in that perspective Knowledge Development took place in a relatively early phase compared to other functions.

Summary and hypothesis:

Thus, based on both theoretical reasoning, the dynamics of motors between functions and empirical evidence of case studies the function Knowledge Development is considered highly fulfilled in all phases. Without improving understanding and development of the technology, that technology cannot progress to further phases of commercial maturity.

H2: fulfilment of the function Knowledge Development for the creation of a successful technological innovation system is of high level in all phases and transitions between phases of commercial maturity.

F3: Knowledge Diffusion

This function is one with less clear evidence on its development over time; however the dynamics of different technologies have similarities. The study on four biomass related technologies concludes that this function is difficult to map and they assume that Knowledge Diffusion and learning take place along with the development of knowledge (F2) (Hekkert and Negro, 2009). The case of cogeneration shows that successful outcomes of Knowledge Development (good practices) were copied by other companies and thereby that Knowledge Diffusion took place (Hekkert *et al.*, 2007). This implies a time lag between these two functions, because first sufficient knowledge on good practices has to be produced in the earliest phase before this useful knowledge can be spread.

Also, the function Entrepreneurial Activity "*is a very good indicator for technology diffusion*" in the case of biomass technologies (Hekkert and Negro, 2009: 21). In addition, Alkemade *et al.* (2007) indicate that knowledge is diffused via learning by interacting by cooperation between large manufacturers (entrepreneurs). Again for cogeneration Knowledge Diffusion is visible in cooperation projects of entrepreneurs from a variety of related industries (Hekkert *et al.*, 2007). This suggests that the dynamics of Knowledge Diffusion are similar to the dynamics of Entrepreneurial Activity and that they could have a reinforcing character.

Summary and hypothesis:

Since case studies show that Knowledge Diffusion takes mainly place when research institutes come together with entrepreneurs and industry in general, it is hypothesized that in the earliest phase, when no entrepreneurial activities are visible also Knowledge Diffusion is low. When Entrepreneurial Activity increases, also more Knowledge Diffusion will take place.
Also Knowledge Development serves as an indicator for Knowledge Diffusion. A time lag may take place between the creation of knowledge and the opportunity to diffuse the useful outcomes. Also, the study of Knowledge Development dynamics showed that Knowledge Development activity increases over time to sustain improvement of the technology and because Knowledge Development is a precondition to Knowledge Diffusion this increase argues for an increase in Knowledge Diffusion fulfilment as well.

The hypothesis is therefore formulated analogous to Entrepreneurial Activity:

H3: fulfilment of the function Knowledge Diffusion for the creation of a successful technological innovation system is of a relative low level in the basic and applied science phase and the first transition, of a medium level in the demonstration phase and the second transition and of a relatively high level in the pre commercial and supported commercial phase.

F4: Guidance of the Search

Guidance of the Search is often the starting point of the appearance of a virtuous cycle or innovation processes in general: "*it stood at the base of many developments and lead to several courses of action*" and "*most of the sequences start with Guidance (F4) and continue with Knowledge Development (F2) via Resource Mobilisation (F6)*" (Hekkert and Negro, 2009: 22, 24). As was already noted, Guidance of the Search is involved in one virtuous cycle together with the functions Knowledge Development and Resource Mobilisation; and in another virtuous cycle with the functions Entrepreneurial Activity and lobby activities.

Also Suurs (2009) determines Guidance of the Search to be evident in the Science and Technology Push motor, as well as all other motors and thus phases.

Due to this crucial position of Guidance of the Search several case studies (four biomass technologies (Negro and Hekkert, 2009), wind energy (Alkemade *et al.*, 2007), biomass in transportation (IMW, 2007) and cogeneration (Hekkert *et al.*, 2007a)) prove that this function is considered of 'high' importance for the early phases. Without sufficient guidance, no renewable energy system can take off successfully.

However, despite the fact that Guidance of the Search is regarded as important for the take off of the technology, fulfilment of the function is not only based on importance but also on activity. This means that the more guidance activity takes place, the more this function is also fulfilled. The level of Guidance of the Search is considered present, but not of positive impact by for example Suurs' (2005) study on bio fuels. From this study appeared that the first scientific results had lead to many negative reactions and created negative expectations. This result can be generalized, because often the first experiments with renewable energy technology show unattractive outcomes such as high costs and complex needs for adapted infrastructures. Despite the guiding activities that stimulate the take off of the system, the fulfilment is not yet considered of a high level in the first phase, because no general enthusiasm for the emerging technology exists in the basic and applied science phase and early negative expectations may cause delayed progress of the technology.

Summary and hypothesis:

Because of the high importance of Guidance of the Search for continuity of progress of the innovation systems and the acceleration of development of other functions, this function could be appointed values for high fulfilment in all phases and especially the transitions to the next phase. However, this function is regarded of medium importance in the basic and applied science phase, because early results of research into a new renewable energy technology may lead to negative expectations and therefore decreased guiding activities. The transition to the demonstration phase is however only possible when expectations are high enough to mobilize sufficient resources to do demonstration projects and therefore the fulfilment of Guidance of the Search is considered high in this transition. It is expected that Guidance of the Search stays on a continuous high level as the technology improves. After all: the better the technology gets, the better the expectations are and thus the better this function is fulfilled.

H4: fulfilment of the function Guidance of the Search for the creation of a successful technological innovation system is of a medium level in the basic and applied science phase and rises to high fulfilment in the transition to the demonstration phase. It stays on a high level during all phases and transitions.

F5: Market Formation

The comparative study of Hekkert and Negro (2009: 22) concluded, "*Market Formation proved to be in most cases the final trigger that leads to innovation system growth. Very often it is one of the last functions to be addressed, after which the build up of the system really accelerates.*" This conclusion for biomass technologies is in line with the emergence of the wind energy system in California (Alkemade *et al.*, 2007). Also the study on cogeneration concluded that Market Formation is not necessary in the first phases but needs to be in place, before commercialization and up scaling can take place (Hekkert *et al*, 2007a). In this case Market Formation was indeed fulfilled as the last function, but this did not seem to hamper the previous innovation process negatively. Negro *et al.* (2008: 67) explain the dynamics of the innovation system of biomass gasification leading towards the fulfilment of Market Formations as follows: "*several established actors in the Dutch energy system express their serious interest in this technology, which results in an advocacy coalition (F7). This, in turn leads to a* mobilisation *of resources (F6) and more research to reduce the initial technical and economic uncertainties (F2). The entire initiative can be regarded as the creation of a niche market for gasification technology (F5).*" This can be exemplary for the dynamics of comparable technologies.

In his study about motors of change Suurs (2009) finds that Market Formation becomes important with the start of the System Building Motor: this motor starts in the pre commercial phase and includes the last remaining inactive function, being Market Formation.

Summary and hypothesis:

The take off for Market Formation is set at the transition to the pre commercial phase. The case studies and the System Building Motor point out that the pre commercial phase can only begin when Market Formation measures are realized. This establishment of Market Formation activity could typically happen during the transition to the pre commercial phase. Market Formation is established after the demonstration phase has delivered successful technological progress and the policy measures may stimulate the take off of commercial activities. Its transition from low to high fulfilment emphasizes this crucial role during the transition. According to the theory on motors of change, Market Formation stays of high fulfilment in the consecutive phases.

H5: fulfilment of the function Market Formation for the creation of a successful technological innovation system is of a low level from the basic and applied science phase up to the demonstration phase. During the second transition it changes to high fulfilment and remains at this high level.

F6: Resource Mobilisation

According to Hekkert and Negro (2009) for bio fuels, finances from government agencies for research and development were rather easily mobilized, while the government was reluctant to invest financial resources for demonstration projects and full-scale installations. The function Knowledge Development has profited from these relatively easy mobilized resources in the earliest life cycle phases, but Entrepreneurial Activity and Market Formation could only profit in later phases and to a lesser extent.
Also in the case of wind energy in California government agencies allocated financial resources to public research laboratories and large established manufacturers (Alkemade *et al*., 2007). Moreover, in California the companies themselves also invested various resources.
The case of cogeneration proved that availability of public subsidies is necessary for the innovation system to grow: "*… in 1982 the investment subsidy WIR-ET was increased. After its evaluation in 1987 it turned out that this subsidy had been decisive in the realization of projects*" (Hekkert *et al*., 2007a).
In the case of biomass digestion not many financial resources were available during the basic and applied science phase, which was appointed as one of the main reasons why the innovation system did not develop successfully. The researchers claim therefore that financial Resource Mobilisation is an essential function to be fulfilled in the first phases (Negro *et al*., 2007). Also Suurs (2009) confirms that Resource Mobilisation from the earliest phase onwards has to be in place to successful progress towards the next phase.

Financial resources do not only include public resources, but also private investments such as venture capital. The availability of venture capital differs among regions, and for example in the United States venture capital investments in general are higher than in Europe. When more venture capital and private investments are in place for technology development (in relation to public investment) a technology has larger chances for success (Hekkert and Negro, 2009). Venture capital and public resources are also of crucial importance to avoid 'the valley of death'.
The phenomenon occurs when high tech start-ups have to evolve from the R&D phase to the commercialization phase (named 'take-off phase' by several authors). According to Meijer (2008) entrepreneurs face the following problems during this 'take-off phase': "*uncertainty about governmental policy, the* mobilisation *of financial resources, the reliability of suppliers, the development of a market, and so on*". In general, public subsidies and private investments are relatively easy to obtain in the earliest phase of the start-up. However, when consecutive financial resources are needed (e.g. after three years) to develop further, for example to perform more in depth R&D or to build high tech machines, these resources are very hard to obtain. It is therefore of crucial importance, that also during the demonstration and pre commercial phase abundant financial resources for renewable energy technology (i.e. high tech technologies) are available (Meijer, 2008).
The comparative study of biomass technologies concludes that in The Netherlands "*the political will to sustain the investments for Market Formation was often unstable. This led to the earlier described*

shifts in guidance and Market Formation." (Hekkert and Negro, 2009: 23). It is therefore further hypothesized that in order to keep Market Formation going, according resource mobilisation is necessary.

Summary and hypothesis:

Case studies have shown that Resource Mobilisation during the basic and applied science phase can be of a relatively low level, because the kind of research that precedes the demonstration projects is relatively cheap. However, to enter and pass the demonstration phase much more financial resources are needed, because continuous experimentation with new technology is expensive. To enter the pre commercial phase also financial resources for Market Formation policy such as investment subsidies is needed. Although during later phases the investments of venture capitalists and firms for R&D may rise, the desired financial resources for continuous growth are needed for Market Formation policy.

H6: fulfilment of the function Resource Mobilisation for the creation of a successful technological innovation system is of a relative medium level in the basic and applied science phase, but of a high level from the transition to the demonstration phase on.

F7: Lobby Activity and Creation of Legitimacy

Lobby activities (also named 'advocacy coalitions') are considered important for the establishment of a successful renewable energy innovation system. However, in the earliest phases it "*proved difficult in most emerging Technological Innovation Systems to form advocacy coalitions with enough strength to align the existing institutional conditions to their needs. We observed that the actors in an emerging innovation system do not easily pack together to form a tight network with a clear and strong standpoint."* (Hekkert and Negro, 2009: 23). Therefore the formation of lobbies that represent a wide variety of actors with a 'clear and strong standpoint' is crucial to strengthen guidance and the development of the innovation system.

For several cases – wind energy in California (Alkemade *et al*. 2007), biomass gasification (Negro *et al*., 2008), twice for biomass digestion (Negro *et al*., 2007) and cogeneration (Hekkert *et al*., 2007b) – the dynamics of functions showed that a growth in the presence of entrepreneurship resulted in a growth of lobby activities. This assumes that lobby activities co-evolve with entrepreneurship in successful innovation dynamics.

Of the four motors between functions that are distinguished by Suurs (2009), two motors do not include this function: these are the Science and Technology Push motor in the basic and applied science phase and the Market Motor in the supported commercial phase and later. In the beginning of the life cycle very little lobbying efforts took place, because the system emerged based on research activities. In the latter phases the lobby groups have done their efforts to reach an attractive supportive infrastructure where in the industry can grow freely.

Summary and hypothesis:

In the basic and applied science phase the number of actors in the innovation system is too small to establish a substantial lobby movement and Entrepreneurial Activity is also too small to gather enough entrepreneurs to form a strong lobby. When more players enter the innovation system during the demonstration phase and an entrepreneurial motor takes place Lobby Activity and Creation of Legitimacy is growing. An important goal of these lobby groups is to establish favourable market conditions and it is hypothesized that a relative high level of activity of this function takes place previous to the implementation of these Market Formation activities. Since Market Formation is established and implemented during the transition to the pre commercial phase, this function is highly fulfilled then. When the Market Formation policy gets settled and proves successful the activity of lobby activities decreases and according to the Market motor it plays only a limited role during the supported commercial phase.

The hypothesis is thus formulated as follows:

H7: fulfilment of the function lobbying activities for the creation of a successful technological innovation system is of a relative low level during in the basic and applied phase and the transition to the demonstration phase. During the demonstration phase this function grows with an average medium level. During the transition to the pre commercial phase it is highly fulfilled and stays so during the pre commercial phase. In the transition to the supported commercial phase it decreases to a medium level and further down to a low level in the supported commercial phase.

2.4 Conceptual model

The hypotheses formulated in the previous subsection are summarized in the conceptual model as shown in Table 1. This conceptual model will be tested by three additional case studies. The method for this is explained in the next chapter.

Table 1 Conceptual model

	Basic and applied science	Transition 1	Demonstration	Transition 2	Pre commercial	Transition 3	Supported commercial
F1: Entrepreneurial activity	Low	Low	Medium	Medium	High	High	High
F2: Knowledge development	High	High	High	High	High	High	High
F3: Knowledge diffusion	Low	Low	Medium	Medium	High	High	High
F4: Guidance of the search	Medium	High	High	High	High	High	High
F5: Market formation	Low	Low	Low	High	High	High	High
F6: Resources mobilization	Medium	High	High	High	High	High	High
F7: Creation of legitimacy and lobby activities	Low	Low	Medium	High	High	Medium	Low

3. Method

Now that the hypotheses are formulated based on existing literature, this study will examine to what extent the hypotheses can be confirmed. This will be done by the analysis of three case studies. The case study selection is explained in section 3.1.
Each case will be studied by three analyses that together give broad input to understand the dynamics of innovation system functions and to formulate values of fulfilment for each function per life cycle phase. Section 3.2 elaborates on the methods for these case study analyses.
Finally the outcomes of the three cases are compared with each other and with the hypothesis, upon which conclusions on similarity of dynamics of emerging innovation systems can be drawn. The methods for this final analysis are explained in section 3.3.

3.1 Case study selection

The three case studies are chosen such that they represent three different technologies, in three different countries in different phases of commercial maturity. By choosing this variance in characteristics of the units of analysis, foundations for differences in dynamics are created. Particular attention will be given to the dynamics of functions that are characteristic for each phase the technology has gone through.
Wind power in Denmark and Photovoltaic power in Germany are chosen as two relatively mature technologies. They are still in the supported commercial phase, because they rely on a supportive financial and institutional infrastructure in order to be purchased. These two technologies are considered relatively mature, because except for hydropower[2] they are the most widely spread and oldest technology. These two case studies give insight about how a renewable technology develops through all phases of commercial maturity and therefore they give an overview of the dynamics of the functions based on much historical data and on many phases. Since these two cases are regarded as successful technologies the dynamics of the functions are representative for successful innovation system building dynamics. These two cases therefore serve as exemplary cases for success and the lessons learned from these cases can be used for the development of innovation systems for other technologies. Eventual mistakes or barriers that occurred in these two cases may be avoided for newer technologies.

Besides two relatively mature and successful case studies, tidal power in the United Kingdom is chosen as a case that gives more insight in the earliest processes and dynamics of a renewable technology. Wind and photovoltaic power emerged in and before the 1970s and this is already too early to be able to accurately reproduce the dynamics of all functions.
Although the earliest signs of tidal power research date back to the 1970s and some earlier, the development of this technology has become visible in society only recently. The dynamics between the 1970s and its first demonstration projects in 2003 are revealing, because now some conclusions may be drawn that indicate crucial success factors for entering the demonstration phase.
This case study will only focus on the dynamics in the basic and applied science phase and the transition to the demonstration phase, while the other two cases give insights about dynamics over the whole life cycle and its phase transitions.

3.2 Case study analysis

Each case study will be examined in three different ways of data gathering, which will result in the formation of values of fulfilment per phase and transition. Fulfilment of a function is expressed in levels of low, medium or high fulfilment. The values of fulfilment are based on the outcomes of three analyses per case study:

[2] Hydropower is not chosen as a case study, because it was developed in the beginning of the 20th century, which is too early to be able to measure and explain the dynamics of the functions. Also this technology did not explicitly develop through the phases of commercial maturity, because it was within a few years already a commercially mature technology.

1. *Historical and technological background study.* The first part of each case study analysis consists of a background study into the technology itself and the history of the development of the technology. This analysis will be conducted via literature research.
2. *Historical activity analysis.* The second part can be regarded as the quantitative part. Each function is operationalised into indicators which together (in the case of multiple indicators per function) result in values of fulfilment per year. For each function a graph is constructed that shows the activity trend of each function. The seven graphs are standardised into a 0-1 scale so that they can be depicted in one graph so that the relations between the activity of functions become clear. In this final graph the boundaries for low, medium and high fulfilment and the life cycle phases are also depicted. In section 3.2.1 the operationalisation of functions is explained. It is the goal of this historical activity study to find general patterns of dynamics and not to perfectly map the activity of the indicators per year.
3. *Qualitative analysis on the importance for success of functions.* For the two most mature case studies – i.e. photovoltaics and wind power – a qualitative analysis on the importance of certain functions to the successful development of the technology is conducted. For photovoltaic power in Germany this was done by interviewing twelve experts[3] and for wind power in Denmark this was done by a discussion with dr. Kamp[4] from Delft Technical University. For tidal power it is not yet possible to determine success factors because the technology is considered too immature. Instead a qualitative interpretation of the historical activity analysis is given, which aims at explaining the crucial success factors of the transition to the demonstration phase.

The combination of these three studies covers a broad knowledge base of information on the dynamics of functions for each case study. Quantitative data are combined with qualitative insights about the historic context and the opinions of field experts, which results for each case study on a historic narrative that explains the role of functions during the development through the life cycle.

Both the historic activity analysis and the qualitative study on importance of functions result in values in terms of low, medium or high activity respectively importance. For each case study finally values of fulfilment for each function for each life cycle phase and transition are composed. This is done with guidance of Table 2.

Table 2 Composition of the final fulfilment value for a life cycle phase

		Importance		
		Low	**Medium**	**High**
Activity	**Low**	Low	Low / Medium	Medium
	Medium	Low / Medium	Medium	Medium / High
	High	Medium	Medium / High	High

Table 2 shows that for example when the historical activity analysis points at high activity of a function for one phase, but when the qualitative analysis shows low importance of a function, the final fulfilment value medium is appointed. This table forms the guideline for the fulfilment values. However, when the background study or the qualitative study on the importance of functions gives substantial argumentation for a choice otherwise, that other conclusion will be drawn. Especially for those cases where Table 2 shows two options, the insights obtained from the historical background study or other sources will guide the choice for a final value of fulfilment of a function.

[3] Technopolis Group The Netherlands has given me the opportunity to join their research activities and to combine interviews with twelve German experts in photovoltaics. These were employees of research institutes, firms and governmental organizations. This expert group created a wide knowledge base on the historic developments of the German photovoltaics industry. These experts were asked to give an historic overview of development of the photovoltaics industry and to appoint the major success factors of the German photovoltaic industry, in other words what the main drivers for the successful industry nowadays were and are.

4 Dr. Linda Kamp has experience with the functions approach of technological innovation systems and expertise on the innovation systems of wind power industries of Denmark and The Netherlands. In cooperation with her for each function the importance of it to the success of the Danish wind power industry was determined and the take off phases of the functions were determined.

3.2.1 Operationalisation of functions for the historical activity analysis and the method to calculate final values per phase

This subsection explains the operationalisation of the seven functions to conduct the historical activity analysis and how these outcomes are transferred into values of low, medium or high activity.

For each function one or more indicators represent the activity of that function over time. They are selected based on whether they can generate historical data; preferably back to the 1970s, because in this period the earliest signs of development of renewable energy technology were visible. Secondly the indicators were chosen as free and easy accessible data. This implies in most cases that the data were freely accessible on the World Wide Web. Thirdly, the indicators had to be representative to the function definitions set in section 2.1.

F1: Entrepreneurial Activity

This function is measured in two dimensions: the first represents the industry size by calculating the cumulative number of start-ups. For two case studies there was proof of a shakeout in the number of firms in the industry and for the year in which the shakeout started the cumulative number of start-ups is divided by two. No information was available for all case studies that could tell about the exact number of firms of the industry for each year and thus this indicator serves as an indicator of a trend, not of valid absolute values for industry size, but that is no problem for the purpose of this study. It is all about the trends over time, not about absolute and valid figures.

The second indicator represents the construction and installation of the technology. For tidal power too few full-scale installations are in place, so that demonstration projects had to serve as an indicator for the number of installations. This is not considered a problem, because the definition set for this function emphasises the importance of experiments to analyze this function.
For photovoltaics is explicitly chosen for installed area of modules and not for installed capacity in MW. This second indicator would cause a more exponential trend, because the efficiency of modules has increased significantly recently. When the area of installed modules is used, every module is treated equally and thus attention to demonstration projects and experimentation is higher then when installed capacity was used as indicator.
For wind power the same argumentation is used not to choose for installed capacity in MW, but for the number of installed wind turbines per year.

Table 3 Operationalisation of Entrepreneurial Activity for the historic activity analysis

Dimension	Indicator	Case studies
Industry size	Cumulative number of firm start-ups in the industry per year	Tidal, Photovoltaics, Wind
	When an industrial shakeout is evident, the cumulative number of startups is devided by 2 for one year representative for the shakeout	Photovoltaics, Wind
Experimentation	Number of demonstration projects starting per year	Tidal
Installations	Area of PV modules in square meters installed per year in the country from national production	Photovoltaics
	Number of installed wind turbines per year	Wind

The choice for installed capacity has the disadvantage that it is also an output indicator and therefore would represent the total innovation system success instead of the support of one function to the overall system. Yet, this indicator is chosen because it gives additional information on the output of entrepreneurs, because industry size does not reflect the impact of the industry. Installed capacity can thus be seen as a correcting indicator for the lack of impact indication in the industry size indicator. After all, the more installations are placed, the more entrepreneurs are active and the more firm experimentation takes place overall.

F2: Knowledge Development

Knowledge Development is mainly focused on national R&D activity. Only for photovoltaics the European component is used, because for solar energy substantial European budgets are available since Framework Programme 5, from 1999 on. Many German firms were included in many FP5 and FP6 projects and therefore European budgets have substantially contributed to national Knowledge Development. For tidal power very few European budgets were available for R&D and only few firms from the United Kingdom participated in these projects. Also for wind energy the influence of European R&D budgets was limited, but this is mainly because the European budgets were introduced when the most important research was already conducted and the industry was close to the dominant design of wind turbines.

For national Knowledge Development an important indicator is the budgets spent on R&D programmes and projects in the technology. This is considered an input indicator for Knowledge Development. The output indicators for Knowledge Development are publications in academic journals and patents. The publications per year are appointed to the year before, because publication procedures take time and the knowledge is assumed to be developed about one year previous to the publication. For patents a time lag of four years is used. The European Patent Office stated as follows: "*The European patent grant procedure lasts about three to five years from when the application is filed. It breaks down into two main stages. The first comprises formalities examination, search report preparation and the drafting of an opinion whether the application and the invention to which it relates seem to meet the requirements of the EPC. The second comprises substantive examination.*" (EPO, 2008)

Table 4 Operationalisation Knowledge Development for the historic activity analysis

Dimension	Indicator	Case studies
National R&D activity	Number of publications in academic journals by national organisations per year, minus one year	Tidal, Photovoltaics, Wind
	Number of publications per year by the two largest national research institutes for wind power R&D	Wind
	Number of patents registered in the European Patent Office per year, minus four years	Photovoltaics
	Total national budget per year	Photovoltaics, Wind
European R&D activity	Number of participating organisations in Framework Programme funded R&D per year	Photovoltaics

F3: Knowledge Diffusion

For Knowledge Diffusion it is not easy to measure historical activity. An important aspect of this function is Knowledge Diffusion through networks, but no databases exist that could map this in general, neither for one technology specifically. One indicator that is useful for this is the number of participants in the European Framework Programme (FP) projects on the specific technology. It is a guideline for the FP subsidies that participants of several countries are included and that a variety of types of research organizations is involved. The more participants take place in the technology specific FP projects per year, the more knowledge is transferred internationally and between fundamental, basic and applied research organizations. Especially the transfer to R&D departments of firms is fruitful for the acceleration of the emerging innovation system, which is emphasized in FP6 since 2003.
Another indicator for Knowledge Diffusion is knowledge transfer via scientific conferences. Although publications in journals also serve the goal of knowledge transfer, the conference papers even more have this goal. Also, on conferences the overall goal is to spread knowledge that is useful for science and the industry to develop the technology further. Also, on conferences many networking activities take place that may result in future cooperation between organizations. The activity on conferences can best be measures by the number of conference papers published on the technology per year. Then one does not have to look for the conferences and their importance, because the number of papers per

year also indicates whether a conference took place and how large this was. Only conference papers by organization from within the case studies national boundaries are chosen, because only then the Knowledge Diffusion in addition to the growth of the technology specific innovation system is analyzed.
For tidal power a lack of data on national conference papers was found to observe the dynamics based on a substantial amount of conference papers. For this case study also the presence of the most important conferences is taken into account, because this conference serves as both an important source of information as a place to make new contacts, so that also for this case study the function could be mapped properly.

Table 5 Operationalisation Knowledge Diffusion for the historic activity analysis

Dimension	Indicator	Case studies
Knowledge diffused on conferences	Number of conference papers published written by national organisations	Tidal, Photovoltaics, Wind
	Number of conference papers published from the two largest national research institutes	Wind
Knowledge gained from conferences	The presence of an influencial conference in a specific year (yes or no)	Tidal
	Number of conference papers internationally per year	Photovoltaics
Diffusion via cooperative research projects	Number of participating organisations in Framework Programme funded R&D per year	Photovoltaics, Wind

F4: Guidance of the Search

To measure this function two dimensions are chosen: the first is public awareness of the presence of the technology, which represents the expectations in society. This is measured as the media attention to the technology. The more attention the media gives to the technology, the more the general public creates expectations and possibly enthusiasm for acceptance and application of the technology. In other studies a distinction was made between positive and negative expectations. It is chosen not to do so for this study, because the three case studies do not include natural reasons for opposition. Also in studying the background information of the case studies no important reasons were found to include negative expectations to measure public awareness.
The second dimension is political awareness and enthusiasm for the technology. Guidance of the Search can only follow from political awareness of the technology. The more politicians are in favour of sustainability or renewables the larger the chances are for successful policy for guidance of the technology. The position of the Green Party is considered a valid input indicator for political willingness and power to provide guidance. It is assumed that an increase in the impact value of the Green Party, will lead to an increase in output of political guidance, such as renewable energy white papers, goals and policy making (Market Formation). The countries of the three case studies have very different outcomes for political guidance for renewable energy, varying from only two seats of the Green Party in the parliament since a few years (United Kingdom), to no formal green party at all (Denmark) to a green party that has been in office for eight years (Germany). For this large spread of influence of green parties, for each case study values are appointed to represent the political awareness relatively as explained in Table X and in the case study results.

Table 6 Operationalisation Guidance of the Search for the historic activity analysis[5]

Dimension	Indicator	Case studies
Public awareness *(expectations)*	Number of articles that discusses the technology in a selection of news papers per year	Tidal, Photovoltaics, Wind
Political awareness (*power and willingness to give guidance*)	A value to represent the number of seats of the Green Party in the national parliament	Tidal
	0.5 points for the presence of Green Party members in the national parliament	Photovoltaics
	1 point for the presence of the Green Party in the national office (cabinet)	Photovoltaics
	A value of maximum 0.5 for the percentage of the votes of elections for the most green party	Wind

F5: Market Formation

For this function several policy instruments are available to fulfil this function. In general, the more incentives for demand are available, the better this function is fulfilled. However, it depends on the state of the technology and the possibilities of governance which incentives are introduced or replaced. The assumption is made that attractive investment subsidies and attractive feed-in tariffs for the specific technology are the most favourable incentives. Therefore the highest values for these two incentives are given 0.5 points for the years they are the most attractive. Theoretically a function may score 1 point (very high fulfilment, see the next subsection) when both are in place at the same moment. In practice this has not happened, because these are two incentives that typically are too expensive to score high attractiveness in the same year. All other values for these two incentives are expressed as a value proportional to the highest value. Other incentives are given scores that are never higher then 0.5 and considered representative for the attractiveness of that incentive for the creation of demand for the specific technology.

Table 7 Operationalisation Market Formation for the historic activity analysis

Dimension	Indicator	Case studies
Presence of tradable certificates for renewables	A value to represent the attractiveness of this instrument	Tidal
Presence of funds for demonstration projects	A value to represent the attractiveness of this instrument	Tidal
Presence of investment subsidies	A value to represent the height of the investment subsidy	Photovoltaics, Wind
Presence of feed-in tariffs	A value to represent the height of the feed-in tariff	Photovoltaics, Wind
Accessibility to cooperatives	The residency criterion in kilometers	Wind
	The consumption criterion in kWh	Wind
Public procurement	Number of MW that energy companies are obliged to install as an average per year	Wind

5 The final value of this function is composed two dimensions with equal weight to the final value. For political guidance 1 point is attributed to the most favourable situation, namely a Green Party in the government. Otherwise, maximum 0.5 points are given to the best years where the Green Party was not in the office. The appendices of the case studies elaborate on the specific considerations and outcomes for this function.

F6: Resource Mobilisation

For this function complete consensus is in place for the measurement of all three case studies. Although this function in other studies also includes human resources and physical resources, for these three case studies those aspects were not considered useful. The physical resources do not play a role because sunlight, wind and tidal streams are abundant and do not need any processing or transportation before they are used by the energy generating technology. For example for nuclear energy or biomass physical resources would play a role, but not for these technologies. Human resources can be regarded important, but their development is not measured for two reasons: first, because human resources are also considered in the functions Knowledge Development and Knowledge Diffusion (although only qualitatively) and overlap could exist; and second, because information on the availability and mobility of human capital is hard to find. A lot of efforts and time would be needed to calculate data on the quantity and / or quality of human capital per case study per year and for this there was not enough time.
Financial resources are measured in the same way for all case studies with the only difference in the currency in which the total expenditures on research, development and demonstration will be expressed (GBP, DKK and Euros). Unfortunately no information was found on the costs of most of the Market Formation incentives. Ideally these costs would also be considered for this function, but the dynamics of Market Formation will be taken into account in the analysis of this function.

Table 8 Operationalisation Resource Mobilisation for the historic activity analysis

Dimension	Indicator	Case studies
Total financial resources allocated to RD&D	The financial budgets related to programmes, appointed to the year before that programme starts	Tidal, Photovoltaics, Wind

F7: Lobby Activity and Creation of Legitimacy

This function exists of two components. The first is the presence of lobby activities. This is measured in the same way for all case studies: each active lobby group of a considerable size gets 0.1 points. These lobby groups can lobby for favourable circumstances for renewables in general of for the specific technology. As long as they are considered to have an impact on the development of the technology they are awarded the points.
The second concept is the creation of legitimacy by events that create enthusiasm for alternative energy sources to overcome the dependence on fossil fuels. The most important events are assumed to be the oil crises of 1973 and 1979 after which more enthusiasm for independency of energy was created. Also, since nuclear energy was a serious alternative to fossil fuels in the 1960s and 1970s and thereby hampered the development of renewable energy sources, the Chernobyl disaster in 1986 is also considered to create legitimacy.

Table 9 Operationalisation of Lobby Activity and Creation of Legitimacy for the historic activity analysis

Dimension	Indicator	Case studies
Events that create legitimacy	0.5 points for the oil crises in 1973 and 1979	Tidal, Photovoltaics, Wind
	0.5 points for the Chernobyl disaster in 1986	Tidal, Photovoltaics, Wind
Activity of lobby groups	0.1 point for each substantial lobby group for renewables in general or supranational lobby group for the specific technology, for each year the organisation exists	Tidal, Photovoltaics, Wind
	0.1 point for each technology specific lobby group, for each year the organisation exists	Photovoltaics, Wind
	0.5 points for evident strong lobbies for the years that lobbying had place	Wind

Calculation of the final values per phase for each function

Now the annual data for the historical activity analysis will be transferred into values of low, medium or high activity per life cycle phase. This process consists of two steps.

1. *Calculating the values of activity per year*

For those functions where multiple indicators are used, these indicators will be combined into a final value per year via standardisation to a 0-1 scale. First, each single indicator is transferred into values on the 0-1 scale. This standardization process takes the highest value of the indicator to be of value 1 and all other values are expressed relative to that on the 0-1 scale. For example: when the highest value of publications would be 200 in the year 2002, the year 2002 is appointed the value 1, and for example the 50 publications in 1990 are appointed the value 0.25 for that year.
Then, when all single indicators are expressed on the 0-1 scale, the indicators have to be transferred into one final value per function. First the average value of the indicators is calculated per year. For example, when for the year 2002 one indicator has the value 1 and another the value 0.8, the average would be 0.9. Then these average values again have to be transferred into the full 0-1 scale. A second standardization is conducted so that the final value of all functions has dynamics that vary between 0 activity and full, thus 1, activity. The advantage of this is that all functions can be plotted into one graph, because the units and boundaries are equal; and the three case studies can be compared more effectively.

2. *Transfer of the values per year into activity values per phase and transition*

Now that for all functions for all years the activity value is calculated, the values for activity per phase are constructed. First the seven graphs are plotted into one graph. The historical background study had already resulted in the determination of life cycle phases and transition years for phases, which are depicted into the graph with the seven functions. Also, the boundaries for low, medium and high activity are depicted in the graph. These are set as follows: activity between 0 and 0.3 is regarded 'low activity', activity between 0.3 and 0.7 is considered 'medium activity' and activity between 0.7 and 1 is considered 'high activity'. Now for each phase and transition year, the average activity is studied and the level of activity in terms of low, medium or high activity is determined. For tidal power an exception is made, because it is considered too immature to have reached high levels of activity yet. Here activity between 0 and 0.5 is considered 'low activity' and activity between 0.5 and 1 'high activity'.

3.3 Comparing the hypotheses and case studies

Now that each case study has resulted in conclusions on the fulfilment of each function per life cycle phase and transition, the case studies will be compared with each other and the hypothesis.

In the analysis chapter the results of the three case studies and the hypothesis are depicted in a table. Now the similarities and differences between the hypothesis and the case studies are clearly visible. These differences will be described and explained qualitatively. These insights result in the construction of a general trend of dynamics per function and conclusions on how the dynamics of the seven functions relate to each other. For these conclusions on interaction and dynamics the boundaries of low, medium and high fulfilment as such are neglected and a more qualitative interpretation is given.
The combined insights from the case studies and the hypothetic framework will result in a comprehensive model of function dynamics, where fulfilment represents the activity and importance of impact of each function. This model finally results in policy recommendations based on the importance of the function during phases and during transitions to the next phase.

4. Tidal power in the United Kingdom

This chapter elaborates on the outcomes of the first case study. Background information on this technology is presented in Appendix I, including the main types of tidal energy devices. Section 4.1 shows the results of the historical activity analysis per function. For each function an Appendix is constructed that presents detailed information on the inputs for these results. Section 4.2 is a storyline of tidal power development in the United Kingdom where the influence of functions is explained and the functions are related to explain this history. Section 4.3 combines the insights of the historical activity analysis and the historic background study on the importance of functions, which results in a final table of function fulfilment for the basic and applied science phase and the transition to the demonstration phase in 2003.

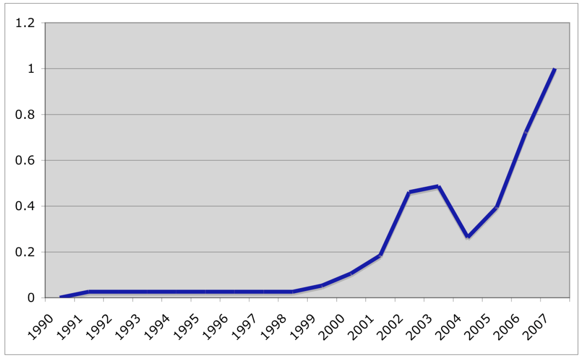
4.1 Results of the historical activity analysis of tidal power in the UK

In this section for each of the functions the results of the historical activity analysis are given. For each function an Appendix gives information on the input data for the final values per year. The final graph of function dynamics is depicted per subsection and some background information is given when this was considered crucial or interesting to understand the function dynamics.

4.1.1 Entrepreneurial Activity

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix II. Figure 2 shows the outcomes of the historic activity analysis for tidal power. The development over time is expressed on the 0-1 scale, where the highest point in time represents the year with the most activity for this function so far.

Figure 2 Development of Entrepreneurial Activity of tidal power in the UK[6]



A successful example of a full-scale demonstration project is the SeaGen, a project that has started in 2003 and which aimed to supply 1000 households in Strangford Lough in Northern Ireland with their electricity (SDC, 2008). Figures 3a and 3b show the SeaGen.

[6] For this report is chosen to draw a graph with a line when more than one indicator forms the input for the trend line. This better represents the trend, rather than the quantitative amounts. For functions where one indicator represents the function's dynamics, a histogram is depicted, which represents single amounts.

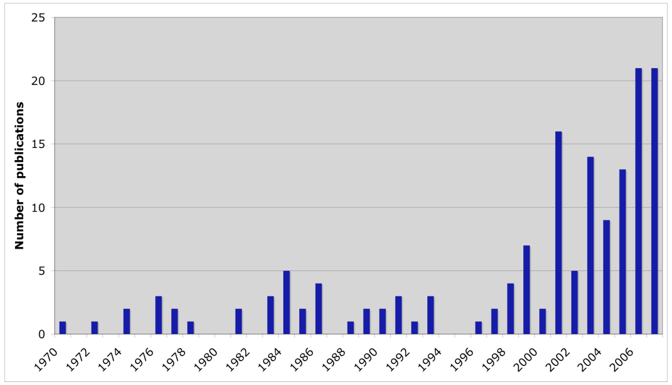
Figure 3a and 3b The SeaGen as positioned in Northern Ireland

Sources: Marine Current Turbines, 2009

4.1.2 Knowledge Development

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix III. Figure 4 shows the outcomes of the historic activity analysis for tidal power.

Figure 4 Development of Knowledge Development

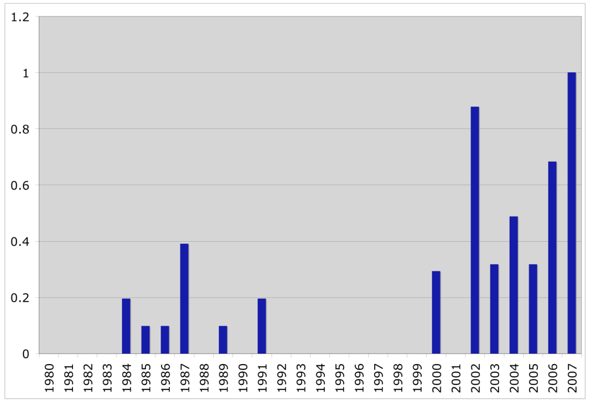


As you can see Knowledge Development has started already in the 1970s before the first oil crisis. The number of publications generally increased over time and since 2001 the number of publications was much higher. This can be explained by large financial Resource Mobilisation for tidal power in 2000, see section 4.1.6.

4.1.3 Knowledge Diffusion

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix IV. Figure 5 shows the outcomes of the historic activity analysis for tidal power.

Figure 5 Development of Knowledge Diffusion in tidal power in the UK



Now that the number of publications for these functions is found, it is interesting to compare the results and rank some research institutes that appear of large importance to knowledge creation and transfer in the UK. Table 10 is created based upon Appendix III and IV concerning the most important research institutes and the number of publications on tidal power or tidal energy as found in Scopus.

Table 10 Main UK research institutes in tidal power and their number of publications

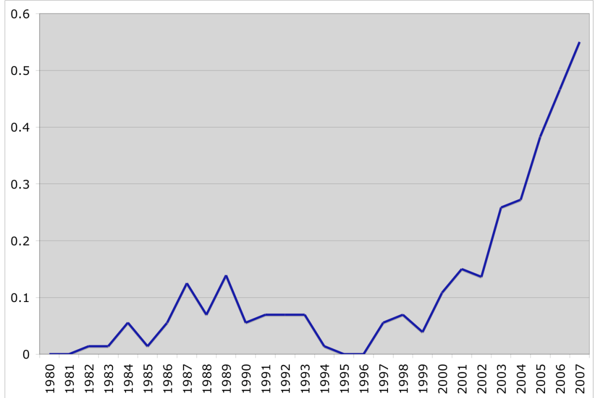
Research institute	Publications in total	Conference papers	Other articles
University of Edinburgh	12	12	0
University of Wales Bangor	12	12	0
Robert Gordon University	11	0	11
University of Southampton	10	0	10
University of Bristol	8	0	8
Bedford Institute of Oceanography	7	0	7
University of Durham	7	0	7
University of Strathclyde	6	0	6
National Oceanography Centre Southampton	5	0	5
Plymouth Marine Laboratory	5	0	5
University of Glasgow	5	0	5
University of Plymouth	5	0	5
Engineering Business Limited	5	5	0
Queen's University Belfast	5	5	0
University of Hull	5	5	0

As you can see, the two main institutions that spread knowledge via conferences are the University of Edinburgh and the University of Wales Bangor. The main writers of articles in journals and other publications - but this number is mainly build up of journal publications - are Robert Gordon University (in Aberdeen) and the University of Southampton. One firm is represented in this Top 15, which is Engineering Business Limited from Newcastle.

4.1.4 Guidance of the Search

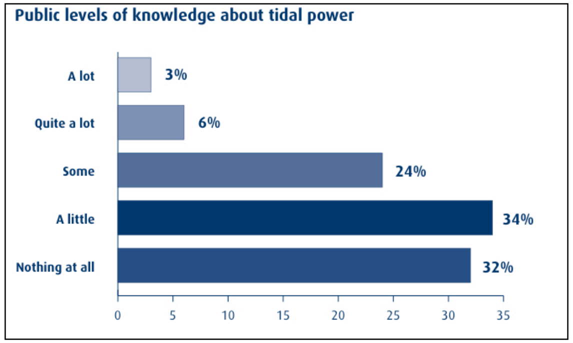
The data sources, input data and calculations of the indicators for this function are elaborated in Appendix V. Figure 6 shows the outcomes of the historic activity analysis for tidal power.

Figure 6 Development of Guidance of the Search for tidal power in the UK



A nice illustration to the public awareness of the possibilities of tidal power is the outcomes of a survey the Sustainable Development Committee of Scotland. As you can see in Figure 7 66% of the general public knows a little or nothing at all about tidal power (SDC, 2008). Only 9% knows a lot about it. Although the data on media attention show a large increase since 2003, apparently 66% of the public did not get the message. If this lack of awareness is representative for renewables in general, it may explain the lack of members of the Green Party in the national parliament.

Figure 7 Public levels of knowledge about tidal power



Source: SDC, 2008: 10

Although the general public does not seem aware of the possibilities of tidal power, there are clear political statements on the value of tidal power for electricity generation. The Energy White Paper of

2007, written by the Department of Business, Enterprise and Regulatory Reform, formulates the political statements on tidal power. This text is shown in Box 1.

Box 1 UK governmental view on marine energy developments in the UK

> Wave and tidal-stream energy technologies have the potential to make a significant contribution towards our energy and climate change objectives. There are currently a number of concepts at various phases of development with a small number of devices having already been demonstrated at full-scale.
> Since 1999, the Government has through the DTI, Research Councils and the Carbon Trust programmes committed in excess of £100 million funding to support RD&D of marine technologies. This includes support for new infrastructure such as the European Marine Energy Centre in Orkney, which provides dedicated testing facilities for marine energy technologies and the proposed "Wave hub" in the South West which could host a number of wave power projects.
> The launch of the £50 million Marine Renewables Deployment Fund (MRDF) and a similar scheme funded by the Scottish Executive has also stimulated the interest of major power companies in the sector. The MRDF moved to an "open call" basis in March 2007, so that the MRDF can fund proposals at any time. The UK has in place the most comprehensive set of support measures for the development of wave and tidal-stream in the world. Even so, progress towards full commercialization of these technologies has been slower than expected. The Government is working closely with the Renewables Advisory Board and others to drive forward progress in this sector.
> The UK is a founder member of the International Energy Agency's Ocean Energy Systems (OES) Implementing Agreement. OES brings together the leading global players in marine energy to work on commercialization issues that need to be addressed at a global level such as standards, testing and resource assessments. *Source: Energy White Paper, 2007*

4.1.5 Market Formation

Literature research showed that the United Kingdom uses two major policy instruments to stimulate Market Formation for renewable energy, which therefore also benefits the tidal power innovation system: the Renewables Obligation since 2002 and the Marine Renewables Deployment Fund (MRDF) since 2006. The first instrument is of an obligatory nature: all electricity suppliers are obliged to invest in renewable energy; otherwise they pay a fine. The second instrument offers capital grants and revenue support to those organizations that do RD&D in marine energy. Its specific focus is on demonstration projects. In Box 2 the Renewables Obligation is explained in more detail. Box 3 explains the MRDF in more detail. Appendix VI explains how these two programmes are transferred into values for the comparative study.

Box 2 The Renewables Obligation

> The Renewables Obligation is the British Government's main policy instrument for supporting renewable energy. The mechanism requires licensed electricity suppliers to source a specific and annually increasing percentage of the electricity they supply from renewable sources, effectively guaranteeing a market for the renewables which are less cost competitive compared to conventional generation.
> The Obligation is enforced by an Order (Statutory Instrument) made under the terms of the Utilities Act 2000, introduced in April 2002. The Obligation requires suppliers to source an annually increasing percentage of their sales from renewables. For each MWh of renewable energy generated, a tradable certificate called a Renewables Obligation Certificate (ROC) is issued. Suppliers can meet their obligation by either acquiring ROCs or paying a buy-out price of GBP 30/MWh, or a combination of the two. When a supplier chooses to pay the buy-out price, the money it pays is put into the buy-out fund. At the end of the 12-month Obligation period, the buy-out fund is recycled to ROC holders.
> The current target is 5.5% for 2005/06, rising to 15.4% by 2015/16. It is expected that the Obligation will help to provide support to industry of GBP 1 billion per year by 2010. Ocean wave and tidal current technologies are eligible under the scheme. *Source: AEA, 2006: 36*

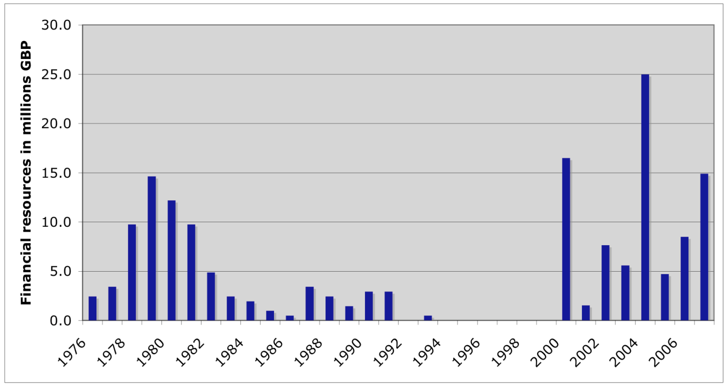
Box 3 The Marine Renewables Deployment Fund

> In 2006 the DTI launched the Marine Renewables Deployment Fund (MRDF). The total amount of funding allocated under this scheme is up to GBP 50 million. The scheme will fund the gap between R&D and pre-commercial deployment on wave and tidal current technology in UK marine areas.
> The aim is to encourage the development of a sustainable UK wave and tidal current industry, and to maximize the successful development of cost-effective marine technologies in the long term. This will be achieved by enabling the early phase pre-commercial operation and sea trials of a number of wave and tidal current energy technologies. [...]
> The MRDF will provide GBP 42 million to fund the Wave and Tidal Stream Energy Demonstration Scheme. The scheme will support the deployment of multiple, full-scale wave or tidal stream electricity generating devices connected to the UK grid. It will do this through a combination of capital grants (25% of eligible costs) and revenue support (GBP 0.1/kWh in place for a maximum of seven years from commissioning). In addition to this, projects are entitled to receive the market value of the electricity and Renewables Obligation Certificates that they generate.
> To ensure that the benefits of the scheme are available to a number of different technologies, the total funding received by any project under the scheme will be subject to a cap of GBP 9 million. The costs of grid connection are eligible for inclusion in project costs. The MRDF will also set aside some funding for the 'infrastructure' required for the scheme and targeted research to better understand the resource. *Source: AEA, 2006: 38*

4.1.6 Resource Mobilisation

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix VII. Figure 8 shows the outcomes of the historic activity analysis for tidal power.

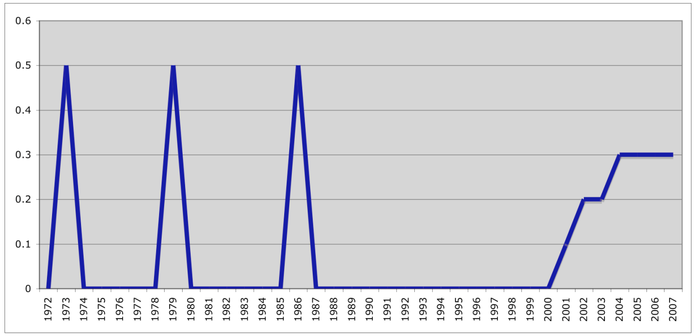
Figure 8 Development of Resource Mobilisation for tidal power in the UK



4.1.7 Lobby Activity and Creation of Legitimacy

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix IX. Figure 9 shows the outcomes of the historic activity analysis for tidal power.

Figure 9 Development of Lobby Activity and Creation of Legitimacy for tidal power

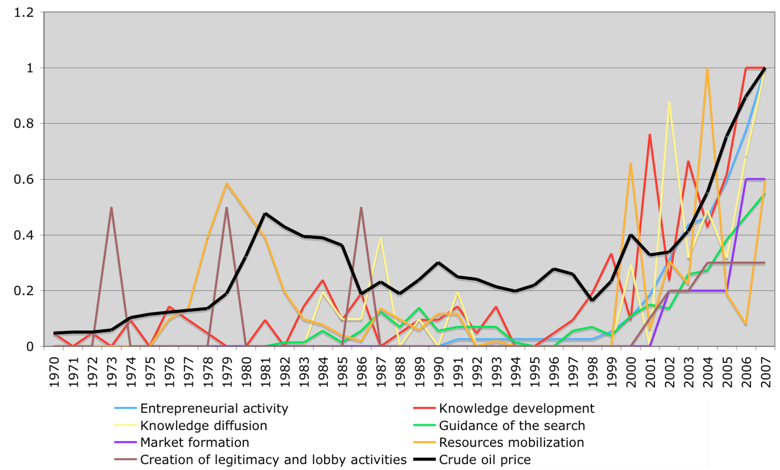


4.2 A storyline of tidal power development in the United Kingdom and the role of functions in the emerging innovation system

Tidal power is in development since the 1960s, when the first publications on tidal power devices were found. Although Knowledge Development is taking place for decades, it has taken a long time to enter the demonstration phase.
Many functions have been visible since the 1970s, as appeared from the historic activity analysis, but some more than other. **Knowledge Development** and **Knowledge Diffusion** were visible mainly in the 1980s, but activity almost disappeared in the 1990s. Then, at the end of the 1990s it increased again.
Creation of legitimacy was achieved by the oil crisis of 1973 and 1979, which resulted in **Resource Mobilisation** at the end of the 1970s and beginning of the 1980s, which resulted again in Knowledge Development and diffusion. Also for guidance there were some early signs of media attention to tidal power in the 1980s. Not only in the UK, but Europe-wide and also in the United States interest was given to alternative energy sources after high oil price increases. The dependency of whole economies on fossil fuels and the political instability of the oil exporting countries in relation to the Western countries made European countries and the US aware that for long term and independent energy supply they had to invest in renewable energy.

Figure 10 depicts the oil price as a standardised value into the dynamics of the seven functions (EIA, 2009). It can be seen that there is similarity in the dynamics of the oil price and the activity of the various functions. Although it could seem as only a little price increase in 1973, in fact the price had doubled from US$ 3.89 in 1973 to US$ 6.78 in 1974 (EIA, 2009). When the oil price rose even further the years after 1974, the United Kingdom mobilized resources for tidal power in the period 1978-1980. The oil price continued to rise and had its highest prices in the years 1980-1985. It could be a reasonable explanation to state that the oil crisis of 1973 triggered **Resource Mobilisation** and that the increasing and stable high oil price **legitimized** this policy measure.

Figure 10 Function dynamics for tidal power and the crude oil price dynamics



Thereby also the protests against nuclear energy in the 1970s, the publications of Limits to Growth of the Club of Rome (Meadows *et al.*, 1972), activism against globalisation and for eco-friendly consumption may also have triggered interest in renewables and thus tidal power in the UK. However, tidal power was at those days in its very early phases of technological development and before any electricity could be obtained of these devices, much research and testing was still to be done. It is thus logical that in the 1980s the functions of **Knowledge Development** and **Knowledge Diffusion** are active, albeit not very much compared to the situation nowadays.

This positive trend was broken in the beginning of the 1990s when all functions had decreasing activity. This downturn can again be explained by the oil prices dynamics. In 1985 the price for crude oil went steeply down – this was from an average of US$ 24.09 in 1985 to an average of US$ 12.51 in 1986 (EIA, 2009) – and during the end of the 1980s and most of the 1990s the oil price stayed at a stable relatively low level. It could be assumed that the continuously low oil price in this decade (1986-1998) explains the decreasing interest in tidal power, or renewable energy in general. In the beginning activity was still continued, but when the oil was on a low level for several years the industry and policy makers may have lost interest in investing in renewable energy sources. It seems that the function **Creation of legitimacy** was active, but in a **negative** way for tidal power, because legitimacy for renewables was lacking during the attractive oil price decade.

The crude oil price started to rise again in 1999. This would be the start of what is sometimes called the '2000s energy crisis': an increasing crude oil price for at least 8 years[7]. The rising oil price since 1999, apparently combined with expectations that this price would not be decreasing to its old level, can have triggered policy makers to start investing again in renewable energy. The continuously increasing oil price since 2000 has similar dynamics to the increasing activity in several functions. These dynamics are especially similar for the functions **Entrepreneurial Activity**, **Guidance of the Search** and **Market Formation**.
The resources mobilised in 2000 – 16 million GBP for the establishment of the European Marine Energy Centre (EMEC) in Corkney – can be an important trigger for the growth of other functions. The budget for the testing of wave and tidal devices could have triggered both research institutes and

[7] At the moment of writing it is known that the oil price would have peaked mid 2008 with an average price of US$ 94.04 for 2008 (but a peak price of 145 US$) (EIA, 2009).

private organisations to start developing (components for) tidal power devices. The fact that **Resource Mobilisation** can be a good starter for the development of a growth period, also appeared from the first temporary growth period. Then, the amount of 27 million GBP also started Knowledge Development, Knowledge Diffusion and some guidance.

To determine the transition from the basic and applied science phase to the demonstration phase, information on the start of activities of demonstration projects is crucial. According to the definitions for the phases of commercial maturity as explained in the method section, the demonstration phase includes both testing on partial and full scale of the devices. Since tidal devices can be very large and expensive this testing with partial scale devices has much activity, before full scale devices are tested. The demonstration projects in the United Kingdom as identified by the AEA (2006) had the following corresponding starting dates:

- Full-scale projects at sea: the Seagen (April 2008), Seaflow (May 2003)
- Partial scale projects at sea: HydroVenturi (November 2005) and TidEL (unknown)
- Partial scale projects in tanks: contra-rotating marine current turbines (unknown) and Lunar Rotech tidal turbines (2003 and in the near future full-scale testing)

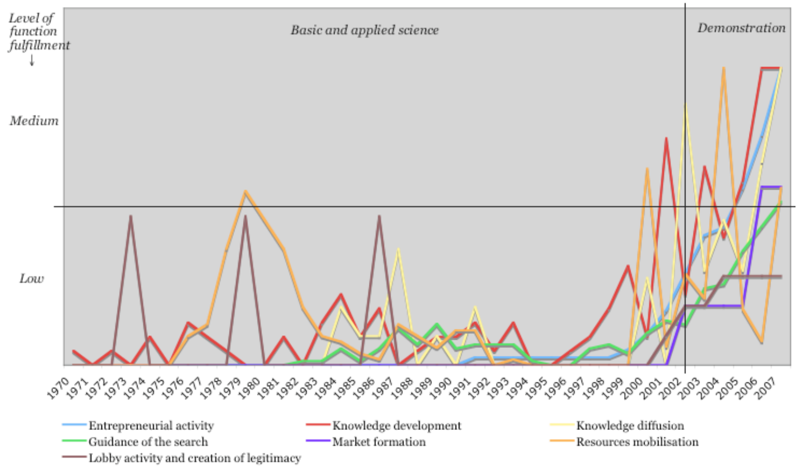
Since the EMEC was officially opened in 2003 and in that same year the first two demonstration projects took place, the demonstration phase is determined to have started in 2003.

Two important programmes for **Market Formation** played a role in the transition to the demonstration phase. These were the Renewables Obligation in the United Kingdom in 2000, which supports all renewable energy technologies and the Marine Renewables Deployment Fund, which mobilised GBP 50 million in 2006. These two measures can have served as a very important stimulation for growth of the tidal power industry. The growth of the renewable sector and tidal power specifically also created more awareness among the general public. Simultaneously, the Green Party is slowly gaining votes so that public enthusiasm can be translated into political action. **Guidance of the Search** is thus slowly taking off these days.
Another function that is becoming more active is **Lobby activity**. Examples of this can be read in subsection 4.1.7 and Appendix XIII. When lobby activity for renewables in the United Kingdom is compared to the other two case studies, it appears that this takes off relatively late.
For now it seems that tidal power has just entered its demonstration phase and much maturing of the technology has to take place before pre commercial activities will start.

4.3 Formulating values of fulfilment for the early life cycle phases of tidal power in the United Kingdom

In Figure 11 the dynamics as they appeared in the historical data analysis are combined into one graph. As explained in section 3.2 it is assumed that the function can only perform on a low or medium level of activity for this case study. Therefore the graph is split in only two levels of fulfilment on the vertical axis. On the horizontal axis the years are plotted and the transition from the basic and applied science phase to the demonstration phase in 2003.

Figure 11 Dynamics of the seven functions of tidal power in the United Kingdom as found in the historical activity analysis



These insights are combined with the insights from the historical background study. This implies that when certain functions are considered highly fulfilled from the qualitative study, a value of high fulfilment can be appointed for a function for a certain phase, although the historical activity analysis may indicate not so. The combined insights on both historical activity and the role of functions in during the life cycle phases and transitions has resulted in Table 11, which represents values for fulfilment of the function for this case study.

Table 11 Model of innovation system dynamics for tidal power in the United Kingdom

Tidal power in the UK	Basic and applied science	Transition 1	Demonstration
Entrepreneurial activity	**Low**	**Low**	**Medium**
Knowledge development	**Medium**	**Medium**	**Medium**
Knowledge diffusion	**Low**	**Low**	**Medium**
Guidance of the search	**Low**	**Low**	**Low**
Market formation	**Low**	**Medium**	**Medium**
Resources mobilization	**Medium**	**High**	**High**
Lobby activity and creation of legitimacy	**High**	**Medium**	**Medium**

5. Photovoltaic power in Germany

In this chapter the results of the case study on photovoltaic (PV) power in Germany are presented. In Appendix IX background information on photovoltaic power is given, including the benefits of PV and the main types of applications. Section 5.1 presents the results of the historical activity analysis and the qualitative analysis on the importance of functions. Section 5.2 is a storyline of PV development in Germany where the role of the functions for the development through the life cycle is emphasized. Also the interactions between the functions are explained. In section 5.3 the insights of the three analyses are combined and fulfilment values for each function for each phase are presented.

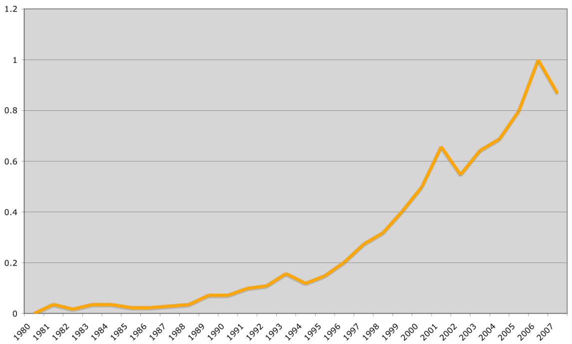
5.1 Results of the historical activity analysis and the expert interviews

In this section for each case study the results of the historical activity analysis are presented. Also the results of the qualitative analysis on the importance of functions for the success of PV in Germany as mentioned in the twelve expert interviews are given. The answers of the experts and the transfer of these answers into a value of importance for the functions are given in Appendix X.

5.1.1 Entrepreneurial Activity

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XI. Figure 13 shows the outcomes of the historic activity analysis for photovoltaic power.

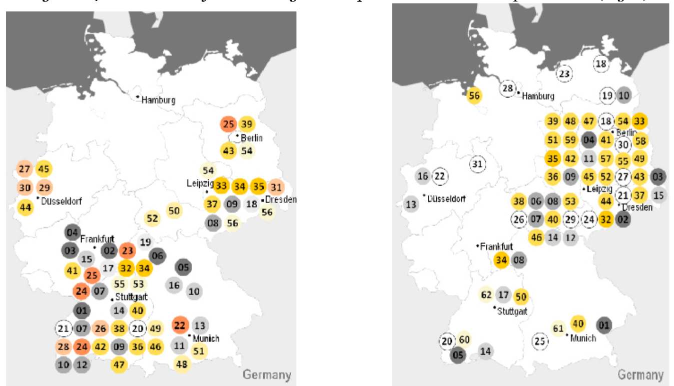
Figure 12 Development of Entrepreneurial Activity for PV in Germany



In Figures 14a and 14b the locations of the 56 equipment manufacturers is depicted and in Figure X the positions of the 62 producers of components and modules. You can see that these firms are concentrated in certain areas, which may provide benefits of networking. Expert M (2009) from Würth Solar explained in an interview that the reason for this is that in former East Germany a firm gets 50% investment cost subsidy for a start-up to stimulate employment in this region. That is why in recent years so many production lines have been established in East Germany. The reason that equipment manufacturers are mostly located in the land Baden-Württemberg (the South-West region) is for a number of reasons: the most important research institutes such as the Fraunhofer Institute and the Zentrum für Sonnenenergie- und Wasserstoffforschung (ZSW) are located here, which have produced various spin-offs. Also, this region is for many decennia strong in industrial processes and has a large highly skilled population establishing industrial services (Expert M, 2009; Expert K & Expert L, 2009).

Figure 13a Locations of the 56 largest equipment manufacturers (left)

Figure 14b Locations of the 62 largest component and module producers (right)



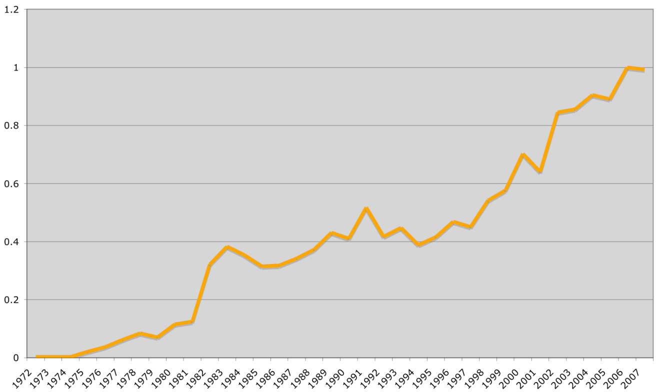
Sources: Invest in Germany, 2008a and 2008b

Since no expert mentions an important role of entrepreneurs or Entrepreneurial Activity, this function is valued of *low* importance to the success of PV in Germany.

5.1.2 Knowledge Development

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XII. Figure 15 shows the outcomes of the historic activity analysis for photovoltaic power.

Figure 14 Knowledge Development of photovoltaics in Germany



From the face-to-face interviews in Germany for the qualitative part of the study, much insight was obtained in the research structure in Germany. Some observations were the following.

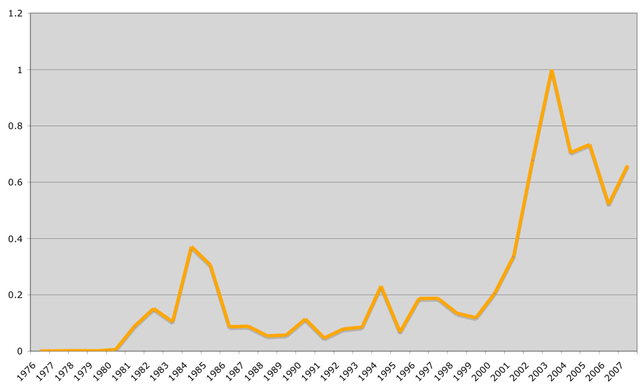
- German research institutes have clear differences in the place of their research activities in terms of the fundamentalness of applicability of the knowledge production to industrial processes. The universities traditionally serve as the most fundamental research organizations. For example the universities of Karlsruhe and Frankfurt have produced useful fundamental knowledge to the PV sector in the early years. An institution as the ZSW has the main goal to transfer knowledge from university into basic research activities and forms as a knowledge transfer organization (Expert K, 2009). This knowledge (not seldom in the tacit form by mobilisation of human capital) is transferred to more basic science institutes such as Forschungszentrum Julich and the Max Planck Institute. In a later phase more application driven research institutes continue the research activities. An important player here is the Fraunhofer Institute which obtains 50% of its sales from research for industry. The time to market of knowledge produced by Fraunhofer is often between 3-5 years (Expert I, 2009). At last, there is a group of firms with a strong R&D department who have research activities that provide outcomes with a clear application drive and a time to market of 1-3 years. Organisation D (Expert D, 2009) and Company H (Expert H, 2009) are typical examples of successful firms with a strong high tech knowledge base based on internal R&D and cooperation with research institutes for research activities with a long-term perspective for implementation.
- Germany has had a continuous funding structure for PV research since the end of the 1970s. As will become apparent in the qualitative study, this long term and continuous investment in knowledge production was one of the key success factors for the German PV industry.
- Germany has always been a strong industrial player worldwide. The economist Michael Porter (1990) explained this by their strong education system, including the typical Fachhochschule, where students are educated in technology with a clear applicability in mind and a close connection to industry by for example school projects at industrial firms and internships. Also the level of academic was valued high by Porter and with a close connection to industrial application.

This function is valued as a *very important* success factor by the experts. The decennia long build-up of knowledge has provided Germany with the strongest knowledge base worldwide on PV.

5.1.3 Knowledge Diffusion

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XIII. Figure 16 shows the outcomes of the historic activity analysis for photovoltaic power.

Figure 15 Knowledge Diffusion of PV in Germany



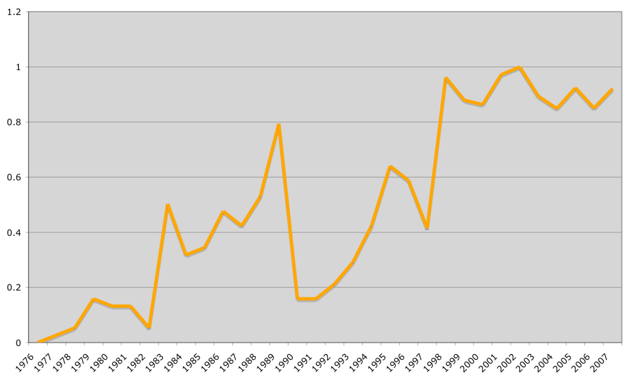
From the previous two functions' analyses, it has become clear that Knowledge Diffusion takes place via various ways. From the entrepreneurial study appeared that the firms are located in geographical clusters. This may encourage Knowledge Diffusion by mobilisation of human resources and close research cooperation activities.
From our interviews with Expert M (2009), Expert K & Expert L (2009) and Expert I (2009) it became clear that much mobilisation of human capital takes place. However, mostly this mobilisation is one-way traffic, because often employees from universities as Karlsruhe and research institutes as ZSW and Fraunhofer move to the private sector, and not the other way around. However, strong connections between the various organizations in the network stay intact. Würth Solar is an illustrative example of this: it was established by a former ZSW manager and still ZSW conducts various research projects for Würth Solar (Expert M, 2009; Expert K, 2009).
Another way of Knowledge Diffusion is via journal articles and conferences. However, this value is considered low by various interviewees. For example Expert H (2009) explained that conferences are mainly meant for networking and the establishment of new relations for research cooperation, but seldom new knowledge is gathered on such a conference. He says that when an organization is looking for specific knowledge they would directly approach a research institute in that field and they would not wait until that knowledge would become publicly available. The firms in need of specific new knowledge would harm their competitive position when they only look for new knowledge on conferences and do not behave actively ahead of their competitors (Expert H, 2009).

Although Knowledge Diffusion is not acknowledged by many experts as a key success factor, the reasoning of the cross fertilization between sectors is considered strong. The German industrial system was already for many decennia in place and indirectly contributed to easy Knowledge Diffusion between sectors and therefore successful Knowledge Development. Since it is not on itself a key success factor, but indeed a significant contributor to the technological innovation system, it is valued of *medium* importance.

5.1.4 Guidance of the Search

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XIV. Figure 17 shows the outcomes of the historic activity analysis for photovoltaic power.

Figure 16 Guidance of the Search for PV in Germany



The expectations expressed by the media are often the consequence of governmental politics and policy making. The party with the strongest 'green feelings' is Die Grünen in Germany. They started as an anti-nuclear group in the 1970s and became a federal political party with broader statements in

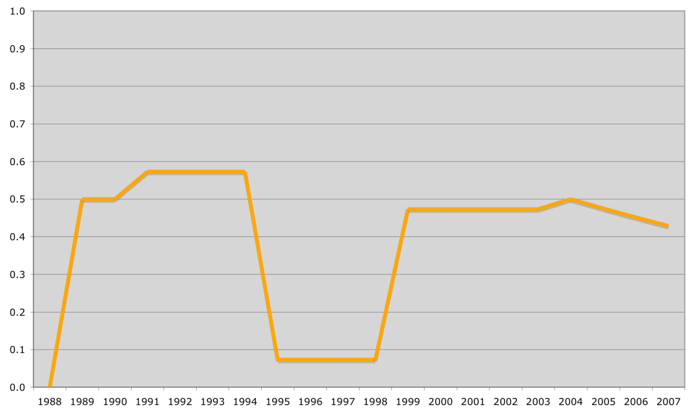
1983. In 1990 in the re-unified Germany they fell out of the parliament because they had to little votes. After the 1994 elections they could take place in the Bundestag again with 7.3% of the votes. In the 1998 elections they received 6.4% of the votes, but were chosen as a coalition partner by the Social Democrats. Their second term in coalition started in 2002 with 8.3% of the votes (Die Grünen, 2009). Together with the social democrats some policy was made in favour of renewable energy, such as the Erneurbare Energien Gesetz (EEG) since 2000 and its successful continuation in 2004 with the high feed-in tariffs. On these topics the next section on Market Formation elaborates more.
Die Grünen could not have been so successful in creating green policy without the support of the social democrats party (SDP). Herrmann Scheer was a SDP politician since the 1980s and had a strong enthusiasm for renewable energy. It was Scheer who was the driving force behind the 1,000 and the 100,000 roofs program. Also, together with the green party, he created the EEG. Some of our interviewees appointed many credits to him for his strong influence on progressive renewable energy policy (Expert A, 2009; Expert E, 2009).

Although the role of media expenditure to PV developments is not considered important for the growth of the industry by experts, guidance was still important from the dimension of government steering and public attitudes. Expert G (2009) and Expert B (2009) make a convincing statement for the importance of the role of the general public, politicians and civil servants. They claim that both consumers and politicians were very willing to help and invest in PV and thereby formed a strong and guiding actor. The importance of this function is therefore valued *high*.

5.1.5 Market Formation

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XV. Figure 18 shows the outcomes of the historic activity analysis for photovoltaic power.

Figure 17 Development of Market Formation for PV in Germany

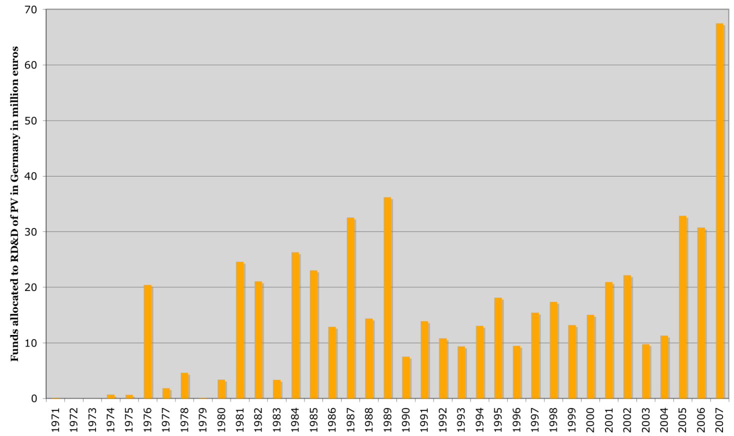


All experts acknowledge the considerable influence of the various policy instruments on the growth of the industry. This function is therefore valued of *high* importance. Its take-off is determined to be in *1989* with the start of the 1,000 roofs program.

5.1.6 Resource Mobilisation

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XVI. Figure 19 shows the outcomes of the historic activity analysis for photovoltaic power.

Figure 18 Development of Resource Mobilisation



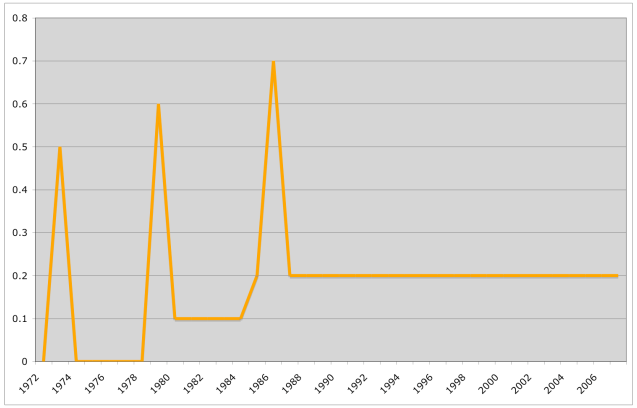
When these dynamics are compared to the Knowledge Development dynamics, it can be observed that Resource Mobilisation follows a less gradual pattern. It has several peaks in between years that almost no resources were allocated. An explanation for this becomes clear when the funds for the single projects are studies. It appears that the average value of funds of a research project is about 1.1 million Euros. However, the peaks can be very well explained by relatively large research funds for research of a relatively large period.
For example, the peak of 20.4 million Euros in 1976 is composed of two large-scale projects starting in 1977. Also the peak in 1981 can be explained by one very large project of 22 million Euros. The largest three projects were all lead by Heliotronic Forschungs- und Entwicklungsgesellschaft für Solarzellen-Grundstoffe GmbH. Other research institutes that gained significant amounts of funds were Forschungszentrum Jülich (in total 33 million Euros), Fraunhofer Institute at large (104 million Euros) of which the division for Solar Energy Systems got 88.6 million Euros. The largest firm was Organisation D with in total 60 million Euros, followed by Siemens with 28.1 million Euros.

The three experts acknowledge the impact of the federal research funds on Knowledge Development in the industry. These research funds were very important, because photovoltaic technology is a high tech sector and therefore research is expensive. The growth and success of the industry thus relies on a strong knowledge base, and the strong knowledge base relies on substantial investments in R&D by the federal government. Because of this direct relation of financial resources on a strong high tech sector, this function is valued as *high* importance.

5.1.7 Lobby Activity and Creation of Legitimacy

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XVII. Figure 20 shows the outcomes of the historic activity analysis for photovoltaic power.

Figure 19 Development of Lobby Activity and Creation of Legitimacy for PV



The experts do not consider this function important and also the historical activity analysis does not give any leads for substantial lobby activities or events the create legitimacy, except for the oil crises. The function is thus considered of *low* influence to the success of PV in Germany.

5.2 A storyline of photovoltaic development in Germany and the role of functions in the emerging innovation system

5.2.1 The basic and applied science phase

The history of photovoltaic energy goes back almost two centuries. In 1839 Edmond Becquerel discovered the photovoltaic effect. Some early inventors succeed in some projects with selenium as the conducting material. In 1904 Albert Einstein publishes about the photon-electric effect and then the working of these selenium constructions is understood better. In the beginning of the 20th century some more experimenting is done and efficiencies between 0,1% and 0,5% are reached. In 1941 professor Ohl from Bell Labs discovers that the photoelectric effect can also take place in silicon. The following year much experimenting with silicon is done by Bell Labs and in 1954 an efficiency of 6% is reached. In 1958 the Vanguard I was the first satellite to be power with solar cells with an efficiency of 12%, which would be the start of continuous solar cell production for space uses. Also in Germany the first organizations are established which produce solar cells for extra terrestrial use. Since about 1975 also thin film technologies were developed for cheaper solar cell production (ORGANISATION G, 2004).

Up to this moment in time the functions **Entrepreneurial Activity** and **Knowledge Development** are visible. For Entrepreneurial Activity mostly experimenting in professional laboratories took place, which resulted in commercialisation of the technology for space use. The knowledge that was created in these laboratories enabled the take off of more institutionalised knowledge production in research institutes and universities. However, in these days the knowledge was mainly produced on a very small scale and for space purposes.

The transition from an experimental and random kind of research towards a better organized and long-term tradition of research in Germany started after the first oil crisis in 1973. The Germans realized that their dependency on foreign fossil fuels could be harmful for their economy and that

solar energy was one of the options to be a more self-sustaining nation. By this oil crisis **creation of legitimacy** took place, which triggered the investment of federal research funds into photovoltaics in 1974 and a clear step was made towards application of the existing knowledge. **Resource Mobilisation** enabled the transition to the demonstration phase.

5.2.2 Transition to the demonstration phase: 1976

The transition from the basic and applied science phase to the demonstration phase is determined to be in 1976, because since this year the federal (financial) support to photovoltaic energy in Germany has lead to demonstration projects and commercial production driven research activities (Expert E, 2009). Also, in 1976 the production of amorphe silicon solar cells was started in the United States. The federal funds for PV research kept rising annually up to 1982, from whereon the funds stabilised to a value of 20-40 million euros per year. Experts consider this increasing and continuous **Resource Mobilisation** crucial for the successful demonstration phase (Expert A, 2009; Expert E, 2009; Expert D, 2009). It has created a stable and strong knowledge infrastructure along the spectrum of fundamental and applied research, varying from universities to firm R&D. Also, networks and clusters are formed for specific research topics such as thin film technology. The human capital is mobile, which creates strong and long-term relationships between the various organisations.

Some commercial and experimental **Entrepreneurial Activity** was visible in the 1970s and 1980s, but the technology was not advanced enough for commercial application in those days. Financial incentives for application were needed to increase commercial activity in the PV industry. These incentives were introduced in 1989 with the 1,000 roofs program: this scheme has supported rooftop applications of PV modules until 2003 with an investment subsidy of 70%.
An important driver for this programme was political enthusiasm. A few politicians of Die Grünen and the SPD with most dominantly SPDs Hermann Scheer persuaded the parliament to support the 1,000 roofs program, to enable acceleration to a large PV industry. A large industry would be good for employment and high tech export products in the future. Also media attention for the first rooftop systems that were placed via the 1,000 roofs program created national awareness and enthusiasm for the technology, which provided a basis for successful transition to the pre commercial phase.
The functions **Guidance of the Search, Resource Mobilisation** and **Market Formation** (in this order) were thus crucial for the successful transition to the pre commercial phase.

5.2.3 Transition to the pre commercial phase: 1990

The 1,000 roofs program increased activity of firms in the photovoltaic industry and thus **Entrepreneurial Activity** increased. Also, learning by using improved the designs of the solar cells and their efficiency rates yearly, which points at successful **Knowledge Development** and **Knowledge Diffusion**.

The 1,000 roofs program was stopped in 1993 and Germany was left with a feed-in tariff of 8 eurocents/ kWh. This program was called the Stromeinspeisungsgesetz and was not sufficient to create enough demand to support the industry and thus a shakeout of the number of firms took place. Räuber (2009) explains that Japanese firms profited from this market opportunity and the small demand after 1993 was mainly supplied by the Japanese. The pre commercial phase thus shows a downturn in fulfilment of the functions **Market Formation** and **Entrepreneurial Activity**.
Yet, this did not initiate the end of the PV industry. **Knowledge Development** went on focussing on more application based research and thus cheaper production methods and higher efficiencies of the cells. This resulted in more patents. Also, the function **Guidance of the Search** put pressure on the continuation of investments in PV, because Die Grünen were elected in the national parliament in 1998 and media attention to solar energy was higher than before. The combination of this political guidance, media attention and continued and application oriented knowledge production, resulted in continued interest in the production and installation of PV modules. A new incentive was however needed for higher growth.

With Die Grünen in the national office and the SPD still in favour of photovoltaics, this new incentive was started and renewed attractive **Market Formation** was achieved. It was the 100,000 roofs program in 1999 in combination with the feed-in tariffs that were already in place. The 100,000 roofs program provided attractive loans to consumers of PV modules.

5.3.4 Transition to the supported commercial phase: 2000

The 100,000 roofs program created demand for modules and as a result more **Entrepreneurial Activity** in the form of start-ups and more **Knowledge Development** especially by R&D departments of firms took place. Also media attention increased with mainly attention for the many installations of modules. With the start of the Fifth Framework Programme in 1999, the European Commission increased funding of PV research of European consortia of research institutions, thereby also creating both more **Knowledge Diffusion** and possibilities for foreign markets.

When the 100,000 roofs program ended in 2003, it was it 2004 succeeded by a feed-in tariff scheme called the Erneuerbare Energien Gesetz in which the existing relatively low feed-in tariffs were replaced with high feed-in tariffs. The feed-in tariff for an average PV module was 51.6 eurocents / kWh in 2004. The feed-in tariffs for all renewable energy generators are reduced with 5% each year. This program proved to be a solid base for demand of PV modules and the quality of **Market Formation** was sustained.
The German PV industry growth since 1999 was therefore continued. Experts consider this continuation of attractive policy as crucial for the success of the PV industry. It is also said that the German government made an effective switch from quantity stimulating policy of investments subsidies, towards quality improving policy with the feed-in tariffs: in the earlier phases of technological maturity high demand (quantity) is needed to learn by using and producing; however, when the technology matures policy should stimulate higher cost and energy efficiencies by a decreasing feed-in tariff. The decreasing feed-in tariff stimulates increasing module efficiencies because the customer chooses for the most profitable technology.

Since 2005 the Germans have passed the Japanese as the largest PV producing nation in the world (Expert H, 2009). Germany has also profited from foreign incentives for solar energy. Because of their strong knowledge base and intensive industrial networks they have a leading position that cannot easily be surpassed.
Up to today the commercial phase has not started, because the system still depends on the feed-in tariffs on renewable energy. The commercial phase could start when grid parity is reached.

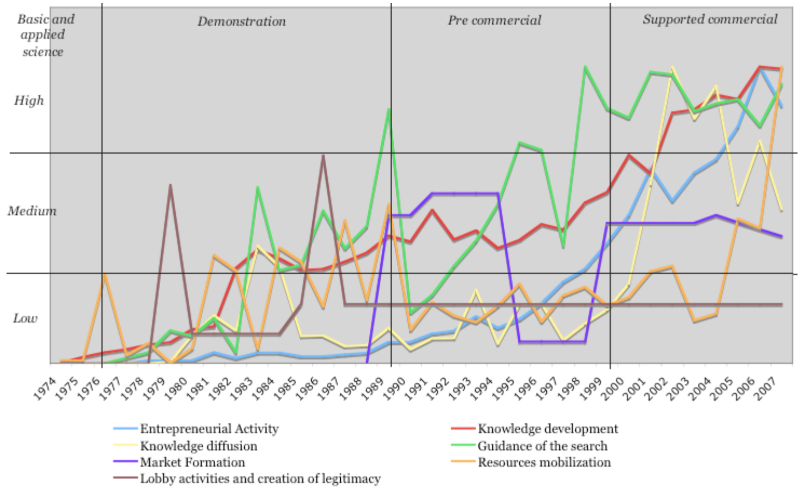
This historical storyline clearly appoints roles to functions in the development of the successful PV industry in Germany. However, experts also appoint some soft circumstances in Germany that have contributed to the acceleration of PV development. The following paragraphs elaborate on these circumstances that cannot straightforwardly be attributed to one or more functions.

- Some experts pointed out that Germans traditionally have enthusiasm for industrial processes and high tech production processes. Because the Germans have high wages, they have to compete with high quality production methods in the industrial sector. A strong automotive sector and large machinery and equipment suppliers are other examples of the strong position of Germany in various industrial sectors.
- A second explanation is the general consciousness of both the public and politicians for the ecology and environment. Germans are for many years involved in materials recycling and energy efficiency plays a large role in many sectors, such as the building and construction sector. This national eco-friendly behaviour has also made the take-off of renewable energy in general easier.
- Another benefit that has to do with this general energy awareness is that policy makers actively cooperate and make effective policy for renewables. Where in other countries the willingness among policy makers and politicians can slow down the take-off or make it completely fail, the German civil servants have good knowledge of the technology and can therefore make effective policy.

5.3 Formulating values of fulfilment for the photovoltaic power life cycle in Germany

In Figure 21 the dynamics as they appeared in the historical data analysis are combined into one graph. The graph is depicted with the life cycle phases on the x-axis. On the y-axis the level of fulfilment is shown, where the value Low represents the lowest 30% of activity, Medium represents the activity between 30% and 70% of the function's total activity and High represents the upper 30% of activity.

Figure 20 Dynamics of the seven functions of photovoltaic power in Germany as found in the historical activity analysis



The results of the qualitative analysis on the importance of functions for the success of PV in Germany were considered as follows: Entrepreneurial Activity: low; Knowledge Development: high; Knowledge Diffusion: medium; Guidance of the Search: high; Market Formation: high; Resource Mobilisation: high; Lobby Activity and Creation of Legitimacy: low.

The combined insights in historical activity, importance of functions for the success and historical insights on the role of functions during the various life cycle phases and transitions, have lead to the model of function fulfilment shown in Figure 22. Methods as explained in section 3.2 were used to determine these final values.

Figure 21 Model of innovation system dynamics for photovoltaic power in Germany

PV in Germany	Basic and applied science	Transition 1	Demon-stration	Transition 2	Pre commercial	Transition 3	Supported commercial
Entrepreneurial activity	Medium	Low	Low	Low	Medium	Medium	High
Knowledge development	Medium	Medium	High	High	High	High	High
Knowledge diffusion	Low	Low	Low	Low	Low	Low	Medium
Guidance of the search	Low	Low	Low	High	High	High	High
Market formation	Low	Low	Low	High	Medium	High	High
Resources mobilization	Low	Medium	Medium	High	High	High	High
Lobby activity and creation of legitimacy	Low	High	Low	Low	Low	Low	Low

6. Wind power in Denmark

In this chapter the results of the case study wind power in Denmark are given. In Appendix XVIII background information on wind power technology is given. The first section presents the results of the historical activity analysis and the qualitative study on the importance of functions. In section 6.2 a storyline of wind power development and the role of functions through the life cycle are given. Section 6.3 combines the insights of the analyses and concludes on the values of function fulfilment for each life cycle phase and transition.

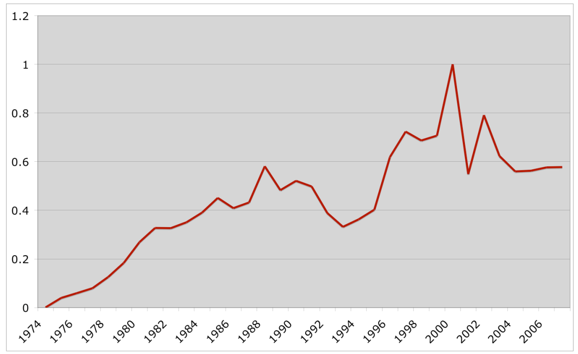
6.1 Results of historical activity analysis and the discussion on the importance of functions for the success of wind power in Denmark

In this section for each function the results of the historical activity analysis are given. Each subsection has an appendix where the data input and sources for the activity analysis and some background information is given. Also the results of the literature study and the discussion with Dr. Linda Kamp on the importance of each function is given in the appendix.

6.1.1 Entrepreneurial Activity

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XIX. Figure 23 shows the outcomes of the historic activity analysis for wind power.

Figure 22 Development of Entrepreneurial Activity for wind power in Denmark

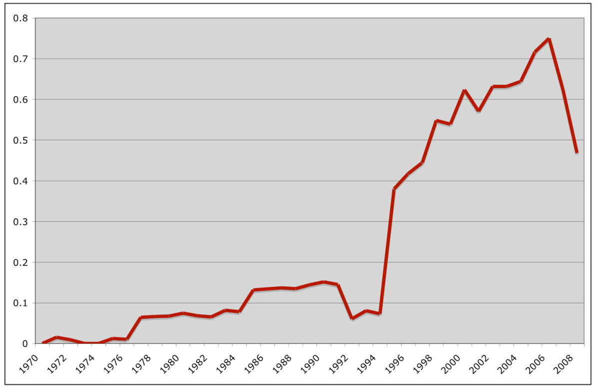


The results of the literature study and the discussion with Dr. Kamp into the importance of this function for the success of wind power are also expressed in the Appendix. The result of this analysis is that this function is of *medium* importance to the successful development of the wind power innovation system.

6.1.2 Knowledge Development

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XX. Figure 24 shows the outcomes of the historic activity analysis for wind power.

Figure 23 Knowledge Development of wind power in Denmark

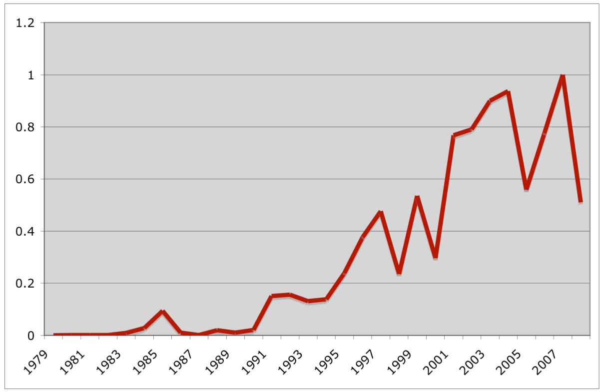


The results of the literature study and the discussion with Dr. Kamp into the importance of this function for the success of wind power are also expressed in the Appendix. The result of this analysis is that this function is of *high* importance to the successful development of the wind power innovation system.

6.1.3 Knowledge Diffusion

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XXI. Figure 25 shows the outcomes of the historic activity analysis for wind power.

Figure 24 Development of Knowledge Diffusion of wind power in Denmark



Although the conference paper data are good indicators for conferences, some additional study is conducted into wind power conferences. Not all peaks could be explained and this could be due to the lack of information on historic conferences on the World Wide Web.

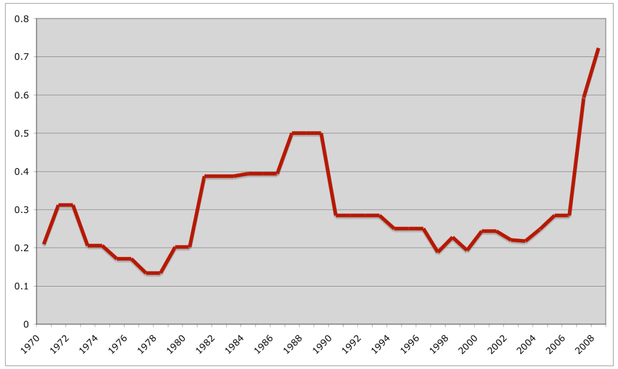
- The Nordic Wind Power Conference (NWPC). The first took place in Trondheim in 2000; the second in Gothenburg in 2004; the third in Espoo in 2006 and the fourth conference was at Risø in Copenhagen in 2007 (NWPC, 2009).
- The Risø International Energy Conference. In 2007 the third edition of this conference took place and the next one will be in 2009. The second conference was in 2005 and the first one in 2003 (Risø, 2009).
- The European Wind Energy Association Conference, also known as the European Union Wind Energy Conference and the European Wind Energy Conference. This is the annual conference organized by the European Wind Energy Association. The first of this series was started in 1993, as far as I could find. It is however likely that since the establishment of the EWEA in 1982 several conferences have taken place, although these could not be tracked down on the World Wide Web.
- The European Offshore Wind Energy Conference is also organized by EWEA and exists since 2005. This conference is biannual, so only two have taken place so far (EWEC, 2009).

The results of the literature study and the discussion with Dr. Kamp into the importance of this function for the success of wind power are also expressed in the Appendix. The result of this analysis is that this function is of *high* importance to the successful development of the wind power innovation system.

6.1.4 Guidance of the Search

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XXII. Figure 26 shows the outcomes of the historic activity analysis for wind power.

Figure 25 Development of Guidance of the Search for wind power in Denmark



Buen (2006: 3893) explains the importance of public and political guidance for the establishment of the technological innovation system as follows:

> *"The oil crisis in 1973-74 had made people understand the need for domestic energy production. Partly as a result of the strong anti-nuclear sentiment, a left-wing government came into office in the late 1970s. Unemployment was rising rapidly. This enabled the let-wing government to link wind power development to industrial development, employment and export revenues. This secured agreement across party lines in line with Denmark's consensus-based tradition. The second oil embargo in 1980-81 threatened Denmark's balance of payment due to its continued dependence on imported petroleum products, and created a benign climate for government intervention. Two increasingly strong industrial*

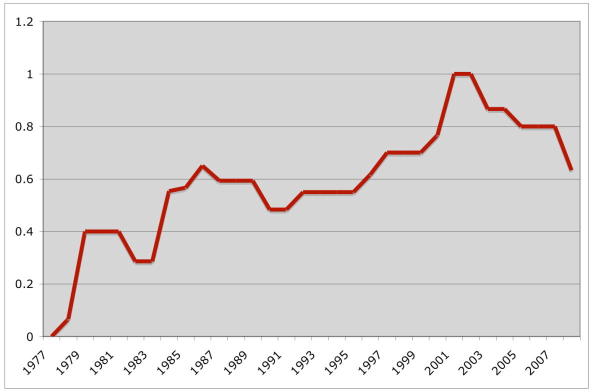
organizations, the Danish Wind Turbine Owners Association and the Danish Wind turbine Manufacturers Association, coordinated their lobbying efforts.
Policy instruments could not have been upheld and would not have had the effect on innovation, niche market commercialization and diffusion, had it not been for this conducive context."

The results of the literature study and the discussion with Dr. Kamp into the importance of this function for the success of wind power are also expressed in the Appendix. The result of this analysis is that this function is of *high* importance to the successful development of the wind power innovation system.

6.1.5 Market Formation

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XXIII. Figure 27 shows the outcomes of the historic activity analysis for wind power.

Figure 26 Development of Market Formation of wind power in Denmark

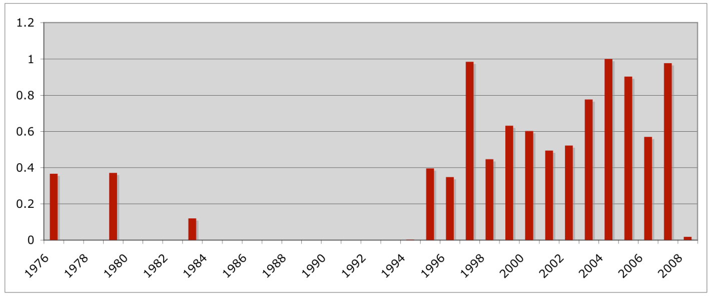


The results of the literature study and the discussion with Dr. Kamp into the importance of this function for the success of wind power are also expressed in the Appendix. The result of this analysis is that this function is of *high* importance to the successful development of the wind power innovation system.

6.1.6 Resource Mobilisation

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XXIV. Figure 28 shows the outcomes of the historic activity analysis for wind power.

Figure 27 Development of Resource Mobilisation of wind power in Denmark

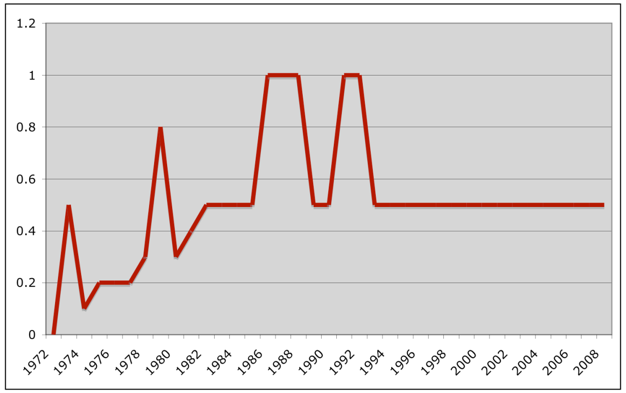


The results of the literature study and the discussion with Dr. Kamp into the importance of this function for the success of wind power are also expressed in the Appendix. The result of this analysis is that this function is of *medium* importance to the successful development of the wind power innovation system.

6.1.7 Lobby Activity and Creation of Legitimacy

The data sources, input data and calculations of the indicators for this function are elaborated in Appendix XXV. Figure 29 shows the outcomes of the historic activity analysis for wind power.

Figure 28 Development of Lobby Activity and Creation of Legitimacy of wind power



The results of the literature study and the discussion with Dr. Kamp into the importance of this function for the success of wind power are also expressed in the Appendix. The result of this analysis is that this function is of *medium* importance to the successful development of the wind power innovation system.

6.2 A storyline of wind power development in Denmark and the role of functions in the emerging innovation system

6.2.1 The basic and applied science phase

For centuries and worldwide there have been windmills of the so-called Dutch type for the milling of grain for flour. These traditional windmills were used for agricultural activities and the pumping for storing of water. In 1931 there were about 30,000 of these in Denmark (Tranæs, 1996). The first engineer to start experimenting with the use of windmills for the production of electricity was Poul la Cour, a Danish high school teacher, in 1891. La Cour was a versatile scientist who combined mechanics and electronics with aerodynamics and craftsmanship to produce the "klaOrganisation Ejler" in 1903 (Heymann, 1998). Since there was no electricity grid and batteries, he used electrolysis to produce oxygen and hydrogen, which were used for lighting in the school and some nearby houses.
In the following decades and especially during the First and Second World War this technology was improved and connected to a local electricity grid. La Cour also got government grants, which resulted in the design of some two, three and four blade windmills and various battery technologies (Kamp, 2002). During the Second World War another scientist, Smith, designed the more advanced Aeromotor of which he sold 60 pieces of about 70 kW.

A third important scientist was Johannes Juul, who received considerable support from SEAS (an electronics firm) and the Association of Danish Utility for research and development of wind turbines. He built a wind tunnel in which he could test his new blade designs, which resulted in a first prototype turbine of 15 kW in 1949 which was in AC and could therefore be connected to the electricity grid of SEAS (Gipe, 1995). Juul also took the initiative to build the 100 kW Gedser and later improved this to a 200 kW wind turbine. These projects were funded with 300,000 DKK from the Marshall Plan and assisted by SEAS engineers (Kamp, 2002). The turbine was shut in 1967 because its output electricity price was twice the market price.

In the 1970s Christian Riisager, a carpenter, started to build wind turbines and after some experimenting, his company had sold about 50 wind turbines of about 22 kW up to 1978 to mostly private customers. Besides the Riisager turbine, the Tvind turbine, built by the Tvind school was a milestone: a world record of a 2 MW turbine with a 54 meter down-wind rotor was completed in 1978. Some more entrepreneurs were experimenting with the manufacturing of small windmills, but the constructions did often not perform satisfactory (Tranæs, 1996).

Up to this point in time there is no visibility of an innovation system. Only experimental projects take place with small scale turbines, but no large turbines are built yet. Although **Entrepreneurial Activity** is thus visible, only very few people – some enthusiastic engineers – fulfil this function. Because of the importance of this function for the take-off of the technologies' development, but the low scale on which this happens, this function is considered of medium fulfilment in this phase.

The second function that is a little visible is **Knowledge Development**: the knowledge that is created through these experiments is useful for the further development of the technology. However, the size of this Knowledge Development is still relatively small to the sizes that it would grow to in later stages and the involvement of research institutes is absent. Also this function is regarded fulfilled at a medium level.
Another function that is visible is **Resource Mobilisation**. The financial and human support from SEAS and the Marshall plan had provided enough resources to experiment with the first turbines of a larger size. These investments, although not very high, were crucial for the development of the technology. Also this function is regarded of a medium level.

The fourth function that comes in place seems to be a trigger for the transition to the next stage. Halfway the 20th century the use of oil and other fossil fuels became cheap and many nations switched their energy system to fossil fuels. For two decades almost no wind turbines were active, until the oil crises of the 1970s. Denmark was before the oil crisis for 94% of its energy depending on oil import and for the other 6% they imported solid fuels like coals (Heymann, 1998). The oil crisis of 1973 with

its increasing oil prices and the dependency on foreign countries, lead to the **creation of legitimacy** for development of alternative energy sources, such as wind power. This proved to be an important trigger for investments in the development of the technology and this function is considered of high importance for the transition to the next phase.

Another important function that triggered the transition to the demonstration phase is **Resource Mobilisation**. In 1975 the Danish Academy for Technical Sciences concluded that wind resources were plentiful in Denmark and that it would take about 50 million DKK to establish sufficient engineering knowledge on wind turbines. In about 10-15 years these wind turbines would deliver about 10% of the Danish energy needs (Van Est, 1999). These results initiated the national Wind Power Programme, largely based on the structure of the US Federal Wind Energy Programme. For the first phase (1977-1980) 35 million DKK was available to research and development activities by the Risø National Laboratory and the Technical University of Denmark (Van Est, 1999). The Wind power programme is considered an important indicator for **Guidance of the Search** and the transition to the next phase.

6.2.2 The start of the demonstration phase: 1977

In 1977 it was decided to build two prototypes: the Nibe A with a stall-controlled rotor and the Nibe B with pitch control. These windmills were designed by two major research institutes and built by a consortium of industrial partners. It was funded by utility company SEAS and the Ministry of Energy (Kamp, 2002). Nibe A was connected to the electricity grid in 1979 and Nibe B in 1980. However, the Nibe A turbine operated only for a few hours from 1983 until 1991. Nibe B outperformed Nibe A by operating more than 18,000 hours from 1983 until 1988 (Kamp, 2002). Besides Nibe A and Nibe B a few more large wind turbines were tested or in operation in the same period.

Small size wind turbines were more successful and in 1978 about 10 small firms were in place, having placed about 170 small turbines by 1979. Although their wind turbines had many problems, collectively – in the Danish Wind Mill Owners Association founded in 1978 – they learned by doing and produced small scale electricity production units for local use (Kamp, 2002). Some small agricultural machine manufacturers as Bonus and Vestas profited from the learning processes in earlier years, bought some patents and started production lines for components of the turbines. They also started more advanced testing procedures to reach stable components and intensive local user-producer interaction speeded up successful development of small turbines (Kamp, 2002). The cooperation between firms and successful user-producer interaction form two components of successful **Knowledge Diffusion** activity. Also, the function **Entrepreneurial Activity** is growing: both the experimental component of Entrepreneurial Activity, as well as the growth of the number of players in and output of the industry start to take-off.

The increasing number of players in the industry and the increasing number of installed turbines resulted in the establishment of the Danish Wind Mill Owners Association in 1978 and the Danish Wind Turbine Manufacturers Association in 1981. In Denmark, the growing size of the industry resulted in better organised lobby activity for a more attractive infrastructure for wind energy. The function **Lobby Activity and Creation of Legitimacy** is considered of high fulfilment in these stages. Also guilds form a part of this function. The first Wind Turbine Guild was established in 1980 in Ny Solbjerg. The Danish have a long and society broad cultural history of associations, corporations and guilds. The current chairman of the Danish Wind Turbines Owners Associations formulates this cultural explanation for the success of the wind turbine industry as follows:

> "*It is my intention to show how the Danes gained a valuable historic experience which has been pronounced in national life ever since, i.e., that if you are going to solve bigger problems it is necessary that you join hands and receive returns according to contribution/deposit, but that everyone - big and small - has the equal right to decide.*"
> (Tranæs, 2000: 4)

The function **Guidance of the Search** strengthens in the demonstration phase. The Wind Power Programme of 1977 was the first sign of strong guidance and this was supplemented with the 'Energiplan' in 1981. It formulated the goal to supply 10% of the Danish electricity consumption with wind turbines in 2005. Most of this goal was to be reached with small scale wind turbines. However, no firms wanted to produce the complete large wind turbines, so in December 1981 the Ministry of

Energy together with SEAS founded the company Danish Wind Technology (Dansk Vindteknik A/S). Kamp (2002: 137) concludes that "*this clearly shows the science-push paradigm within the Danish large-scale wind turbine innovation subsystem*".

6.2.3 Transition to the pre commercial phase: 1981

In between 1981 and 1985 group efforts lead to the up-scaling of production of small wind turbines from a capacity of 30 kW to 55 kW and from about 10 meter to a 20-meter rotor diameter. The combination of incremental process innovations and the elimination of design weaknesses lead to a cost effectiveness increase of 50%. Considerable **Knowledge Development** was thus created and this function is considered of high fulfilment since this phase. In these years also export of Danish turbines to California increased, because of unsatisfactory results of American produced turbines. With a stabilizing home market, these exports were beneficial to the growth of the Danish industry (Kamp, 2002) and thus further growth of **Entrepreneurial Activity**. Also this function is regarded to be highly fulfilled since the pre commercial phase.

With the success of the adapted Nibe B wind turbine, the Danish utility company Elkraft ordered five large windmills from Danish Wind Technology of the Nibe B type in 1984. Again, the design was conducted by the Danish Technical University and Danish Wind Technology built the turbine and the blades. This project was funded by Elkraft, the European Union and the Danish government (Kamp, 2002). The Tsaereborh turbine was a similar project with a larger and more advanced windmill production was conducted in the same period, just like other projects in Koldby, Hundested and Avedøre.

A stabilizing home market with mostly local production and ownership and incremental process innovation as the main source of Knowledge Development characterized the beginning of the 1980s. Later, California became an increasing market for the Danish turbines, which caused increasing competition among Danish manufacturers. This resulted in the foundation of the Test and Research Centre, which was to control the quality and further development of wind turbine technology.
In 1985, when problems in California arose and export decreased, many partners in the wind turbine industry withdrew. A combination of more negative factors made exports to California ultimately stop in 1988. Furthermore, the Danish investment subsidies had already ended in 1986, resulting in "*a collaOrganisation E of small wind turbine sales and to bankruptcy of many Danish manufacturers in 1985 and 1986*" (Kamp, 2002: 175).

The revival of the wind power industry at the end of the 1980s can be attributed to fierce efforts of the Danish Wind Turbines Owners Association who lobbied for governmental support. The competition from Japanese manufacturers and a strong voice from the Danish Wind Turbines Owners Association made the national government set up the Wind Turbine Guarantee Company who would guarantee the long-term financing and of large export projects with a budget of 750 million DKK (Van Est, 1999). This gave Danish manufacturers attractive export opportunities. The sequence of functions that were important for this revival were first **Lobby Activity and Creation of Legitimacy**, followed by better **Guidance of the Search** which was by means of strengthening **Market Formation**.

In 1990 the Wind Power Programme was abolished and the Danish state sold its shares in Danish Wind Technology. At that moment, no Danish companies were willing to take over the activities in large-scale windmills. At the same time, small-scale windmills had proven efficient, cheaper, more reliable and ready for export, and thus the interest in the large windmills was small (Kamp, 2002).
Although the industry and market for large scale turbines seemed to decrease, especially now that the oil prices were decreasing (see section 4.3) and the attractiveness of alternative energy resources decreased, the Danish Wind Industry Association kept lobbying actively for better circumstances for the wind power industry. This lobby was tough, but their efforts resulted in the establishment of the Law for Wind Turbines. This law opened the road further for large scale wind turbines, because now the embedding to the national electricity grid became better regulated and more attractive demand creating policy was constructed. The transition to the supported commercial phase was thus mainly due to high activity in the function **Lobby Activity and Creation of Legitimacy**, which resulted in high fulfilment of **Guidance of the Search** and the establishment of better **Market Formation** policy.

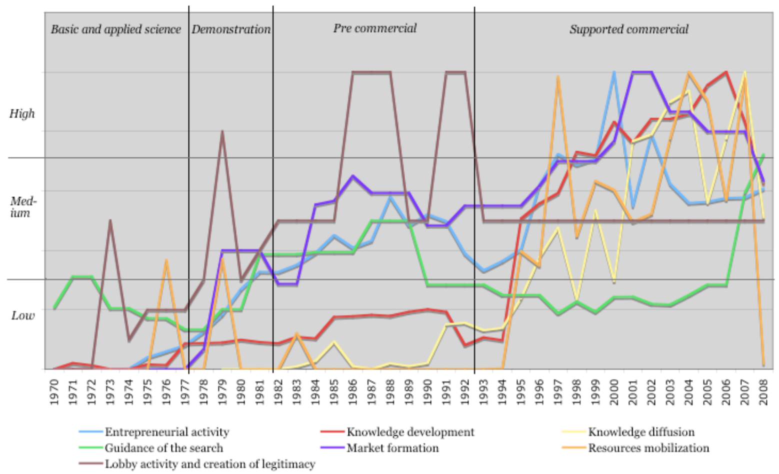
6.2.4 Transition to the supported commercial phase: 1992

Until 1992 the power companies and the corporations had always operated on private agreements for the prices of electricity, but institutionalization was necessary to protect the rights of the wind turbine owners. From 1992 on all corporation participants would pay only 85% of the market electricity price. Up to today wind power is not yet fully commercial. Government regulation is still necessary because grid parity has not been reached. The functions Market Formation and Guidance of the Search thus have to stay of high fulfilment in this phase.
Since the start of the supported commercial phase, **Knowledge Diffusion** shows a considerable take-off in the historic activity analysis. Although the qualitative analysis already showed that Knowledge Diffusion took place in earlier times, the interest for knowledge transfer via conferences grew much in this latter stage. This may also have to do with a global growing interest for renewables, since the oil prices have gone up since the beginning of the 2000s and therefore have created legitimacy for renewable energy technologies at large. It can be expected that with continuous high oil prices, legitimacy for wind power will always be high. On the other hand, lobby activities are not as necessary anymore as in the previous phase. With the infrastructure that has been reached to be able to enter the supported commercial phase, the work of the lobby groups is mostly done and their activity will mainly exist of trying to keep the attractive infrastructure the way it is. This twofold fulfilment of the same function has resulted in the value of medium fulfilment of **Lobby Activity and Creation of Legitimacy** in the supported commercial phase.

6.3 Formulating values of fulfilment for the wind power life cycle in Denmark

In Figure 30 the dynamics as they appeared in the historical data analysis are combined into one graph. The graph is depicted with the life cycle phases on the x-axis. On the y-axis the level of fulfilment is shown, where the value Low represents the lowest 30% of activity, Medium represents the activity between 30% and 70% and High represents the upper 30% of activity.

Figure 29 Dynamics of the seven functions of wind power in Denmark as found in the historical activity analysis



The results of the qualitative analysis on the importance of functions for the success of wind power in Denmark were considered as follows: Entrepreneurial Activity: medium; Knowledge Development: high; Knowledge Diffusion: high; Guidance of the Search: high; Market Formation: high; Resource Mobilisation: medium; Lobby Activity and Creation of Legitimacy: medium.

The combined insights in historical activity, importance of functions for the success and historical insights on the role of functions during the various life cycle phases and transitions, has lead to the model of function fulfilment shown in Figure 31.

Figure 30 Model of innovation system dynamics for wind power in Denmark

Wind power in Denmark	Basic and applied science	Transition 1	Demon-stration	Transition 2	Pre commercial	Transition 3	Supported commercial
Entrepreneurial activity	**Medium**	**Low**	**Medium**	**Medium**	**High**	**High**	**High**
Knowledge development	**Medium**	**Medium**	**Medium**	**Medium**	**Medium**	**Medium**	**High**
Knowledge diffusion	**Low**	**Low**	**Medium**	**Medium**	**Medium**	**Medium**	**High**
Guidance of the search	**Low**	**Medium**	**Medium**	**High**	**High**	**High**	**High**
Market formation	**Low**	**Low**	**Low**	**Medium**	**Medium**	**High**	**High**
Resources mobilization	**Medium**	**High**	**High**	**High**	**High**	**High**	**High**
Lobby activity and creation of legitimacy	**Medium**	**High**	**Medium**	**High**	**High**	**High**	**Medium**

7. Analysis

In this chapter the results of the process analyses for the case studies are compared with the hypotheses. Each section elaborates on one function and discusses the similarities and differences of fulfilment value for the hypothesis and the case studies. Differences are explained and a conclusion is drawn on a general pattern of dynamics for that function over the phases of commercial maturity of renewables energy technologies in general.

7.1 Entrepreneurial Activity

Table 12 shows the values of function fulfilment as proposed in the hypothesis and as found for the three case studies.

Table 12 Function fulfilment of Entrepreneurial Activity

F1	Basic and applied science	Transition 1	Demon-stration	Transition 2	Pre commercial	Transition 3	Supported commercial
Hypothesis	Low	Low	Medium	Medium	High	High	High
Tidal power in the UK	Low	Low	Medium				
Photovoltaics in Germany	Medium	Low	Low	Low	Medium	Medium	High
Wind power in Denmark	Medium	Low	Medium	Medium	High	High	High

The difference of low or medium fulfilment of this function in the basic and applied science phase is likely to be caused by the fact that this function exists of two main components with a different dynamics over the life cycle. From the three case studies it seems plausible that experimentation takes mainly place in the basic and applied science phase: in this phase a few creative engineers produce the first knowledge and prototypes of the technology. This experimental behaviour is replaced with institutionalised Knowledge Development in the demonstration phase, resulting in lower fulfilment of this function. However, when the technology matures and appears to be commercially maturing as well, this function gets fulfilled again, but now by the other component: entrepreneurs who establish small firms and thereby create an emerging industry. This typically takes off in the pre commercial phase and increases further in the supported commercial phase.
Although the speed of fulfilment differs among the case studies and the hypothesis, it is concluded that this function is medium fulfilled in the basic and applied science phase with experimentation, then slows down because experimenting is professionalized and refulfills with an continuous growth from the pre commercial phase on when the technology becomes commercially attractive.

7.2 Knowledge Development

The case study results and the hypotheses are summarized in Table 13.

Table 13 Function fulfilment of Knowledge Development

F2	Basic and applied science	Transition 1	Demon-stration	Transition 2	Pre commercial	Transition 3	Supported commercial
Hypothesis	High	High	High	High	High	High	High
Tidal power in the UK	Medium	Medium	Medium				
Photovoltaics in Germany	Medium	Medium	High	High	High	High	High
Wind power in Denmark	Medium	Medium	Medium	Medium	Medium	Medium	High

Knowledge Development clearly plays a role from the earliest signs of a technology on. By definition a technology typically matures, also commercially, when the technology is improved and this is done by

Knowledge Development. Although this function is fulfilled relatively early, it stays necessary to have continuous Knowledge Development and not to lower investments in this, as long as the technology is not mature.
The speed in which this function gets fulfilled differs among case studies and might be explained by the complexity of the technology. It is likely that a more high tech and complex technology demands more Knowledge Development activity from the early days on, because to overcome complexity and to mature towards a commercially viable technology, relatively much improvement has to take place. Improving a technology that has expensive materials and production processes like photovoltaic power, needs to overcome higher cost and knowledge barriers, whereas a relative simple technology as wind power, has lower material and production costs and less technological complexity, so that high fulfilment of this function in the early phases plays a smaller role.
Also the type of knowledge production differs among technologies and phase. For wind power a dominant design was relatively soon established and a switch from product innovation to process innovation was made in the pre commercial phase. From that moment on Knowledge Development increased, because now specific research on optimisation of materials and production methods was attractive. For photovoltaic power still no dominant design is reached and still product innovation for new variants takes place, while older designs are optimised.
Although the phase of transition to high fulfilment and the intensity of Knowledge Development differs among case studies, it can be concluded that this function is fulfilled at a medium level in the earliest phase and that it gets better fulfilled up to the pre commercial phase where the technology is almost commercially attractive and where Knowledge Development continues with an focus on application and process innovations. A continuous and consistent policy for Knowledge Development is necessary for all renewable technologies.

7.3 Knowledge Diffusion

The case study results and the hypotheses are summarized in Table 14.

Table 14 Function fulfilment of Knowledge Diffusion

F3	Basic and applied science	Transition 1	Demon-stration	Transitio n 2	Pre commercial	Transition 3	Supported commercial
Hypothesis	Low	Low	Medium	Medium	High	High	High
Tidal power in the UK	Low	Low	Medium				
Photovoltaics in Germany	Low	Low	Low	Low	Low	Low	Medium
Wind power in Denmark	Low	Low	Medium	Medium	Medium	Medium	High

The hypothesis and the case studies agree that fulfilment of this function is low in the basic and applied science phase. A substantial rise in Knowledge Diffusion takes place on a different moment in time for the case studies. According to the hypothesis Knowledge Diffusion has reached high levels from the pre commercial phase on, but this is not confirmed. It typically happens later and for PV in Germany still Knowledge Diffusion is not very highly fulfilled. For wind power Knowledge Diffusion has increased since the demonstration phase, but it only gets highly fulfilled from the supported commercial phase on.
These conclusions could exist from a lack of valid data on Knowledge Diffusion because of its bad accessible character. An accessible indicator is conference papers, but conferences appeared to be organised mainly recently. The amount of conference papers seems not so much related to the amount of knowledge production, but rather on external incentives to organise and present on conferences. That is why only recently the amount of conference papers could have increased. More soft indicators of Knowledge Diffusion, such as mobility of human capital and cooperation between research institutes on specific topics are often not available publicly.
Furthermore Knowledge Diffusion is likely to be dependent more on external factors than the phase of commercial maturity. For all three case studies a Knowledge Diffusion bubble took place in the period 1984-1987 and a linear growth since around the year 2000. These dynamics were thus similar over time in terms of years and not in terms of commercial maturity phases. This can be explained by for example the enthusiasm for renewable energy conferences in the 1980s, but because of decreasing oil prices in the 1990s a simultaneous decrease of conferences. The rise since the end of the 1990s can then be explained by renewed legitimacy created by rising oil prices. Furthermore since the end of the

1990s the European Union promotes cooperation in research projects and increased its budgets on renewable energy research, which also created increased Knowledge Diffusion.

Despite the lack of data and the impression that Knowledge Diffusion relays on creation of legitimacy, a general trend of dynamics can be sketched based on the qualitative analyses and impressions of the historical activity data. This would be that Knowledge Diffusion does not play a role in the basic and applied science phase. When more research funds become available for demonstration projects cooperation between research institutes emerges, but Knowledge Diffusion is considered medium fulfilled. When the technology becomes commercially more attractive also firms enter research activities, the knowledge to be produced becomes more complex and thus more cooperation is needed. Finally, when sufficient mass of knowledge production is reached, conferences and knowledge centres are established that further increase Knowledge Diffusion.

7.4 Guidance of the Search

The case study results and the hypotheses are summarized in Table 15.

Table 15 Function fulfilment of Guidance of the Search

F4	Basic and applied science	Transition 1	Demon-stration	Transitio n 2	Pre commercial	Transition 3	Supported commercial
Hypothesis	Medium	High	High	High	High	High	High
Tidal power in the UK	Low	Low	Low				
Photovoltaics in Germany	Low	Low	Low	High	High	High	High
Wind power in Denmark	Low	Medium	Medium	High	High	High	High

Although in the basic and applied science phase the case studies show less fulfilment than the hypothesis, from the transition to the pre commercial phase the fulfilment is for all considered high. Guidance is considered an important driver for Market Formation and its dynamics are rather alike. Since the pre commercial phase typically takes off when Market Formation is successful (see subsection 7.5), Guidance of the Search also is highly fulfilled during the transition to the pre commercial phase. Guidance appeared to be rather low in the first transition, while it is likely that Guidance is necessary for the mobilisation of financial resources to be able to enter the demonstration phase. However, the case studies show that this guidance is still of a relatively low level.
One component of this function is expectations and this can explain the low fulfilment in the transition to the demonstration phase. Expectations are mostly created by media attention to the technology, but media attention was found to be very low in the early phases. This is also logical, because a technology that is not yet visible or only in a few places, does not attract attention and it thus not create awareness and expectations. The other component of this function, political awareness, is active is early phases, but only little. In the early phases no explicit visions and policy are created, but guidance in most cases exists of a small programme to mobilise resources.
The findings lead to the following conclusion on dynamics. In the basic and applied science phase no Guidance of the Search took place and only during the transition to the demonstration phase it emerges, because financial resources are mobilised. However, the function is still considered little fulfilled. As the technology becomes established, it gains more media attention and thus expectations are increased. These dynamics increase continuously during the life cycle, ending in high expectations when the technology is in its supported commercial phase and it is applied successfully at various places. The political component of this function is typically visible during transitions when political support has initiated Market Formation programmes and it thereby pushed technological development. Also, when the technology matures it more becomes a part of visions and policy for renewable energy and Guidance of the Search strengthens even more. Although Guidance keeps increasing during the life cycle of commercial maturity, it is considered fulfilled from the pre commercial phase on, because then enough Guidance was in place to fully support the technology.

7.5 Market Formation

The case study results and the hypotheses are summarized in Table 16.

Table 16 Function fulfilment of Market Formation

F5	Basic and applied science	Transition 1	Demon-stration	Transition 2	Pre commercial	Transition 3	Supported commercial
Hypothesis	Low	Low	Low	High	High	High	High
Tidal power in the UK	Low	Medium	Medium				
Photovoltaics in Germany	Low	Low	Low	High	Medium	High	High
Wind power in Denmark	Low	Low	Low	Medium	Medium	High	High

According to the hypothesis and two case studies Market Formation is a clear stimulus for enter of the pre commercial phase. There is a clear connection between the start of attractive Market formatting policy such as investments subsidies and attractive feed-in tariffs and the growth of the output of technology, start-ups, media attention and other growth indicators. Also Knowledge Development increases after such policy in introduced, because the commercialisation of the technology takes away uncertainty barriers and firms perform R&D to improve their competitive advantage for the growing market.
Market Formation plays two times a crucial role: for the transition to the pre commercial stage, where mostly investment subsidies were successful. This type of policy can be regarded as 'demand stimulating' policy. The second crucial role is in the transition to the supported commercial phase: here the policy should stimulate better quality of the product, which is suited with for example feed-in tariffs. Customers who depend on feed-in tariffs desire the most cost effective products, because their profits depend on the costs and profits of the technology. Therefore feed-in tariffs stimulate lower production cost processes and higher efficiencies of the technology. Investment subsidies mainly stimulate the purchase of the technology, but not directly the improvement of the technology. Also, in the beginning of the pre commercial phase the number of industrial players is still low, so that competition for the best product is not as high as in later phases.
The dynamics of this function can be described as very low fulfilment up to the demonstration phase. The transition to the pre commercial phase is evidently determined by the implementation of Market Formation policy. The function is now fulfilled, but for successful and continuous growth of the innovation system, Market Formation should be sustained and be changed according to the technological maturity, i.e. quality stimulating policy should be implemented to make the transition to the supported commercial phase.

7.6 Resource Mobilisation

The case study results and the hypotheses are summarized in Table 17.

Table 17 Function fulfilment of Resource Mobilisation

F6	Basic and applied science	Transition 1	Demon-stration	Transition 2	Pre commercial	Transition 3	Supported commercial
Hypothesis	Medium	High	High	High	High	High	High
Tidal power in the UK	Medium	High	High				
Photovoltaics in Germany	Low	Medium	Medium	High	High	High	High
Wind power in Denmark	Medium	High	High	High	High	High	High

The case studies show much similarity to the hypothesis. For most technologies a medium level of financial resources is necessary to perform Knowledge Development and experimentation in the basic and applied science phase. Since upscaling from experimentation to demonstration projects has substantial costs, this function should at least be of medium fulfilment to enable the transition to the demonstration phase. Resource Mobilisation should have a consistent character to enable continuous

Knowledge Development throughout the demonstration phase and thereafter; when this is not done the so-called 'valley of death'[8] may not be survived. Furthermore increased financial resources are crucial for the transition to the pre commercial phase. Since Market Formation in this transition consists of investment subsidies, financial resources need to be mobilised to pay for this policy measure. From the pre commercial phase on Resource Mobilisation stays important for continuous Knowledge Development and successful Market Formation policy.
The dynamics of this function can be described as of medium level in the basic and applied science, and fulfilled from the transition to the demonstration phase on. However, the contents and height of the financial resources will have to change over time, according to the maturity of the technology.

7.7 Lobby Activity and Creation of Legitimacy

The case study results and the hypotheses are summarized in Table 18.

Table 18 Function fulfilment of Lobby Activity and Creation of Legitimacy

F7	Basic and applied science	Transition 1	Demon-stration	Transition 2	Pre commercial	Transition 3	Supported commercial
Hypothesis	Low	Low	Medium	High	High	Medium	Low
Tidal power in the UK	High	Medium	Medium				
Photovoltaics in Germany	Low	High	Low	Low	Low	Low	Low
Wind power in Denmark	Medium	High	Medium	High	High	High	Medium

The function is the most volatile and has the largest differences among case studies. While on the one hand this function played almost no role for Photovoltaic power in Germany except in the transition to the demonstration phase, for Wind power it was a large influence on success of the technology throughout the life cycle. For tidal power its role is crucial, when the oil price is used as an indicator for creation of legitimacy for renewables.
First a conclusion is drawn on the legitimacy component of the function. Legitimacy seems to be created independent of the phase of commercial maturity. For all case studies the same dynamics of legitimacy take place in terms of timing in years. The most important indicator for legitimacy is the oil price and the case studies show that this influence can be very high; especially for tidal power, but likely for all relatively new renewable technologies, the oil prices determine the enthusiasm and thus the mobilised resources and policy for renewable technologies. With the high oil prices in the 1970s and beginning of the 1980s, many functions performed well, especially Knowledge Development and Resource Mobilisation. When in the 1990s the oil prices were low for about a decade, all functions stabilised or had lower activity. However, when the oil prices continued increasing since the year 2000, all functions again grew in activity. A combination with successful Market Formation policy would make the technology and industry substantially grow.
The second component is Lobby activity. This differs much among case studies. In Denmark since early days lobby groups were active and their influence on policy has been very large. Both users of wind turbines and the wind turbine producers have successfully lobbied for more favourable legislation, connection of turbines to the grid, public procurement, the introduction of feed-in tariffs and more. In Germany on the other hand, almost no lobby groups were active and technology development can be regarded as a 'policy push'. In the United Kingdom some lobby groups were active for the promotion of renewables at large, but they did not have much success. This may be due to the typical liberal politics in the UK, where government intervention in society is much less than on the European continent, resulting in relatively late introduction of policy for renewables.
Lobby activities in my view are very nation-specific and not technology-specific. Also, the earliest renewable technologies such as wind power have to overcome more barriers and thus are lobby activities more present and more effective. Furthermore, the case studies do prove that with increasing industry size (Entrepreneurial Activity) the quantity and power of lobby groups grows.

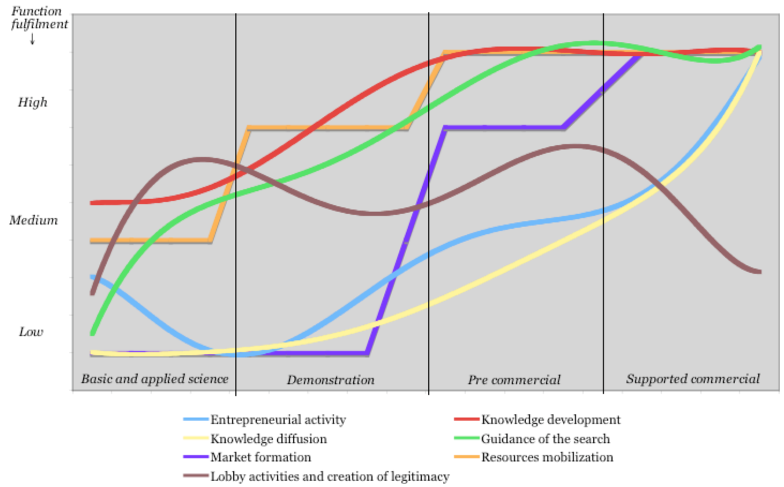
[8] The Valley of Death describes the situation where a technology cannot develop further because sufficient and continuous financial resources are lacking for the investments in the improvement and up scaling of the technology.

Since lobby activity is so nation-specific and creation of legitimacy very independent of technological maturity, it is hard to describe a general pattern. The following can however be said. Some legitimacy has to be in place before Resource Mobilisation rises for the transition to the demonstration phase. This legitimacy is often created by high oil prices. Secondly, for the transition to the pre commercial phase, when Market Formation takes place, again legitimacy has to be in place. Then, as the industry is gradually growing, lobby activities emerge and grow and especially for the transition to the Supported commercial phase when a strong institutional infrastructure for the technology is created these lobby activities were most active. It is likely that the impact of lobby groups reduces when this supportive infrastructure is reached and that thus the function will have less impact and importance.

8. Conclusion

Now that the final analyses are conducted, the conclusions of this master thesis can be formulated. This is done by answering the main research question: *"What are the dynamics of functions of innovation systems for renewable energy technologies during the first phases and the transition to the growth phase of its life cycle?"* These dynamics are formulated in terms of low, medium or high fulfilment of the functions per phase of commercial maturity and during the transition from one phase to the next. A comprehensive model is formed that graphically expresses the dynamics of the functions. This model is depicted in Figure 31.

Figure 31 The model of function dynamics of renewable energy technologies shown as the level of fulfilment throughout the life cycle stages



In the basic and applied science phase the earliest active function is Knowledge Development. A limited but sufficient level of Resource Mobilisation enables this Knowledge Development. Entrepreneurial Activity exists of small experimentation projects. Also early signs of legitimacy and Guidance of the Search are visible. The other two functions have very low levels of fulfilment.

The transition to the demonstration phase is characterized by increased Resource Mobilisation for the more costly demonstration projects. These resources are mobilised in a background of legitimacy and with some fulfilment of the political component of Guidance of the Search. The single experimentation projects are replaced by institutionalised research, which implies growth of the function Knowledge Development and decreased Entrepreneurial Activity.

During the demonstration phase of the technology all functions except Knowledge Development and Guidance stay in the same fulfilment as they already were: low Entrepreneurial Activity, almost no Knowledge Diffusion, no Market Formation activities, high mobilisation of financial resources and low impact of legitimacy and lobby activities. Knowledge Development increases further during the demonstration phase; and Guidance of the Search rises to high fulfilment in this phase, because since the technology becomes more visible, public and political awareness of its potential rises. Also, high guidance is needed for the take off of the next phase, which could typically start off when the expectations and awareness are high enough.

In the transition to the pre commercial phase Knowledge Development is highly fulfilled. During the demonstration phase Knowledge Development already increased and the high level of applied technological knowledge make the transition to (pre) commercial activities possible. At this stage the appearance of a dominant design could typically indicate the transition to pre commercial activities, but this was not the case for all case studies.
Another important development to cause the transition to the pre commercial phase is the start of Market Formation activities. It seems that the technology first has to be developed to a successful proof of concept before Market Formation policy is set up. These early forms of Market Formation are often demand stimulating instruments, such as investment subsidies. Market Formation seems to be the decisive factor in the transition to the next phase, where many other functions take off or grow as a reaction to this demand push.
The third crucial function to cause transition to the pre commercial phase is increased Resource Mobilisation. While the first increase in Resource Mobilisation was spent on Knowledge Development, this second increase is allocated for the Market Formation policy.

The pre commercial phase is characterized by a take off of the functions Entrepreneurial Activity and Knowledge Diffusion. As a reaction to the increasing industry size and to make its goals better reachable, lobby activities also take off in the pre commercial phase. In this phase a wider innovation system around the technology becomes established which even more stimulates its growth.

Since in the pre commercial phase many functions were growing to high fulfilment, the situation during transition to the supported commercial phase is almost the same as in the pre commercial phase with two main differences. The impact of lobby activities during the pre commercial phase has resulted in a strong supportive infrastructure for continuing growth of the innovation system. Therefore lobby activities have reach the highest impact in this transition. Market Formation stays highly fulfilled, but now with a different character: instead of the quantity stimulating policy in the pre commercial phase, now quality stimulating policy is introduced to stimulate continuously improving performance of the technology.

With the stable foundations laid in the transition to the supported commercial phase, the circumstances for further growth are so favourable that more players enter the system and the industry grows further. In the supported commercial phase Knowledge Development continues, but the role of firm R&D increases. Also in Knowledge Diffusion the impact of firms increases and more formal cooperation between organisations takes place. In this supported commercial phase all functions are fulfilled on a high level, except Lobby Activity and Creation of Legitimacy. The lobbies have done their work well and created legitimacy for a supportive infrastructure for further maturing of the technology. When all functions keep performing well, all we have to do is wait for grid parity to become a fully commercial technology.

9. Policy recommendations

This research has shown that for different phases of the life cycle of a renewable energy technology different activities are crucial for maturing of that technology. The following recommendations to policy makers result from the conclusions. The main goal of all recommendations together is to achieve a successful innovation system by stimulating the right functions in the right stages of development. The recommendations are therefore specific for the life cycle phase of the technology.

- In the earliest phases of development of the technology the most important driver for growth in Resource Mobilisation for knowledge creation. This means that sufficient R&D funds need to be available to research institutes. The more financial resources are allocated to Knowledge Development, the earlier the knowledge will become ready for testing projects with the technology.
- To enter the phase of demonstration projects, additional funding is crucial, because building prototypes for experimentation is more expensive. To allocate these financial resources political awareness and enthusiasm for the technology have to be present.
- Continuous allocation of higher financial resources will result in the evolution of a basic prototype to a more mature, reliable and effective technology. During the demonstration phase the first initiatives for Market Formation should be developed. Political guidance should stimulate to investigate opportunities for policy measures to stimulate demand by private customers or energy companies for the technology.
- When the technology is sufficiently improved and systems are available for installation ‘in the real world’ for use by private customers or energy companies, transition to the pre commercial phase can take place. This happens when the Market Formation policy measures are introduced that aim on stimulating demand, such as investment subsidies. Mobilisation of financial resources to pay for the Market Formation policy is necessary and this can only happen when political awareness of the potential of the technology is high.
- With the introduction of Market Formation policy and the rise in Resource Mobilisation the pre commercial phase enters. The government should have enough funds available for a continuous funding scheme for both Knowledge Development and Market Formation. This typically results in niche markets, where experiences from producing and using result in improved technology and thus increased fulfilment of the functions Knowledge Development and Diffusion. Consistency and continuity of these policy measures are necessary to overcome the danger of ‘the valley of death’, which implies stagnation of further development by a lack of funding. If all policy is successful in this phase the industry will grow and the innovation system becomes stronger: a network of full supply chains from raw materials to production to installation and maintenance will appear, employment in the industry rises and Knowledge Development also appears as firm R&D.
- To grow from this immature innovation system to a larger industry even more supportive infrastructure is to be realized. The innovation system has to transfer from niche market to a full industry. Therefore two important changes have to be made: first a fully supportive institutional system is to be created in which the renewable energy technology can compete with incumbent technologies. This implies an attractive supportive financial, physical and legal infrastructure. Growing pressure from the industry – lobby activity – will push the government to implement such favourable measures. When the wishes of the industry are fulfilled, substantial improvement to the system can be made. Secondly, the Market Formation policy has to change from demand stimulation to quality improvement to enforce optimisation of the technology. This can for example be done by feed-in tariffs.
- The establishment of a favourable context for further growth starts off the supported commercial phase. Now the supportive infrastructure persuades even more firms to enter the industry. Also demand will grow, because the positive and visible results in the previous phases have raised positive expectations and the attractive climate now makes organisations and customers willing to invest in the renewable technology. In this growth phase it is essential to sustain the attractive climate. When the technology still depends on the supportive infrastructure, it means that is not mature enough to compete with the incumbent system. Thus, continuous support to Knowledge Development and Diffusion, Market Formation and according Resource Mobilisation is necessary. This can be reached by listening to the wishes of lobby groups to counteract resistance and to sustain the favourable political climate. Commercial maturity is reached when grid parity is established: the technology then can survive in a commercial and independent environment.

10. Discussion

While using the functions approach and the framework of technological innovation systems, observations on difficulties and ambiguities were made. Many of these observations would result in general recommendations as the need for sharper definitions and boundaries, but that is evident in the status of the relatively immature theoretic frameworks of the technological innovation system and the functions approach. The more specific recommendations in improving the use of the functions approach in studying technological innovation systems (TIS) are as follows.

- The use of national boundaries for the study of a TIS seems very fruitful. Although the TIS is designed to be supranational many of the functions have a national character. For example guidance is politically dependent and culturally embedded; financial Resource Mobilisation takes place by national funding schemes, although programmes from the European Union form an exception to this, and Market Formation measures are typically introduced by national governments.
- Using the four phases of Foxon (2005) to study the dynamics is experienced as a very fruitful way to study in-depth the dynamics within the exploratory phase. It appears that within the exploratory phase – the first three phases of Foxon – the functions behave uniquely and although many of them show growing fulfilment throughout the first three phases, the moments and curves in which the functions develop are unique and clearly visible when the exploratory phase is split into three separate phases.
- Also the use of the four phases in combination with specific attention to the dynamics on the transition moment has resulted in clear insights into success factors of transitions. It has appeared specifically interesting to study the dynamics of functions just before a new phase enters and to appoint crucial factors for acceleration of the technology to the next phase.

To improve the establishment of a comprehensive understanding of the functions, clarity of definitions of functions is necessary. For each function the contents, the emphasis on certain components and indicators to measure the fulfilment of a function should be agreed upon and used accordingly by all who work with it. The following recommendations regard such issues of the functions.

- The measurement of Entrepreneurial Activity as one function appeared difficult in this study. On the one hand experimental behaviour of engineers and start-ups is crucial for the demonstration phase and the overall built up of an innovation system. These processes typically take place in the earliest phases. On the other hand this function includes entrepreneurship and thus the start-up of firms and the activities these start-ups perform. This component typically serves as an output indicator, because indicators as installed capacity are in my view a valid indicator for the number and activity of start-ups and entrepreneurs. These processes typically take-off in a later phase in the emerging innovation systems and they grow gradually along with the growth of the innovation system. In this study it has appeared difficult to combine these two indicators with different purposes and trends. A better way to define the functions is recently proposed by Bergek *et al.* (2008) by replacing this function by two different ones: 'Entrepreneurial experimentation' and 'Materialisation', where the first emphasizes early experimentation activity and the latter the development and installation of products for the consumer market. This is in my view a better method to analyse Entrepreneurial Activity in innovation systems.
- Measuring Guidance of the Search by splitting the function into a dimension of public awareness and governmental awareness was new and has provided interesting insights. However, the national scale was not sufficient, because for example European Union guiding could not be included directly. From the qualitative analysis appeared many aspects that were not measured with historical data, such as cross-fertilization between sectors and a general environmental consciousness that accelerated the innovation system of photovoltaic power in Germany. These aspects are again very cultural and national embedded and should always deserve attention.
- Creation of legitimacy and lobby activities (also referred to as 'advocacy coalitions') is the most ambiguous function in my perspective. These two components are hard to study as one comprehensive function, because legitimacy-creating events have different trends from lobby activity. While lobby activities start relatively late and have a rather linear pattern that evolves with growth of the industry size, creation of legitimacy is high in the early phases and further

on less. Moreover, creation of legitimacy is independent of the maturity of the technology, but it depends on external factors. Especially the tidal power case study, but also the others showed that development of the innovation system is closely related to oil prices. My suggestion is as follows:
    - To skip the component of lobby activities, because the dynamics of this component are rather equal to Entrepreneurial Activity. In the case that lobbies are formed by industrial firms, the dynamics of this function are likely to be similar to the dynamics of Entrepreneurial Activity, because when more players enter the industry they form a stronger bargaining base. In the case that lobbying is performed by NGO's or environmental groups, the dynamics are likely to be similar to Guidance of the Search or creation of legitimacy and also for now their efforts shown only very little impact on the success, so to not give to much weight to lobbying by non-industrial organisations does not seem invalid.
    - To make the component 'creation of legitimacy' a function on its own by clearly including the importance of external factors such as the oil crisis. Other authors such as Suurs (2009) and Bergek (2008) in earlier work have emphasised this influence of external factors on the development of a technology specific innovation system. These external factors also include the developments of alternatives, as mentioned by Suurs (2009). Bergek *et al.* (2008) regard this as the creation of positive externalities.

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Appendices

Appendix I Introduction on tidal power technology

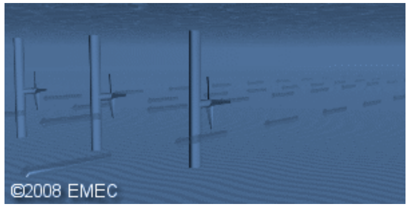
Tidal energy, obviously, is extracted from the movement of water due to tides. Since these tide differences are the highest near the shore, installations are often placed close to land in areas with high tidal variance. Tidal energy has the potential of delivering about 20% of the UK's electricity consumption (IEA, 2007).

The European Marine Energy Centre is the first large testing facility for marine power technologies (which includes wave and tidal technology) and is situated in Orkney, in the North of the United Kingdom. They test the following four main types of tidal energy technology (EMEC, 2008a (cited)):

- **Horizontal axis turbine**

This device extracts energy from moving water in much the same way as wind turbines extract energy from moving air. Devices can be housed within ducts to create secondary flow effects by concentrating the flow and producing a pressure difference. See Figure 32.

Figure 32 The horizontal axis turbine technology

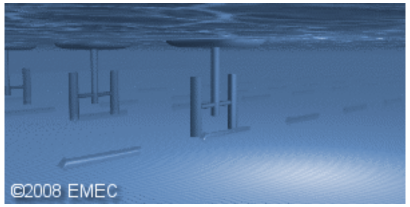


Source: EMEC, 2008a

- **Vertical axis turbine**

This device extracts energy from moving in a similar fashion to that of the horizontal turbine, however this turbine is mounted on a vertical axis. See Figure 33.

Figure 33 The vertical axis turbine technology

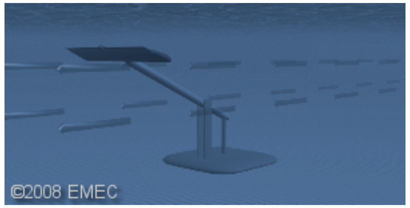


Source: EMEC, 2008a

- **Oscillating hydrofoil**

A hydrofoil is attached to an oscillating arm and the tidal current flowing either side of a wing, which results in lift, causes the motion. This motion can then drive fluid in a hydraulic system to be converted into electricity. See Figure 34.

Figure 34 The oscillating hydrofoil technology

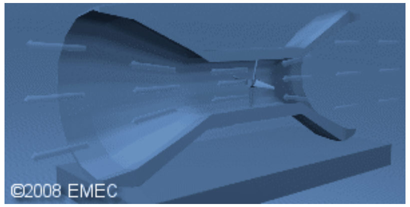


Source: EMEC, 2008a

- **Venturi effect**

By housing the device in a duct, this has the effect of concentrating the flow past the turbine. The funnel-like collecting device sits submerged in the tidal current. The flow of water can drive a turbine directly or the induced pressure differential in the system can drive an air-turbine. See Figure 35.

Figure 35 The Venturi effect technology



Source: EMEC, 2008a

Tidal energy is often compared to offshore wind energy and has compared to this the following advantages (Tidal Generation Ltd, 2008):

- High energy intensity: the resource has four times the energy intensity of a good wind site, so tidal turbines need only a quarter of the swept area of a wind turbine - and size has a significant impact on cost. Also, tidal devices can be closely spaced in a string across a flow, since the flow axis is constant and there is no need for wide spacing of the machines to avoid wake interference as there is in wind farms.
- Predictable energy capture: the regular pattern of the tides enables both the amount of energy, and the timetable to which it will be produced for years to come, to be determined with great accuracy, using data gathered over period of only one month. Energy generated to a timetable is more valuable than energy from randomly intermittent and variable sources such as wind, wave and solar, and has a lower impact on the efficiency of displaced thermal generating plant. Having confidence in the energy production of a renewable installation overcomes one of the biggest hurdles in achieving project finance and brings higher revenue per MWh generated.
- Sustainable installations: the degree of over-engineering needed to cope with the "worst case" operating conditions is much lower than for wind or wave powered devices, as conditions under water, for fully submerged devices, even in the severest of weather, do not vary considerably and less heavy extreme weather circumstances can occur under water.
- Small environmental impact: the installations have slow moving rotors (much slower than a ship's propellers) and so will cause far less disturbance to sea mammals. Also, they are passive energy absorbers, so they will produce less underwater noise than ships of a similar power rating. Marine life disturbance is therefore minimized.
- Small social impact: the machines are less visually intrusive or not visible at all, and will therefore cause less visual intrusion and bird disturbance.

Appendix II Data sources, calculations and final values for Entrepreneurial Activity for tidal power in the United Kingdom

Entrepreneurial Activity is measured by two dimensions with each one indicator:

- The size of the tidal power industry: the cumulative number of start-ups in the UK on tidal power. This concerns both new enterprises with a focus on tidal power, or existing firms who start activity in tidal power generation. The selection of firms is made via two sources: the EMEC list of companies in the UK that perform tidal power activity (EMEC, 2008b) and the list from the AEA (2006) comprising of all international wave and tidal power projects. From these two lists all UK firms were selected and of these firms their years of establishment (for the new start-ups or spin-offs) or the year in which tidal power activity started were searched for. The number of firms with the same start-up date was counted and a cumulative value was calculated to represent the size of the industry. The firms and their starting dates that form the input for the analyses are shown in Table 19.
- Installed capacity: this was indicated by the number of demonstration projects that were in place for each year in the UK. Since installed capacity can not be measured in MW for a lack of data, the number of demonstration projects is chosen to represent activity in the construction of tidal power installations.

Table 19 Firm selection for tidal power industry development and their foundation years

Firm	Start of tidal power activity of the firm
Aquamarine Power	2005
Edinburgh Designs	no data
Greenheat Systems Ltd	2008
Hydroventuri	1999
Lunar Energy	2001
Marine Current Turbines	1991
Neptune Renewable Energy Ltd	2006
Overberg Limited	2005
Pulse Generation	2005
Robert Gordon University	2000
Rugged Renewables	2005
Scotrenewables	2002
SMD Hydrovision	2005
Swanturbines Ltd.	2000
The Engineering Buisiness	2004
Tidal Generation Limited	2003
Tidal Hydraulic Generators Ltd	2001
Woodshed Technologies - CleanTechCom Ltd	2006
QinetiQ Winfrith	2001
Hales Energy	2007
McMenemie	2006

Data for Entrepreneurial Activity for tidal power in the UK

Year	Number of start-ups	Cumu-lative	Standardised value	Number of demon-stration projects	Standardised value	Final value (average of standardised values)
1990	0	0	0	0	0	0
1991	1	1	0.052631579	0	0	0.026315789
1992	0	1	0.052631579	0	0	0.026315789
1998	0	1	0.052631579	0	0	0.026315789
1999	1	2	0.105263158	0	0	0.052631579
2000	2	4	0.210526316	0	0	0.105263158
2001	3	7	0.368421053	0	0	0.184210526
2002	1	8	0.421052632	1	0.5	0.460526316
2003	1	9	0.473684211	1	0.5	0.486842105
2004	1	10	0.526315789	0	0	0.263157895
2005	5	15	0.789473684	0	0	0.394736842
2006	3	18	0.947368421	1	0.5	0.723684211
2007	1	19	1	2	1	1

Appendix III Data sources, calculations and final values for Knowledge Development for tidal power in the United Kingdom

This function is measured by one dimension, namely academic publications by UK organisations on tidal power. No other useful data could be found on other indicators of Knowledge Development. The international database Scopus was used to conduct a search on academic knowledge production, by searching for the terms 'tidal power' or 'tidal energy' in title, keywords and abstracts of articles by UK organisations.

Table 20 Selection of research institutes for Knowledge Development of tidal power in the UK

University of Wales Bangor (12)
University of Edinburgh (12)
Robert Gordon University (11)
University of Southampton (10)
University of Bristol (8)
University of Durham (7)
Bedford Institute of Oceanography (7)
University of Strathclyde (6)
University of Glasgow (5)
Plymouth Marine Laboratory (5)
National Oceanography Centre Southampton (5)
University of Plymouth (5)
Queen's University Belfast (5)
University of Hull (5)
University of Salford (4)
Bristol Polytechnic (4)
University of Liverpool (4)
The Scottish Association for Marine Science (4)
Engineering Business Ltd. (3)
Loughborough University (3)
Swansea University (3)

Proudman Oceanographic Laboratory (3)
Newcastle University (3)
Imperial College London (3)
University of Aberdeen (3)
Queen's University (3)
CSIRO Marine and Atmospheric Research (3)
University of Sussex (3)
Commonwealth Scientific and Industrial Research Organization (3)
University of Cambridge (3)
Entec UK Ltd. (2)
Engineering Business Limited (2)
National University of Ireland, Dublin (2)
University of Newcastle (2)
Trinity College Dublin (2)
Stanford University (2)

The number behind the research institute indicates how many publications were found in Scopus on tidal power by that organization.

Appendix IV Data sources, calculations and final values for Knowledge Diffusion for tidal power in the United Kingdom

Knowledge Diffusion is measured with two indicators.

- The number of conference papers written by UK organizations. This was found via a Scopus search for conference papers containing the terms 'tidal power' or 'tidal energy' in title, keywords or abstracts (Scopus Search, 2009b). For Knowledge Development a larger selection of organizations was made, because there were more organisations that published academic articles in general (153 hits) then conference papers only (45 hits). The selection of organisations for this function is shown in Appendix III. This indicator is standardised to a 0 - 0.8 scale.
- The presence of a European Wave and Tidal Energy Conference (EWTEC). If an EWTEC had place this year was granted 0.2 points for that. EWTEC conferences had place in 2003, 2005 and 2007 (EWTEC, 2007).

The first indicator is standardised to a 0 – 0.8 scale and the second indicator to the 0 – 0.2 scale. The first one has a higher weight because its data go back o the 1980s and the EWTEC conferences only represent Knowledge Diffusion since recent times. However, the EWTEC conferences serve as an important event in knowledge transfer on tidal energy worldwide and deserve this special attention. UK organizations obtain much information on these conferences, although that value may not be reflected in the first indicator. For this importance of EWTEC for international knowledge transfer, it is accounted a weight of 20%.

Table 21 Selection of research institutes

University of Wales Bangor (12)
University of Edinburgh (12)
Queen's University Belfast (5)
University of Hull (5)
University of Salford (4)
Bristol Polytechnic (4)
University of Liverpool (4)
The Scottish Association for Marine Science (4)
Engineering Business Ltd. (3)
Loughborough University (3)
Swansea University (3)
Proudman Oceanographic Laboratory (3)
Newcastle University (3)
Imperial College London (3)
University of Aberdeen (3)
Queen's University (3)
CSIRO Marine and Atmospheric Research (3)
University of Sussex (3)
Commonwealth Scientific and Industrial Research Organization (3)
University of Cambridge (3)
Entec UK Ltd. (2)
Engineering Business Limited (2)
National University of Ireland, Dublin (2)
University of Newcastle (2)
Trinity College Dublin (2)
Stanford University (2)

The number in brackets is the number of conference papers as found in the Scopus search (2009b).

Table 22 Data on Knowledge Diffusion in tidal power in the UK

Year	Conference papers by UK organizations	Standardised value to 0.8	EWTEC	Average of the two variables	Final value
1980	0	0		0	0
1981	0	0		0	0
1982	0	0		0	0
1983	0	0		0	0
1984	2	0.177777778		0.17777778	0.195122
1985	1	0.088888889		0.08888889	0.097561
1986	1	0.088888889		0.08888889	0.097561
1987	4	0.355555556		0.35555556	0.390244
1988	0	0		0	0
1989	1	0.088888889		0.08888889	0.097561
1990	0	0		0	0
1991	2	0.177777778		0.17777778	0.195122
1992	0	0		0	0
1993	0	0		0	0
1994	0	0		0	0
1995	0	0		0	0
1996	0	0		0	0
1997	0	0		0	0
1998	0	0		0	0
1999	0	0		0	0
2000	3	0.266666667		0.26666667	0.292683
2001	0	0		0	0
2002	9	0.8		0.8	0.87805
2003	1	0.088888889	0.2	0.28888889	0.317074
2004	5	0.444444444		0.44444444	0.487805
2005	1	0.088888889	0.2	0.28888889	0.317074
2006	7	0.622222222		0.62222222	0.682928
2007	8	0.711111111	0.2	0.91111111	1

Appendix V Data sources, calculations and final values for Guidance of the Search for tidal power in the United Kingdom

This function is analysed by using a public and a political dimension:

- The public awareness of the possibilities of tidal power is measured by the number of articles on tidal power in newspapers. This is done with a search in Lexis Nexis, an international newspaper database. The following selection of UK newspapers was made: The Guardian, Financial Times, The Observer, The Independent and The Herald Glasgow. These newspapers have archives that go the furthest back in time and they have a substantial amount of articles on tidal power. This search was conducted by searching the terms 'tidal power' or 'tidal energy' in the title or opening paragraph of the article and then to count the number of articles per year. This gave 209 hits in the period 1982-2007 (Lexis Nexis search, 2008).
- The political awareness for the development of tidal power is calculated as explained in the method section. The Green Party was established in 1973 and in those days only active in local and regional governments. The Green Party was not represented in the UK parliament up to 1998. In 1999 this changed when Robin Harper from the Green Party was elected in the national government. He has retained his seat until today. In 2003 a second member of the Green Party entered the national parliament: Patrick Harvie, who is also still in place. The UK parliament counts 1,388 members: 742 Lords and 646 Commoners. These 2 seats thus are of very little influence to national policy making. A relatively high value of 0.05 is appointed to each seat in parliament to reflect political awareness.

Table 23 Guidance of the Search for tidal power in the UK

Year	Public awareness	Standardised value	Political awareness	Final value (average)
1980			0	0
1981			0	0
1982	1	0.027777778	0	0.013888889
1983	1	0.027777778	0	0.013888889
1984	4	0.111111111	0	0.055555556
1985	1	0.027777778	0	0.013888889
1986	4	0.111111111	0	0.055555556
1987	9	0.25	0	0.125
1988	5	0.138888889	0	0.069444444
1989	10	0.277777778	0	0.138888889
1990	4	0.111111111	0	0.055555556
1991	5	0.138888889	0	0.069444444
1992	5	0.138888889	0	0.069444444
1993	5	0.138888889	0	0.069444444
1994	1	0.027777778	0	0.013888889
1995	0	0	0	0
1996	0	0	0	0
1997	4	0.111111111	0	0.055555556
1998	5	0.138888889	0	0.069444444
1999	1	0.027777778	0.05	0.038888889
2000	6	0.166666667	0.05	0.108333333
2001	9	0.25	0.05	0.15
2002	8	0.222222222	0.05	0.136111111
2003	15	0.416666667	0.1	0.258333333
2004	16	0.444444444	0.1	0.272222222
2005	24	0.666666667	0.1	0.383333333
2006	30	0.833333333	0.1	0.466666667
2007	36	1	0.1	0.55

Appendix VI Data sources, calculations and final values for Market Formation for tidal power in the United Kingdom

Market formation is composed of two demand stimulating instruments:

- The Renewables Obligation supports renewables in general and it only includes the tradable certificates. These measures only favour tidal power indirectly, because it is not specifically targeted at tidal power and it does not include direct obligations for investments in the national installation and use of renewables. The Renewables Obligation includes the tradable certificates, which encourages investing in renewables only directly. However, it is still an incentive to invest in tidal power, so it gets 0.2 points.
- The MRDF gets 0.4 points per year. This instrument is directly targeted at the development of tidal power, although this is in combination with wave energy. Also, it directly influences the development of installations and use of tidal power because of the high funds available to demonstration projects. Since this policy measure is more specific and output-based it gets twice the points that the Renewables Obligations got.

No table or graph is constructed in this subsection, because this information is clear enough. The graph of this function is shown in the final paragraph 4.3.

Appendix VII Data sources, calculations and final values for Resource Mobilisation for tidal power in the United Kingdom

Literature search has resulted in an overview of financial measures for the stimulation of tidal power. When a measure was for marine or ocean energy in general and the specific budget for tidal power could not be found, this budget would be divided by 2. The literature has resulted in the following funding schemes:

- Funds by the UK Ministry of Energy (1976-2000), the UK Department of Trade and Industry (2001-2005) or the Department of Business, Enterprise and Regulatory Reform (2006-now). For the period 1976-2000 this information was found in BERR sources (2007). For 2001-2007 these funds consisted of 16 projects of which all data and status of progress and planning could be found in the DTI annual report of 2004 (DTI, 2005). Most of these projects were funded under the Marine Renewables Deployment Fund mobilized in 2004, which was 25 million GBP (AEA, 2006).
- Funds by the Carbon Trust. The Carbon Trust is the funding agency of the MEC and the MEA: the Marine Energy Challenge included 3 million GBP funding to accelerate the development of 8 ocean energy technologies, allocated in 2001 and succeeded in 2003 and 2006 (AEA, 2008; Carbon Trust, 2008). The MEA is the Marine Energy Accelerator and is regarded as the follow-up of the MEC. The MEA started in 2007 and "*aims to accelerate progress in cost reduction of marine energy (wave and tidal stream energy) technologies, to bring forward the time when marine energy becomes cost-competitive so that significant carbon emissions reductions are achieved*" (Carbon Trust, 2008). All values for MEC and MEA are divided by 2.
- The Technology Program of the New Energy Act in 2000. This was a single subsidy to marine energy of 32 million GBP of which a part was allocated to the establishment of the EMEC in Corkney (AEA, 2008).
- Other subsidies to the establishment of EMEC. The EMEC was subsidized by various organisations. The funding that is not included in other mentioned programs was calculated based upon information on total budgets and funds by EMEC itself. The Scottish Executive, the Carbon Trust and the MRDF are included in other categories. The rest of the funds is 5 million GBP, which is allocated in the years 2002 and 2005 (EMEC, 2008c), of which is assumed that half is allocated each year, so 2.5 million in 2002 and 2005. Two of the main sources of this 5 million GBP are the Regional Development Funds budget from the European Commission and the Highlands and Islands funds (EMEC, 2008c), but exact information of the sources of this 5 million could not be found.

- The Scottish Executive. The main goal of their financing was the EMEC in the North of Scotland. This was done via a few programs. One large program is the wave and tidal energy support scheme of 13 million GBP starting in 2006. This is about 6.5 million GBP to tidal power (AEA, 2006). In 2007 Scotland allocated 1.2 million GBP to the EMEC and 7 million GBP to basic research on tidal power. The figures of 2002 to 2005 are all allocated to the EMEC. (EMEC, 2008c).

Table 24 Data on Resource Mobilisation for tidal power in the UK

	All values are expressed in millions GBP						
Year	**Ministry of energy / DTI / BERR**	**Carbon Trust**	**NEA/ Technology Programmes**	**EMEC other partners**	**Scottish Executive**	**Total funds**	**Standar-dised value**
1976	2.4					2.4	0.097561
1977	3.4					3.4	0.1365854
1978	9.8					9.8	0.3902439
1979	14.6					14.6	0.5853659
1980	12.2					12.2	0.4878049
1981	9.8					9.8	0.3902439
1982	4.9					4.9	0.195122
1983	2.4					2.4	0.097561
1984	2.0					2.0	0.0780488
1985	1.0					1.0	0.0390244
1986	0.5					0.5	0.0195122
1987	3.4					3.4	0.1365854
1988	2.4					2.4	0.097561
1989	1.5					1.5	0.0585366
1990	2.9					2.9	0.1170732
1991	2.9					2.9	0.1170732
1992	0					0	0
1993	0.5					0.5	0.0195122
1994	0					0	0
1995	0					0	0
1996	0					0	0
1997	0					0	0
1998	0					0	0
1999	0					0	0
2000	0.5		16			16.5	0.6595122
2001	0.036	1.5				1.5	0.06144
2002				2.5	5.15	7.7	0.306
2003	1.6	2			2	5.6	0.224
2004	25					25.0	1
2005				2.5	2.2	4.7	0.188
2006		2			6.5	8.5	0.34
2007	5.7	1			8.2	14.9	0.596

Appendix VIII Data sources, calculations and final values for Lobby Activity and Creation of Legitimacy for tidal power in the United Kingdom

Literature search has resulted in the following events and advocacy coalitions that directly or indirectly create legitimacy for tidal power. It is hard and ambiguous to determine the most influential events for the development of tidal power. After comparing some potential events in the pre study, the oil crises and Chernobyl were selected as those key events that may have triggered follow-up events in creating legitimacy for alternative energy sources.

- The oil crises in 1973 an 1979. The oil crises made European countries aware of their dependency on fossil fuels from the oil and petroleum exporting countries (OPEC). The crises in the 1970s created (political) interest in alternative sources of energy, among which renewable energy types. Although tidal power technology was still in a very early development phase, these events may have triggered the start of its development. Below more information on the 1973 oil crisis is given.
- The Chernobyl disaster of 1986. In those countries were nuclear energy was chosen as an important and substantial solution to the dependency on fossil fuels from OPEC, the Chernobyl disaster may have caused renewed interest into renewable energy sources, not including any kind of nuclear power generation. Below more information on the Chernobyl disaster is given.
- The Renewable Energy Association (REA) – known as the Renewable Power Association up to 2005 - was established is 2001 and represents the British renewable energy producers. It also promotes the use of.1 renewable energy to the UK consumers and politics (REA, 2009). The Ocean Energy Group is part of the REA and specifically promotes ocean energy technology. This activity creates special legitimacy for tidal power and therefore REA-OEG gets 0.1 points for the period since its establishment in 2001.
- The Renewable Energy Foundation (REF) was established in 2004 *"by a group of individuals and conservation bodies concerned at the lack of balance in the United Kingdom's energy policy, and in the information available regarding the major renewable energy technologies. REF has attempted to supply this deficit by commissioning studies from major academics and professionals."* (REF, 2009).
- The European Ocean Energy Association (EU-OEA) is established for the execution of the European Framework Project 'Coordinated Action on Wave and Tidal Energy'. It is thus a wide European network of various types of actors active in research and demonstration of wave and tidal energy. It was founded in 2002 (EU-OEA, 2009).

The events got 0.5 points for the year they had place and the lobby groups got 0.1 point for each year that they were active. No data table is drawn, but the results are depicted in paragraph 4.3.

Background information on the Oil crisis of 1973 and the Chernobyl disaster is given in the following two paragraphs.

The 1973 oil crisis

"The 1973 oil crisis started on October 15, 1973, when the members of Organization of Arab Petroleum Exporting Countries or the OAPEC (consisting of the Arab members of OPEC plus Egypt and Syria) proclaimed an oil embargo "*in response to the U.S. decision to re-supply the Israeli military during the Yom Kippur war.*" OAPEC declared it would no longer ship oil to the United States and other countries if they supported Israel in the conflict. Independently, the OPEC members agreed to use their leverage over the world price-setting mechanism for oil in order to stabilize their real incomes by raising world oil prices. This action followed several years of steep income declines after the end of Bretton Woods, as well as the recent failure of negotiations with the "Seven Sisters" earlier in the month.
For the most part, industrialized economies relied on crude oil and OPEC was their predominant supplier. Because of the dramatic inflation experienced during this period, a popular economic theory has been that these price increases were to blame, as being suppressive of economic activity.

However, the causality stated by this theory is often questioned. The targeted countries responded with a wide variety of new, and mostly permanent, initiatives to contain their further dependency. The 1973 "oil price shock", along with the 1973–1974 stock market crash was regarded as the first event since the Great Depression to have a persistent economic effect."
Source: Perron, 1988 and Barskey & Kilian, 2004

The 1986 Chernobyl disaster

The Chernobyl disaster was a nuclear reactor accident in the Chernobyl Nuclear Power Plant in Ukraine, then part of the Soviet Union. It is considered to be the worst nuclear power plant disaster in history and the only level 7 instance on the International Nuclear Event Scale. It resulted in a severe release of radioactivity into the environment following a massive power excursion, which destroyed the reactor. Two people died in the initial steam explosion, but most deaths from the accident were attributed to radiation.
On 26 April 1986 01:23:45 a.m. (UTC+3) reactor number four at the Chernobyl plant, near Pripyat in the Ukrainian Soviet Socialist Republic, exploded. Further explosions and the resulting fire sent a plume of highly radioactive fallout into the atmosphere and over an extensive geographical area. Four hundred times more fallout was released than had been by the atomic bombing of Hiroshima.
The plume drifted over extensive parts of the western Soviet Union, Eastern Europe, Western Europe, Northern Europe, and eastern North America, with light nuclear rain falling as far as Ireland. Large areas in Ukraine, Belarus, and Russia were badly contaminated, resulting in the evacuation and resettlement of over 336,000 people.
Source: IAEA, 2008

Appendix IX Introduction on photovoltaic technology

Photovoltaic power (PV) is the most widely applied type of solar energy worldwide. Besides photovoltaic energy, also concentrated solar power or thermal power are technologies that transform solar energy into electricity and / or heated water, but this thesis only includes photovoltaic technology. Furthermore, only terrestrial use of photovoltaic technology is considered.

The European Photovoltaic Industry Association (EPIA) recommends photovoltaic systems for the following ten reasons (EPIA, 2004: 5):

1. The fuel is free.
2. It produces no noise, harmful emissions or polluting gases.
3. PV systems are very safe and highly reliable.
4. PV modules can be recycled.
5. It requires low maintenance.
6. It brings electricity to remote rural areas.
7. It can be aesthetically integrated in buildings.
8. The energy payback time of a module is constantly decreasing.
9. It creates thousands of jobs.
10. It contributes to improving the security of Europe's energy supply.

There are two main types of PV technology: crystalline silicon technology and thin film technology. Within the crystalline type, there are monocrystalline cells, polycrystalline cells and ribbon sheets. These cells together represent about 90% of the market today. Their efficiencies have increased from about 10% in 1990, to 13% today, with the best performers having an efficiency of 17% (EPTP, 2007).

Figure 36a Crystalline silicon solar modules

Source: BWI, 2007: 26

Figure 36b A thin film application

Source: Würth Solar, 2009

The main difference between crystalline cells and thin film cells is that thin film cells are directly deposited on large area substrates such as glass, stainless steel or plastic foils, instead of first producing separate cells and then putting these together in a module. Thin film cells are cheaper because they use less expensive materials (especially silicon), but also have a lower efficiency rate, varying between 7% and 9% for commercially available cells (EPTP, 2007). The main types of thin film cells are amorphous silicon, cadmium telluride, copper indium / gallium diselenide / disulphide (CIS / CIGS) and multi junction cells, of which the first is the mostly applied one now.

Appendix X Answers of the experts on photovoltaic power in Germany on the questions regarding the success factors for PV in Germany

In this section the results of the interviews on success factors of PV in Germany are presented. Besides general background on each of the functions, the question was asked how the expert explains the success of PV. They answered this question either by pointing out two or three main reasons, or by giving a larger (historic) overview of events and context of how the success of PV can be explained. Although 12 interviews with experts on the German PV system were held, 4 of them did not reveal enough information on key success factors. Only the experts who had a well-explained answer are described here.

1. *Expert A*

PV is not yet successful. It takes 20-30 more years to be fully successful and unsupported. A large system part is missing: the users (those whose apply it), such as the electronics suppliers, as LED lamps producers. Producers of electrical consumer goods do not integrate PV possibilities. When government support goes back in the coming years, the growth of the industry will slow down and the industry may get destructed. Nowadays it already is hard to lower costs by 10% every year to stay competitive. It has been hard in the past as well to make large efficiency gains and reach cost effectiveness. Not all machinery manufacturers are able to build better machines. The consumers of these machines have to help them.

> *"The industry is not a market, but a supported system. The customers of electricity pay an extra fee and thereby the solar industry is supported. This is the best way at the moment, but it is not good for the long term. Now it helps a lot to reach market introduction of PV technology."*

Three main explanations for the 'success' are the continuous and long term funding by the German government of both research and pilot projects, and economical support by feed-in tariffs. The start of the EEG characterized the take-off of the growth period.
He ranks the functions as follows, starting with the most important function: Market Formation (1), Knowledge Development, Knowledge Diffusion and Entrepreneurial Activity (2), lobby activities (3) and last expectations triggered by media attention (4).

2. *Expert B*

The success of PV in Germany can be explained by the following reasons:

- Feed-in tariffs and public funding for private activities such as the 1,000 roofs program.
- The mood of the people in Germany. For many years the general public values sustainable development high. E.g. recycling has a long tradition. Somehow Germany is forced to live ecologically responsible. The willingness to invest private money into renewables is also common. First there was a mostly idealistic approach to save energy, but now it is also economically attractive which made it even more appealing. Also the green political parties that were in charge for many years in the federal government, built many green policy. A lot of people voted green parties because they supported their ideas, although sometimes unrealistic. Other parties also changed towards more green thinking.

Were there any lobbies and what was their effect?

There was almost no industrial push for the feed-in tariffs or other policy on renewables. The industry was only very small back then. The policy pushed the industry.

3. *Expert C*

The success of PV in Germany can be explained by the following reasons:

- Very attractive feed-in tariffs.
- A long PV research tradition. Firms that were started in the beginning, profited from the research institutes: spin-offs en labour moved to companies from research institutions.

Do you experience lobbies for funding?

Always. The last years the available funding has increased little, but many more players are in the field, which raises competition. Especially research institutes lobby, but also universities and firms. Research institutes can also get funds from industry for applied research, but when they would do that too much, they would loose in the end because they do not build fundamental (= competitive) knowledge anymore. They need public funding the most, because they have no other income sources. Besides these strategic reasons, also status rises when a research institution does more fundamental instead of applied research.

Firms and research institutes both separately and together lobby for more funding.

NGOs only seldom visit the ministry of environment. They more lobby at the department that makes policy for the feed-in tariffs.

4. *Expert D*

Research funds and feed-in tariffs were both necessary for success. Without one of these the success would not have been there. The 1,000 roofs program in the beginning of the 1990s brought some production, but this was only for testing purposes. When it stopped in 1994, all German producers stopped, except Organisation D. Also Siemens and DASA shut down their German departments. Siemens went to the US. Then the new programmes came and Japanese jumped in. In 100,000 roofs program Japanese firms sold much. Continuity is important.

Luckily in 1998 a feed-in tariff was introduced, but the German feed-in law does not differentiate between German, Japanese, US or Chinese modules. In the mean time the Japanese grew much and until 2005 they were the world leading manufacturers. German firms really fell behind from not producing anything. German firms had to produce extra good products, because the wages are higher here. You need to produce the highest quality to compensate for the costs. For this extra good research is needed.

The rules will change when grid parity is reached [fully commercial phase, MvdK]. In 2011-2015 this will happen. When it is cost competitive, and economically and ecologically good, no market stimulation will be needed anymore. Now research is focused on going down the learning curve as fast as possible.

5. *Expert E*

In 1993 the 1,000 roofs program had ended and many manufacturers stopped their activities completely or moved to foreign markets. Siemens was one of the major players during the 1,000 roofs program, but stopped its activities in 1993 and moved its PV activities to California. The 1,000 roofs program was mainly meant for testing of modules in field projects and included mostly applied research. However, the German government did not continue its policy.
The little demand that was left in Germany after 1993 was mainly supplied by Japanese firms such as Sharp. Especially when 100,000 roofs program was introduced in 1998 it was mainly the Japanese suppliers who profited from the growing market.
In 2002 the Germans realized that they had to catch up with the Japanese and in 2004 a higher feed-in tariff was introduced to create more demand for PV modules. The Erneuerbare Energiengesetz from 2004 created major growth of the industry. Not only the feed-in tariffs were attractive, but also the utilities were forced to buy electricity supplied by renewable energy sources and to connect the systems to the grid. This last measure was also very important. Utilities had to follow the rules of supply from the government and they had to guarantee the electricity sales of solar panels.
Nowadays the development of large MW solar plants are decreasing; there are only a few installed this year. This is also influenced by the gradual reductions of the feed-in tariffs. Small roof top systems are still very successful, because their policy is more successful and investing is financially more attractive.

6. Expert F

The success of PV in Germany can be explained by the following reasons:

- Continuous funding of research since 1974 (after the first oil crisis) and therefore a continuous build up of the technologies.
- A good technology base in Germany: presence of expert equipment manufacturers in e.g. semiconductors and glass, coatings, flat panel displays manufacturing and more. They were already there and very involved in the early take-off of PV in Germany.
- Cross-fertilization of solar cell producers and glass industry, and other industries was successful. In fact it where the manufactures of production equipment that pushed the development of the PV industry. Production of PV modules is very similar to production of flat-panel LCD-televisions. The same production technology is used for PV and this caused that production of PV modules became very efficient and hence strong reduction of costs of PV modules and hence increase in demand. The whole environment was enabling innovation.

Did this take-off have a specific event that initiated the growth?

It was mostly a continuous process; there was no specific date. If one had to tell, it would be the 1990s. In the late 1990s the equipment companies pushed the development of production lines and sales. The better the sales of solar cells, the more sales they had of their equipment machinery.

Did lobbies aid this take-off?

This is a sensitive subject, but the EPIA may have pushed a lobby in the name of the equipment manufacturers. They have been very successful with this.

What is the role of the EEG?

"It was really important to have feed-in tariffs". In the beginning there was the 1,000 roofs program, but this alone was not enough. The feed-in tariffs ("a broader funding scheme") of the EEG were necessary for the successful market introduction.

The EEG is really good. It costs about 1 billion euros, but nobody realizes where this money comes from. There is no ministry that pays a lot, but every energy consumer in the country pays a very little amount. Therefore it does not hurt anybody. This method is therefore very friendly. It is a save long-term instrument which provides continuity in the policy.

Did media attention influence the development of PV visibly?

"Personally, I have no idea". Maybe their influence could do more in this respect.

7. Expert G

The first success factor of PV in Germany is that the central government has a stimulating drive by believing in the possibilities of solar power. This enthusiasm is widely spread up to the most powerful people. The government translates their vision into effective policy instruments and are now afraid to do new things, set trends and enlarge the industry. They spend a lot of money on these goals, despite criticism on the high expenditures and maintain strong continuity in their policy.
Germany is a real industry-nation: they do not only want to implement technology, but also to manufacture the systems themselves and to create employment throughout the country thereby.
On the other hand, the Dutch government is too lazy. They are afraid to be the first-movers and should copy German policy. Germans have 'vision, passion and conviction on a high level'. For example Hermann Scheer, the politician from the SPD has a strong standpoint and continuously acts to make it a success.
The German government had a consistent vision on the importance of solar energy: they wanted to created markets and economic growth and make German companies global competitors. They say to solar energy companies 'you are welcome; what can we do for you?' The Dutch government is too sceptic. They do not want to invest and make new policy, but only buy successful concepts from abroad.

The second reason for the success was the continuous structural funds for research and development. A substantial amount of funding was always available, which upgraded the knowledge base worldwide.

The third explanation is the positive national and international market developments. This started with the 1,000 roofs program, which was a small pilot and the experiences from this project served further development of technology and policy. By having only a small project, emphasis could be put on the development of high quality processes and products.
For example in Spain and China also solar cells are produced, but the quality of the German cells is much better. The German customer likes high tech products, while the Dutch for example only want cheap products.

Furthermore the German civil servants have good knowledge of technology and can therefore make better policy. For example the Dutch policy makers are not good. Also, German organizations like firms and research institutes like to provide education material to scholars and students to teach them about technology; the German installation firms are very customer friendly and provide good services when the solar cells do not work anymore.

8. Expert H

The success of PV in Germany can be explained by the following reasons:

- The feed-in tariffs: initiated by a green-red government.
- Attractive East Germany development programmes. When you build a company there, you get 50% public funding. That is why these expensive high tech firms have started there. Company H also based its scaling up activities for that reason in East Germany.

Now that the government is more liberal and Merkel is president renewables get less support. Liberals do not like subsidies and Merkel personally is in favour of nuclear energy. The government cannot change existing long-term policy, but some kinds of policy may be cut down. He expects that solar energy will neither be made more attractive nor less; also because of the current unemployment in East Germany.

Transcribing the interview answers to the importance of functions

These interview outcomes are restructured into the opinions of the experts on the importance of the functions. Those experts who appoint aspects of a function to be important for the take off of the technological innovation are named for each function with a short description of what they say to be a crucial success factor for PV in Germany.

F1: Entrepreneurial Activity
- Expert A values Entrepreneurial Activity of medium importance for the success of PV in Germany.

F2: Knowledge Development
- Expert C: a very long PV research tradition
- Expert F: continuous funding of research since 1974
- Expert G: the continuous availability of structural funds for solar energy research. The knowledge produced in Germany strengthened the global knowledge base.

F3: Knowledge Diffusion
- Expert F: cross fertilization of related industries such as producers of glass, semiconductors, coatings, flat panels. They were already involved in the early take-off of the PV industry.

F4: Guidance of the Search
- Expert A values expectations raised by media as one of the least important functions.
- Expert B; 'the mood of the people in Germany': a long tradition of eco-friendliness and wide public support for green parties in the parliament.

- Expert F: no idea whether media attention has helped the successful development.
- Expert G: the spirit from the central government and its civil servants to make solar energy a success. The government dares to make new policy and consistently continues its efforts to make it a success. Germany is a real industry-nation and develops high quality products. Furthermore, the German policy makers have a good knowledge base of PV, which improves policy.

F5: Market Formation
- Expert A: the economic support that was created by the feed-in tariffs. The start of the EEG in 2004 characterized the take-off of the growth period. Expert A values Market Formation as the most important function.
- Expert B: feed-in tariffs and funding of the 1,000 roofs program.
- Expert C: very attractive feed-in tariffs
- Expert D: feed-in tariffs, the 1,000 roofs program and the 100,000 roofs program. Especially the higher feed-in tariff of 2004 triggered the German industry.
- Expert E: the EEG from 2004 triggered the growth of the German industry; and utilities were forced to guarantee the sales of electricity from renewable sources. It depends on the attractiveness of the feed-in tariffs to what extent it triggers the demand in the market.
- Expert F: the broader funding scheme of the EEG was really important.
- Expert G: the 1,000 roofs program triggered improvement of technology and policy, whereupon continued policy and production could be based.
- Expert H: the feed-in tariffs as initiated by a green-red government; and the development programs for East Germany, which offer 50% public funding for starting firms.

F6: Resource Mobilisation
- Expert D: federal research funds
- Expert G: the substantial amounts of money spent on research and pilot projects
- Expert J: the continuous funding by the German government of research and development projects.

F7: Lobby Activity and Creation of Legitimacy
- Expert A values lobby activities as one of the least important functions.
- Expert B: almost no industrial push for the feed-in tariffs: the policy has pushed the industry.
- Expert F: the EPIA may have acted on behalf of the equipment manufacturers for favourable regimes. Also, the equipment manufacturers on their own pushed the industry forward in the beginning of the 1990s.

Appendix XI Data sources, calculations and final values for Entrepreneurial Activity for photovoltaic power in Germany

Entrepreneurial Activity per year is measured with two dimensions and the following indicators:
- The installed capacity of PV modules per year. This is measured as the installed area in 1,000 m^2 covered with PV modules in Germany by German firms. For 1990 – 2007 these data were available through the Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU, 2008a). For the period 1981-1989 a correction value was formulated based on information form the European Solar Thermal Industry Association (ESTIF, 2004) on the area of PV modules installed per year in Europe. The value of ESTIF for the area in 1990 (i.e. 500,000 m^2) was coupled to the value for the area in Germany in 1990 (i.e. 340,000 m^2), resulting in a divider of 1,47. Thus, the European values for installed area were divided by 1,47 to obtain a representative value for installed area of PV modules in Germany.
- The size of the PV industry. This is measured as the cumulative number of start-ups and firms per year. Two lists formed our selection of firms representing the PV industry and its sizes' development over time. The first lists sums the 56 leading PV equipment manufacturers in Germany (Invest in Germany, 2008a) and a second list considers the 62 leading PV producers in Germany (Invest in Germany, 2008b). Of each of the companies on these two lists the foundation year was searched for on the Internet and the number of start-ups per year was counted this way. Then, a cumulative sum was made of all firms in place per year. One correction was made, based on the interview sections with Mr. Räuber (2009), Mr. Expert A (2009) and Mr. Expert D (2009), who acknowledged there was a shakeout in the industry in the mid 1990s due to a demand decrease. It is assumed that half of the industrial firms stopped their PV activities in those days. The firms that are included in the start-ups count and their foundation years are presented below.

The data for the two indicators are standardized to a 0-1 scale in order to create a final value for Entrepreneurial Activity per year. This calculation was explained in Chapter 3. The results of both dimensions are presented below.

Table 25 Firm selection for PV industry development and their foundation years

Reference number	Company	Year that involvement in PV technology was started
1	Abakus solar AG	1995
2	ACI-ecotec St. Georgen	2004
3	AiC Chemnitz	irrelevant
4	ALD VacuumTechnologies Hanau	2007
5	Aleo Solar Prenzlau	2001
6	Algatec Elsterwerda	no data
7	Amb bernhard brain Gersthofen	1995
8	Applied Materials Alzenau	1989
9	Archimedes Solar Stuttgart	2002
10	Arise Technologies Bischofswerda	2008
11	Arntjen Solar GmbH	no data
12	ASi Industries3 Arnstadt	1997
13	Asola Erfurt	2001
14	ASYS Automatisierungssysteme	1992
15	Avancis Torgau	1981
16	Calyxo Thalheim	2004
17	Carl Baasel Starnberg	1995
18	Caverion Stuttgart	irrelevant
19	Centrosolar / Solara Wismar	1997
20	Centrosolar Group AG	2005

21	Centrotherm Photovoltaics Blaubeuren	1997	
22	CGS / PVA Tepla Asslar	no data	
23	CIS-Solartechnik Bremerhaven	1999	
24	City Solar AG	2003	
25	Colexon Energy AG	2003	
26	Concentrix Solar Freiburg	2005	
27	Conergy Frankfurt	1998	
28	CSG Solar Thalheim	2004	
29	Decker Berching	2005	
30	Donauer Solartechnik Vertriebs GmbH	1995	
31	Donauer Solartechnik Vertriebs GmbH in Nürnberg	2001	
32	Energiebau	1983	
33	Energiebau Solarstromsysteme GmbH	2001	
34	EPV Solar Energy Senftenberg	2008	
35	ersol Solar Energy AG	1997	
36	Ersol Thin Film Erfurt	1997	
37	Feintool Automation Berlin	irrelevant	
38	FHR Anlagenbau Ottendorf-Okrilla	2000	
39	First Solar Frankfurt	1999	
40	G&N Erlangen	2000	
41	Gebrüder ScOrganisation Cd Freudenstadt	1998	
42	Global Solar Energy Berlin	1996	
43	GSS Löbichau	1992	
44	Heckert Solar Chemnitz	2001	
45	Herbert Arnold Weilburg	no data	
46	HMS Höllmüller Herrenberg	no data	
47	IB Vogt Berlin, Thalheim	1998	
48	IBC SOLAR	1982	
49	IMO Antriebseinheit GmbH & Co. KG	irrelevant	
50	InnoLas Krailling	2001	
51	Intico Solar Halle	2007	
52	Inventux Berlin	2007	
53	IRES GmbH	2004	
54	Jenoptik Automatisierungstechnik Jena	1998	
55	Johanna Solar Technology Brandenburg	2006	
56	Joint Solar Silicon	2002	
57	Jonas & Redmann Photovoltaics Berlin	1999	
58	JRT Photovoltaics	2008	
59	juwi solar GmbH	1999	
60	K&S Solarsysteme GmbH	2000	
61	KOSTAL Industrie Elektrik GmbH	1998	
62	KOSTAL Solar Elektrik GmbH	2006	
63	Kuka Systems Augsburg	2005	
64	Leybold Optics Alzenau, Dresden	no data	
65	Logomatic Mainaschaff	1989	
66	Lotus Systems Gutmadingen	no data	
67	LPKF SolarQuipment Suhl-Friedberg	no data	
68	M+W Zander FE GmbH	2001	
69	Malibu Osterweddingen	2007	
70	ManzAutomation Reutlingen	1993	
71	Maschinenbau Gerold Nettetal	2004	
72	Masdar PV Arnstadt	2008	
73	Meier Vakuumtechnik Bocholt	1999	
74	Minitec Maschinenbau Waldmohr	no data	
75	Mola Solaire Pasewalk	2003	
76	MondragonAssembly Stockach	no data	

77	M-O-T Speyer	no data	
78	Nanosolar Luckenwalde1	2006	
79	natcon7 GmbH	irrelevant	
80	Odersun Frankfurt (Oder), Fürstenwalde	2005	
81	Olbricht Hamminkeln-Brünen	no data	
82	Phoenix Solar AG	1999	
83	PV Silicon Bitterfeld-Wolfen	1997	
84	PV Silicon spin-off Crystalox	1999	
85	PVflex Solar Fürstenwalde Pilot	no data	
86	Q-Cells	1999	
87	Q-Cells Thalheim	1999	
88	Ramgraber Hofolding b. Braunthal	no data	
89	Reis Robotics Obernburg	no data	
90	Rena Gütenbach, Berg	1993	
91	Robert Bürkle Freudenstadt	no data	
92	Robust Remscheid	irrelevant	
93	Roth & Rau Hohenstein-Ernstthal	1996	
94	Scheuten Solar Cells Gelsenkirchen	2002	
95	Scheuten Solar Germany GmbH	1999	
96	Schiller Automation Sonnenbühl-Genkingen	no data	
97	Organisation D Alzenau	2001	
98	Organisation D Thin Film Jena, Putzbrunn	1993	
99	Schüco International KG	1991	
100	SES 21 AG	2001	
101	Signet Solar Mochau	2006	
102	Singulus Kahl	irrelevant	
103	SMA Technologie AG	1981	
104	Solar-Fabrik AG	1996	
105	Solarion Leipzig	2000	
106	Solarnova Wedel	1996	
107	SolarTec Munich	2002	
108	Solarwatt Heilbronn	1993	
109	Solarwatt Cells Dresden	2005	
110	SolarWorld AG	1998	
111	Soleos Solar GmbH	1993	
112	Solibro Thalheim	2001	
113	Solland Solar Cells Aachen	2004	
114	Solon Berlin, Greifswald	1997	
115	Somont Umkirch	no data	
116	Sontor Thalheim	2006	
117	Stangl Semiconductor Eichenau, Puchheim	1998	
118	Sulfurcell Berlin Pilot	2003	
119	Sunfilm Großröhrsdorf	2006	
120	Sunset Energietechnik GmbH	no data	
121	SunWare Duisburg	1987	
122	Sunways Konstanz, Arnstadt	1993	
123	Teamtechnik Freiberg am Neckar, Berlin	2003	
124	Thieme Teningen	irrelevant	
125	USK Karl Utz Sondermaschinen Limbach-Oberfrohna	1990	
126	Valentin EnergieSoftware GmbH	1988	
127	Ventotec Future Energy GmbH	1997	
128	Viessmann Werke GmbH & Co. KG	no data	
129	Von Ardenne Anlagentechnik Dresden	no data	
130	Wacker Organisation D Alzenau, Jena	2007	
131	Webasto Solar Landsberg/Lech	2007	
132	Würth Solar Schwäbisch Hall	no data	

No data =	*no data found on the start of wind power related activity*
Irrelevant =	*a too small affiliation to the wind power industry*

Table 26 Data for Entrepreneurial Activity for PV in Germany

Year	Number of start-ups	Shake-out after the 1,000 roofs program stopped	Cumulative number of start-ups (industry size)	Standar-dised value	Area of solar modules built in Germany in 1,000 m2 per year	Area of solar modules built in Europe in 1,000 m2 per year	Correction value for 1981-1989 (divided by 1.47)	Standar-dised value	Average of the two standar-dised values	Final value
1980	0		0	0				0	0	0
1981	2		2	0.022727		100	68.027211	0.047974	0.035351	0.0366
1982	1		3	0.034091		-50	-34.01361	0	0.017045	0.0176
1983	1		4	0.045455		50	34.013605	0.023987	0.034721	0.0359
1984	0		4	0.045455		50	34.013605	0.023987	0.034721	0.0359
1985	0		4	0.045455		-25	-17.0068	0	0.022727	0.0235
1986	0		4	0.045455		-75	-51.02041	0	0.022727	0.0235
1987	1		5	0.056818		0	0	0	0.028409	0.0294
1988	1		6	0.068182		0	0	0	0.034091	0.0353
1989	2		8	0.090909		100	68.027211	0.047974	0.069442	0.0719
1990	0		8	0.090909		100	68.027211	0.047974	0.069442	0.0719
1991	1		9	0.102273	128			0.090268	0.09627	0.0997
1992	2		11	0.125	122			0.086037	0.105518	0.1092
1993	6		17	0.193182	159			0.11213	0.152656	0.158
1994	0	-9	8	0.090909	197			0.138928	0.114919	0.119
1995	4		12	0.136364	213			0.150212	0.143288	0.1483
1996	4		16	0.181818	298			0.210155	0.195987	0.2029
1997	8		24	0.272727	364			0.2567	0.264713	0.2741
1998	7		31	0.352273	373			0.263047	0.30766	0.3185
1999	10		41	0.465909	447			0.315233	0.390571	0.4044
2000	4		45	0.511364	643			0.453456	0.48241	0.4994
2001	10		55	0.625	915			0.645275	0.635138	0.6576
2002	4		59	0.670455	550			0.38787	0.529162	0.5478
2003	5		64	0.727273	729			0.514104	0.620689	0.6426
2004	6		70	0.795455	757			0.53385	0.664653	0.6881
2005	6		76	0.863636	962			0.67842	0.771028	0.7982
2006	6		82	0.931818	1418			1	0.965909	1
2007	6		88	1	961			0.677715	0.838858	0.8685

Appendix XII Data sources, calculations and final values for Knowledge Development for photovoltaic power in Germany

The following dimensions and indicators determine Knowledge Development per year:

- The number of publications by German organizations on photovoltaics. The indicator used is the result from an article search in the academic literature database Scopus. This search was on the word photovoltaic in titles, abstracts and keywords. A selection of 40 German organizations was made, which represents the total German research population. This selection of organisations is presented below. This literature search resulted in 1007 articles since 1977 (Scopus search, 2009a). The articles were counted per publications year and then counted for one year earlier. This is because there is a time lag between the period of knowledge creation and the date the article is published.
- Patents are the second indicator for knowledge production, especially to measure tacit and high tech knowledge, as is photovoltaics. The European Patent Office was chosen as the most applicable patent office. Also for this indicator a time lag is applied, being 4 years (see section 3.2.1 for the explanation). The search resulted in 2193 patents (Scopus search, 2009b).

- European budgets for solar energy research are another indicator for Knowledge Development. Since no data was available on budgets and outputs of the single research projects, the number of organizations that were involved in European Framework Programme research in solar energy was used as indicator for the size of Knowledge Development from European budgets. Only for FP5 and FP6 this detailed information was available (Technopolis Group, 2008). For FP4 and earlier a correction value was used. The calculation of this value is explained in Appendix VI.
- The fourth indicator is the German federal budgets spent on PV research per year. This information was retrieved from the Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU, 2008b). For each research project the costs of that project were spread over the years that the project was running.

Table 27 Knowledge Development values for photovoltaic research in Germany

Year	Number of publications on PV by German organisations (-1 year)	Standard-ised value	Granted patents on PV technology at the European Patent Office (-4 years)	Standard-ised value	Number of organisations involved in projects in the EU FPs on solar energy	Compen-sation value for before FP5	Standard-ised value	German research budgets spent on PV research (million euro)	Standard-ised value	Avarage of standar-dised values	Final value
1972	0	0	0	0	0		0	0.1	0.00204082	0.0020	0.00284
1973	0	0	0	0	0		0	0.1	0.00204082	0.0020	0.00285
1974	0	0	0	0	0		0	0.1	0.00204082	0.0020	0.00285
1975	0	0	8	0.03587444	0		0	0.5	0.01020408	0.0153595	0.02142
1976	1	0.01	11	0.04932735	0		0	1	0.02040816	0.0265785	0.03706
1977	2	0.02	21	0.0941704	0		0	1	0.02040816	0.0448595	0.06255
1978	0	0	36	0.16143498	0		0	1	0.02040816	0.0606144	0.08452
1979	1	0.01	34	0.15246637	0	0	0	2	0.04081633	0.0508207	0.07086
1980	3	0.03	53	0.23766816	0	1	0.00191571	3	0.06122449	0.0824626	0.11498
1981	5	0.05	50	0.22421525	0	1	0.00191571	4	0.08163265	0.0892014	0.12438
1982	2	0.02	73	0.32735426	0	1	0.00191571	28	0.57142857	0.2299352	0.32061
1983	32	0.32	46	0.20627803	0	1	0.00191571	28	0.57142857	0.2746661	0.38299
1984	18	0.18	45	0.20179372	0	0	0	31	0.63265306	0.2536117	0.35363
1985	9	0.09	58	0.26008969	0	2	0.00383142	27	0.55102041	0.2257565	0.31479
1986	6	0.06	53	0.23766816	0	2	0.00383142	30	0.6122449	0.2279572	0.31786
1987	11	0.11	53	0.23766816	0	2	0.00383142	31	0.63265306	0.2455592	0.3424
1988	8	0.08	56	0.25112108	0	2	0.00383142	36	0.73469388	0.2669327	0.3722
1989	13	0.13	55	0.24663677	0	2	0.00287356	42	0.85714286	0.3088041	0.43059
1990	6	0.06	39	0.17488789	0	5	0.00862069	46	0.93877551	0.2944934	0.41063
1991	14	0.14	75	0.33632287	0	8	0.01340996	49	1	0.370757	0.51697
1992	17	0.17	41	0.1838565	0	7	0.01149425	41	0.83673469	0.2990846	0.41703
1993	40	0.4	67	0.30044843	0	16	0.02586207	28	0.57142857	0.321202	0.44787
1994	16	0.16	92	0.41255605	0	13	0.0210728	26	0.53061224	0.2784262	0.38823
1995	37	0.37	70	0.31390135	0	22	0.03639847	24	0.48979592	0.2979741	0.41549
1996	31	0.31	104	0.46636771	0	22	0.03639847	27	0.55102041	0.3363968	0.46906
1997	32	0.32	99	0.44394619	0	22	0.03639847	25	0.51020408	0.3230874	0.4505
1998	35	0.35	91	0.40807175	0	124	0.20306513	34	0.69387755	0.3883705	0.54153
1999	57	0.57	94	0.42152466	0	111	0.18199234	28	0.57142857	0.4134874	0.57655
2000	58	0.58	125	0.56053812	170		0.27914614	36	0.73469388	0.5037013	0.70235
2001	49	0.49	111	0.49775785	313		0.51395731	29	0.59183673	0.4591433	0.64022
2002	98	0.98	134	0.60089686	504		0.82758621	21	0.42857143	0.6058153	0.84473
2003	68	0.68	175	0.78475336	609		1	24	0.48979592	0.6136373	0.85564
2004	72	0.72	223	1	496		0.81444992	23	0.46938776	0.6491532	0.90516
2005	71	0.71		1	259		0.42528736	31	0.63265306	0.6388242	0.89076
2006	90	0.9		1	285		0.4679803	36	0.73469388	0.717171	1
2007	100	1		1	213		0.34975369	33	0.67346939	0.7120866	0.99291

Table 28 The selection of German research institutes for the publications counting for Knowledge Development

Reference number	Research institute (number of publications per organisation)
1	Fraunhofer-Institut für Solare Energiesysteme (162)
2	Hahn Meitner Institut Berlin (142)
3	Johannes Kepler Universitat Linz (114)
4	Universität Stuttgart (98)
5	Forschungszentrum Julich in Der Helmholtz Gemeinschaft (66)
6	Siemens (50)
7	Universität Jena (47)
8	Universität Osnabrück (45)
9	McGill University (42)
10	Universität Konstanz (41)
11	Universidade Federal de Santa Catarina (37)
12	Deutsches Zentrum fur Luft- Und Raumfahrt (33)
13	Institut für Solarenergieforschung GmbH Hameln/Emmerthal GmbH Hameln/Emmerthal (31)
14	Universität Kassel (20)
15	Universität Freiburg im Breisgau (18)
16	Solarex Corp (12)
17	Universität Oldenburg (9)
18	Martin-Universität Halle-Wittenberg (8)
19	WIP - Renewable Energies (7)
20	Rheinisch-Westfälische Technische Hochschule Aachen (7)
21	Institute of Physics Nasu (6)
22	Universität Potsdam (6)
23	Technische Universität Ilmenau (6)

Appendix XIII Data sources, calculations and final values for Knowledge Diffusion for photovoltaic power in Germany

The following indicators are used for the composition of a value for the development of Knowledge Diffusion over time for PV.

- Number of conference papers as found in Scopus per year internationally (all conference papers). This would indirectly reflect imported scientific conferences on photovoltaics. The Scopus search resulted in 9205 articles (Scopus search, 2009c).
- Number of conference papers published by German organizations per year. For the selection of research institutes, the same selection is used as for Knowledge Development, which can be found in Appendix V. The search resulted in 343 conference papers (Scopus search, 2009d).
- Number of organizations involved in European research on solar energy. This is the same indicator as used for Knowledge Diffusion. In Appendix VI is shown how the compensation values for earlier than FP5 research are created.

Table 29 Knowledge Diffusion development of PV in Germany over time

Year	Number of conference papers on PV internationally (-1 year)	Standardized value	Number of conference papers on PV by German organisations (-1 year)	Standardized value	Number of organisations involved in projects within the EU FP 5+6 on solar energy	Compensation value for earlier FP programmes	Standardised value	Avarage of standardised values	Final value
1976		0	0	0	0	0	0	0	0
1977	1	0.0010627	0	0	0	0	0	0.000354233	0.000388
1978	3	0.0031881	0	0	0	0	0	0.001062699	0.001165
1979	1	0.0010627	0	0	0	0	0	0.000354233	0.000388
1980	12	0.0127524	0	0	0	1	0.00191571	0.004889367	0.005361
1981	226	0.24017	0	0	0	1	0.00191571	0.080695247	0.088472
1982	387	0.4112646	0	0	0	1	0.00191571	0.137726774	0.151
1983	251	0.2667375	1	0.0151515	0	1	0.00191571	0.094601579	0.103718
1984	641	0.6811902	22	0.3333333	0	0	0	0.338174519	0.370765
1985	584	0.6206164	14	0.2121212	0	2	0.00383142	0.278856332	0.30573
1986	219	0.2327311	0	0	0	2	0.00383142	0.078854185	0.086453
1987	209	0.2221041	1	0.0151515	0	2	0.00383142	0.080362359	0.088107
1988	121	0.1285866	1	0.0151515	0	2	0.00383142	0.049189848	0.05393
1989	144	0.1530287	0	0	0	2	0.00287356	0.051967419	0.056976
1990	200	0.2125399	6	0.0909091	0	5	0.00862069	0.104023211	0.114048
1991	78	0.0828905	2	0.030303	0	8	0.01340996	0.042201178	0.046268
1992	177	0.1880978	1	0.0151515	0	7	0.01149425	0.071581179	0.07848
1993	151	0.1604676	3	0.0454545	0	16	0.02586207	0.077261401	0.084707
1994	317	0.3368757	18	0.2727273	0	13	0.0210728	0.210225245	0.230485
1995	111	0.1179596	2	0.030303	0	22	0.03639847	0.061553705	0.067486
1996	304	0.3230606	10	0.1515152	0	22	0.03639847	0.170324731	0.186739
1997	278	0.2954304	12	0.1818182	0	22	0.03639847	0.171215681	0.187716
1998	126	0.1339001	2	0.030303	0	124	0.20306513	0.122422757	0.134221
1999	76	0.0807651	4	0.0606061	0	111	0.18199234	0.107787847	0.118175
2000	153	0.162593	8	0.1212121	170		0.27914614	0.187650416	0.205734
2001	228	0.2422954	11	0.1666667	313		0.51395731	0.307639801	0.337287
2002	531	0.5642933	31	0.469697	504		0.82758621	0.620525494	0.680326
2003	693	0.7364506	66	1	609		1	0.912150195	1
2004	635	0.674814	29	0.4393939	496		0.81444992	0.642885962	0.704842
2005	833	0.8852285	46	0.6969697	259		0.42528736	0.669161845	0.73365
2006	574	0.6099894	23	0.3484848	285		0.4679803	0.475484839	0.521308
2007	941	1	30	0.4545455	213		0.34975369	0.60143305	0.659394

Appendix XIV Data sources, calculations and final values for Guidance of the Search for photovoltaic power in Germany

Guidance of the Search exists of two dimensions and its indicators are as follows:

- Public awareness: this is measured with a media attention value, being the result of various newspaper searches. Die Zeit was the newspaper that had the largest digital available archive in terms of available years. For the years 1976-1994 the number of articles on certain topics therefore serves as the indicator for media attention in general. Also for the years 1995-2007 Die Zeit is used as an indicator, together with a broader study on Lexis Nexis, an international news paper database. The search terms for both the Die Zeit and the Lexis Nexis search were 'Photovoltaik' or 'photovoltaisch' or 'Solarenergie'. The Die Zeit searches gave 150 hits for Photovoltaik / photovoltaisch and 265 hits for Solarenergie (Die Zeit, 2009). From Lexis Nexis 1482 hits were used for the analysis (Lexis Nexis, 2009b). The selection of newspapers in Lexis Nexis was limited to the following: Die Tageszeitung, Die Welt, Börsen-Zeitung, Berliner Morgenpost, Die Welt am Sonntag and Tages-Anzeiger.
- Governmental awareness. As explained in the method section this value is based on whether a Green party exists in de federal government (0.5 points) and whether it is in the national cabinet (1 point). In Germany this party is Die Grünen and they have been in the cabinet for eight years, making it possible to implement effective policy for renewable energy applications (Die Grünen, 2009).

Table 30 Guidance of the Search for PV in Germany

Year	Articles containing Photo-voltaik, photo-voltaisch or Solar-energie in Die Zeit	Standar-dised value	Number of articles on Lexis Nexis	Standar-dised value	Average value for public aware-ness	Final value public aware-ness	Govern-ment aware-ness value	Average of public and govern-ment values	Final value
1976	0	0			0	0	0	0	0
1977	1	0.0416667			0.041667	0.043849	0	0.0208333	0.026465
1978	2	0.0833333			0.083333	0.087699	0	0.0416667	0.05293
1979	6	0.25			0.25	0.263097	0	0.125	0.158791
1980	5	0.2083333			0.208333	0.219247	0	0.1041667	0.132326
1981	5	0.2083333			0.208333	0.219247	0	0.1041667	0.132326
1982	2	0.0833333			0.083333	0.087699	0	0.0416667	0.05293
1983	7	0.2916667			0.291667	0.306946	0.5	0.3958333	0.502837
1984	0	0			0	0	0.5	0.25	0.317581
1985	1	0.0416667			0.041667	0.043849	0.5	0.2708333	0.344046
1986	6	0.25			0.25	0.263097	0.5	0.375	0.476372
1987	4	0.1666667			0.166667	0.175398	0.5	0.3333333	0.423442
1988	8	0.3333333			0.333333	0.350796	0.5	0.4166667	0.529302
1989	18	0.75			0.75	0.789291	0.5	0.625	0.793953
1990	6	0.25			0.25	0.263097	0	0.125	0.158791
1991	6	0.25			0.25	0.263097	0	0.125	0.158791
1992	8	0.3333333			0.333333	0.350796	0	0.1666667	0.211721
1993	11	0.4583333			0.458333	0.482344	0	0.2291667	0.291116
1994	16	0.6666667	22	0.0995475	0.666667	0.701592	0	0.3333333	0.423442
1995	18	0.75	59	0.2669683	0.508484	0.535123	0.5	0.5042421	0.640551
1996	16	0.6666667	41	0.1855204	0.426094	0.448416	0.5	0.4630468	0.58822
1997	2	0.0833333	49	0.2217195	0.152526	0.160517	0.5	0.3262632	0.41446
1998	17	0.7083333	71	0.321267	0.5148	0.541769	1	0.7574001	0.962144
1999	9	0.375	87	0.3936652	0.384333	0.404467	1	0.6921663	0.879276
2000	9	0.375	76	0.3438914	0.359446	0.378276	1	0.6797229	0.863469
2001	14	0.5833333	105	0.4751131	0.529223	0.556948	1	0.7646116	0.971305
2002	19	0.7916667	79	0.3574661	0.574566	0.604667	1	0.7872832	1
2003	8	0.3333333	106	0.479638	0.406486	0.427781	1	0.7032428	0.893347
2004	9	0.375	66	0.2986425	0.336821	0.354467	1	0.6684106	0.849099
2005	5	0.2083333	155	0.7013575	0.454845	0.478674	1	0.7274227	0.924063
2006	22	0.9166667	168	0.760181	0.838424	0.882347	0.5	0.6692119	0.850117
2007	24	1	199	0.9004525	0.950226	1	0.5	0.7251131	0.921129

Appendix XV Data sources, calculations and final values for Market Formation for photovoltaic power in Germany

The following German policy instruments form input for the values of Market Formation.

Stromeinspeisungsgesetz: 1991

The feed-in tariff of about 8 eurocents (16,61 DM pfennig) was part of the Stromeinspeisungsgesetz or Energy Feed-in Law, which started in 1991. However, the grid operators were not obliged to connect the modules to the electricity grid, resulting in either denied access to the grid for small-scale suppliers or heavy opposition to their attempts (Salje, 1999).

Erneuerbare Energien Gesetz: 2000, 2004

The low feed-in tariff was sustained, but better regulation for connection of electricity from renewable sources into the grid came in place. Also a transition programme was started which would cover de change from the 100,000 roofs program to the EEG of 2004.
In the EEG 2004 the feed-in laws were differentiated for different types of renewable energy sources, differences in energy capacity of the installations and the year the investment was done. For PV modules of three size categories on roofs and noise reduction walls this resulted in the feed-in tariffs in Figure X. Different feed-in tariffs exist for modules on facades of buildings, other surfaces and power plants (Gesetz für den Vorrang Erneuerbarer Energien, 2004).

Figure 37 Feed-in tariffs of PV modules on roofs and noise reduction walls, stated in the EEG 2004

7. Zu § 11 EEG: Mindestvergütungen für Strom aus solarer Strahlungsenergie (Neuanlagen)

	„Anlagen auf Dachflächen und Lärmschutzwänden" (Anlagen im Sinne von Absatz 2 Satz 1)		
Jahr der Inbetriebnahme	bis einschl. 30 kW in ct/kWh	ab 30 kW in ct /kWh	ab 100 kW in ct /kWh
2004	57,40	54,60	54,00
2005	54,53	51,87	51,30
2006	51,80	49,28	48,74
2007	49,21	46,82	46,30
2008	46,75	44,48	43,99
2009	44,41	42,26	41,79
2010	42,19	40,15	39,70
2011	40,08	38,14	37,72
2012	38,08	36,23	35,83
2013	36,18	34,42	34,04

Degression 5,0 %; Vergütungszeitraum 20 Jahre
Der für das Inbetriebnahmejahr der Anlage geltende Mindestvergütungssatz wird über den gesamten Vergütungszeitraum in unveränderter Höhe gewährt.

Source: Gesetz für den Vorrang Erneuerbarer Energien, 2004: 17

For this study the average PV module on roofs and noise reduction walls is chosen as the indicator for Market Formation development. All other feed-in tariffs have values relatively close to this average and the decrease values per year are for all PV systems the same (5%).

The 1,000 and 100,000 roofs program: 1989, 1999

The 1,000 roofs program was in place from 1990 until 1993 and the 100,000 roofs program from 1999 until the end of 2003. Both were considered successful instruments for creation of demand for PV technology in relation to international policies (PV Policy Group, 2006). Also Haas (2003) conducted an international comparison and concludes the following on the impact of the 1,000 roofs program and the differences with the 100,000 roofs program (Haas, 2003: 3):

> *"In 1989 Germany was world-wide the first country that launched a substantial dissemination programme the "1000 roofs program". This program was completed in 1994. Some 2250 German roofs were equipped with PV systems of an average size of 2.6 kWp and a total capacity of about 6 MW. Average system costs were 15000 US$/kWp, average subsidies 70% of the investment costs. During the program and in the aftermath comprehensive investigations on technical and sociological aspects of this program took place. The major results of this program were that PV systems reached a certain standard of technical reliability, that PV system cost dropped, and that the acceptance of this technology increased considerably. Moreover, experiences gained in this program were also used for similar activities in Austria and Japan. […]*
> *Since 1999 a new financial approach is pursued in Germany with the 100,000 roofs programme. Within this programme very attractive credits (soft loans) are provided by the*

public. In the first nine months of this programme about 3000 new projects (about 7000 kWp) have been approved"

Market Formation is composed of the following indicators:

- The availability and height of investment subsidies: this is reflected by the 1,000 roofs program which offered an investment subsidy of 70%, and the 100,000 roofs program which offered attractive loans to customers of PV modules (Haas, 2003). Investment subsidies can have a value of maximum 0.5. The 1,000 roofs program is considered highly attractive and therefore gets the 0.5 points. The 100,000 roofs program was however less attractive financially, but had a larger budget to spend: it is appointed the value of 0.4.
- The other 0.5 points that can be obtained for this functions are made up of the availability and attractiveness of a feed-in tariff. The highest feed-in tariff is assigned the value of 0.5 (i.e. a tariff of 54,6 eurocents / kWh in 2004), and all other feed-in tariff values are calculated relatively to this.

Table 31 Market Formation for PV in Germany

Year	Investment subsidy	Value	Feed-in tariff (eurocent / kWh)	Value	Final value
1988					0.0
1989	1,000 roofs programme	0.5			0.5
1990		0.5			0.5
1991		0.5	8	0.07326007	0.573
1992		0.5	8	0.07326007	0.573
1993		0.5	8	0.07326007	0.573
1994		0.5	8	0.07326007	0.573
1995			8	0.07326007	0.073
1996			8	0.07326007	0.073
1997			8	0.07326007	0.073
1998			8	0.07326007	0.073
1999	100,000 roofs programme	0.4	8	0.07326007	0.473
2000		0.4	8	0.07326007	0.473
2001		0.4	8	0.07326007	0.473
2002		0.4	8	0.07326007	0.473
2003		0.4	8	0.07326007	0.473
2004			54.6	0.5	0.500
2005			51.87	0.475	0.475
2006			49.28	0.45128205	0.451
2007			46.82	0.42875458	0.429

Appendix XVI Data sources, calculations and final values for Resource Mobilisation for photovoltaic power in Germany

This function is composed from only one indicator, which is the funding allocated to PV research, development and demonstration (RD&D) projects per year. These funds are mainly composed from governmental support, but also include private spending in the project or funds made available by research institutes.
The data for this indicator comes from a database from the Bundesministerium für Bildung und Forschung (BMBF, 2009). They operate a national research projects database in which project descriptions and funds of all projects are stored. A selection was made of projects concerning PV, but unfortunately not all PV projects could be selected, because only a search for PV related keywords in the project description was conducted, thereby excluding project that indirectly were related to PV,

but for which this was not found during the keyword search. However, from a comparison with our data selection and the BMU's (2008a) data on funds allocated to PV RD&D per year, it appeared that by this search about ¾ of all projects on PV were included. Therefore it is considered a representative selection.
The difference with the Knowledge Development (F2) indicator is that for Knowledge Development the funds were spread over the years that the research projects were running. For Resource Mobilisation the year before the starting year of the research project is chosen as the year in which the funds were allocated.

Table 32 Resource Mobilisation to PV research, development and demonstration

Year	Funds allocated to PV research in Germany, in Euros	Standardised
1971	132936	0.001970049
1972	0	0
1973	0	0
1974	685130	0.010153314
1975	639115	0.009471389
1976	20408749	0.302448315
1977	1828710	0.027100652
1978	4621058	0.068481957
1979	100459	0.001488758
1980	3391488	0.050260303
1981	24591708	0.364437848
1982	21085309	0.312474627
1983	3331556	0.049372133
1984	26323035	0.390095318
1985	23049819	0.341587768
1986	12884337	0.190939969
1987	32553240	0.482424115
1988	14399709	0.21339709
1989	36224044	0.536823737
1990	7545408	0.111819487
1991	13920578	0.206296587
1992	10816715	0.160298758
1993	9350771	0.138574143
1994	13083402	0.193890026
1995	18107428	0.268343793
1996	9445612	0.139979649
1997	15427712	0.228631632
1998	17370211	0.257418578
1999	13210794	0.195777912
2000	15052144	0.22306588
2001	20952257	0.310502859
2002	22164994	0.32847506
2003	9767723	0.144753186
2004	11306612	0.167558808
2005	32884135	0.487327822
2006	30737523	0.455516008
2007	67478468	1

Appendix XVII Data sources, calculations and final values for Lobby Activity and Creation of Legitimacy for photovoltaic power in Germany

This function is measured by events and the presence of lobby groups, such as industry associations. In the pre-analysis was found that the oil crises of 1973 and 1979 caused global awareness of the

disadvantages of fossil fuel dependency. This creates legitimacy for renewable energy, such as PV. However, the oil crises also caused legitimacy for nuclear energy somehow. Despite global anti-nuclear protests in the 1960s and 1970s, still reactors were being built. The disaster in Chernobyl in 1986 where a reactor crashed, did also increase legitimacy for (safer) renewable energy and thereby PV. No events were found that could have significant impact on PV legitimacy only. Each event gets 0.5 points for the year they caused legitimacy. In Appendix XIII more background information on the 1973 oil crisis and the Chernobyl disaster can be found.
The second indicator is the presence of lobby groups. Two influential associations were identified: the Bundesverband Solarindustrie, later known as the Bundesverband Solarwirtschaft (BSW), and the European Photovoltaic Industry Association. Both lobby groups get 0.1 point for each year they are active. The first one is active since 1979 and lobbies at both national and regional level and says it moves between politics, research and consumers in the solar energy field (BSW-Solar, 2009). The latter was founded in 1985 and nowadays represents 90% of the European PV industry and 85% of the global PV industry with over 200 members (EPIA, 2009). Although this is a Europe broad association, it says it conducts substantial lobby activities for the German industry.

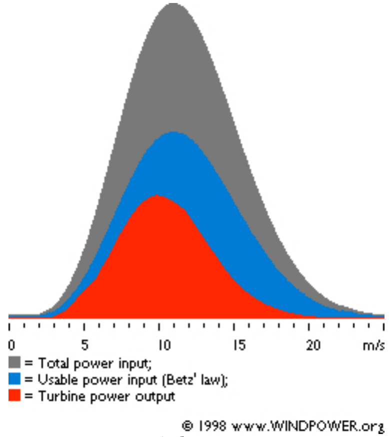
Table 33 Lobby Activity and Creation of Legitimacy for PV in Germany

Year	Bundesverband Solarwirtschaft / Solarindustrie	European Photovoltaic Industry Association	Chernobyl	Oil crisis	Total
1973				0.5	0.5
1974					0
1975					0
1975					0
1976					0
1977					0
1978					0
1979	0.1			0.5	0.6
1980	0.1				0.1
1981	0.1				0.1
1982	0.1				0.1
1983	0.1				0.1
1984	0.1				0.1
1985	0.1	0.1			0.2
1986	0.1	0.1	0.5		0.7
1987	0.1	0.1			0.2
1988	0.1	0.1			0.2
1989	0.1	0.1			0.2
1990	0.1	0.1			0.2
1991	0.1	0.1			0.2
1992	0.1	0.1			0.2
1993	0.1	0.1			0.2
1994	0.1	0.1			0.2
1995	0.1	0.1			0.2
1996	0.1	0.1			0.2
1997	0.1	0.1			0.2
1998	0.1	0.1			0.2
1999	0.1	0.1			0.2
2000	0.1	0.1			0.2
2001	0.1	0.1			0.2
2002	0.1	0.1			0.2
2003	0.1	0.1			0.2
2004	0.1	0.1			0.2
2005	0.1	0.1			0.2
2006	0.1	0.1			0.2
2007	0.1	0.1			0.2

Appendix XVIII Introduction on wind power technology

Wind power is generated by wind speeds between 4 m/s and 19 m/s. In Figure 38 you can see that most power can be generated by wind with a speed of about 10 m/s and that its power revenues are shaped as a parabola.

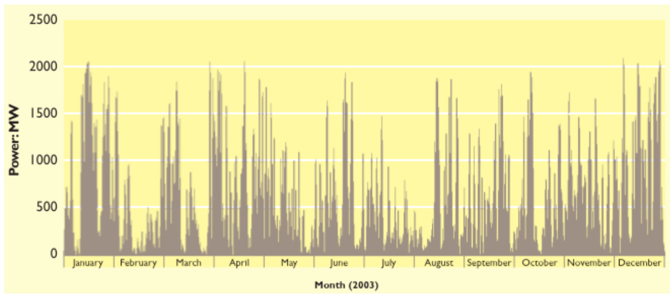
Figure 38 Turbine power output at various wind speeds



Source: Windpower.org, 2009

The variance in wind speeds can be large, which results in large differences in power generating capacity and thus electricity. In Figure 39 you can see that over the year 2003 the power generation per day varies between 50 and 2000 MW.

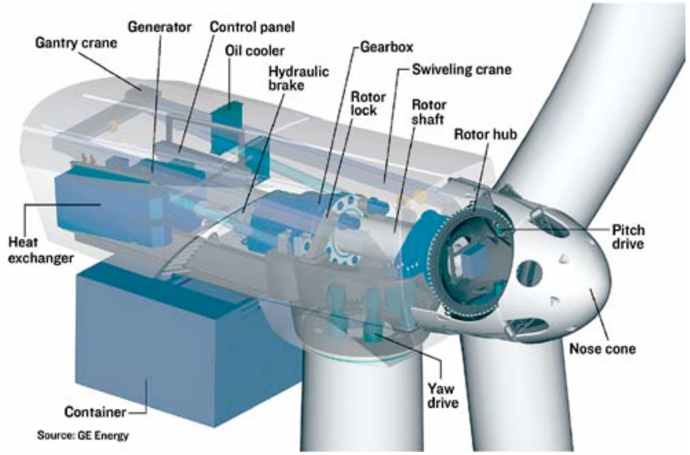
Figure 39 Wind power output per day in 2003



Source: Sharman, 2005: 69

When wind speeds are too high, this may harm the turbine if it would continue to generate power. A hydraulic brake has place in the nacelle, which brakes down the rotor speeds, when this is the case. In Figure 40 one can see the components in the nacelle. Another crucial part are the yaw drives: these turn the nacelle and the rotors towards the wind direction.

Figure 40 Components of a wind turbine nacelle



Source: GE Energy, 2009

Appendix XIX Data sources, calculations and final values for Entrepreneurial Activity for wind power in Denmark; and argumentation for the qualitative analysis on the importance of this function.

Entrepreneurial Activity per year is measured with two dimensions and their indicators:

- Installed capacity: the number of installed wind turbines per year: these data were found at the website of the Danish Energy Authority that monthly publishes on the active, installed and decommissioned turbines in Denmark (DEA, 2009). They also monthly publish detailed data on the productivity of each single wind turbine in Denmark.
- Industry size: the number of start-ups with an industrial character in the wind power sector. The selection of the firms was based on the member list of the Danish Wind Energy Association (DWEA, 2009). Of the members list those firms that have an industrial (i.e. they produce components or equipment for wind turbine production, or provide services directly related to wind turbine installation, use and maintenance) character were selected. Of these firms the year of establishment was searched for. These results are presented in Appendix VIII. The number of start-ups per year as such is an indicator for industry size growth. The start-ups are counted cumulatively to represent the total industry size.
  The industry size is corrected with a 50% shakeout in the year 1985. A shakeout does not become apparent in the above way of data gathering for industry size, but according to Buen (2006) this shakeout had place. Since it cannot be said how many firms went bankrupt or stopped their activities in wind power, it is assumed that this was 50%.

Kamp in all her studies (2002, 2004, 2008) acknowledges large differences in Entrepreneurial Activity between the small-scale wind turbine innovation system and the large-scale turbines innovation system. For the small turbines Entrepreneurial Activity started already in the early 1970s. In 1979 10 small firms were producing (components of) small turbines. That number grew gradually over the following decade (Kamp, 2002). For the large turbines, there were no firms willing to

produce complete turbines for many years. The first large turbines were produced by a government-funded firm or consortia of component producers (Kamp, 2002). The early success of small scale turbines with much Entrepreneurial Activity, in comparison to the unsuccessful results in entrepreneurship – there were no independent private producers – for large scale wind turbines, indicates that Entrepreneurial Activity serves as a success factor for an emerging innovation system.
However, when she compared the Danish Entrepreneurial Activity with the emerging innovation system in The Netherlands, it was concluded that both systems were rather similar (Kamp, 2008). Since the Dutch system was unsuccessful and the Danish system not, this similar state of Entrepreneurial Activity does now not explain the success of Denmark.
These two considerations, (I) the similarity in Entrepreneurial Activity between Denmark and The Netherlands on the one hand and (II) the lack of Entrepreneurial Activity in the Danish large-scale turbines innovation system and its late success in comparison to the presence of Entrepreneurial Activity in the small scale innovation system and its early success on the other hand, resulted that this function's importance is considered a *medium* level.

Table 34 Start-ups in the Danish wind power industry

Reference number	Firm	Year that wind power related activities were started
1	A2SEA	2000
2	ABB A/S	1988
3	AH Industries	1977
4	Arvid Nilsson Denmark	irrelevant
5	AVANTI	1976
6	AVN Energy	1981
7	Bachmann electronic	not Danish
8	BALLUFF	no data
9	BattShip	irrelevant
10	Bladt Industries	1999
11	Blue water shipping	2001
12	Brondberg & Tandrup International	no data
13	BSB Maskinfabrik	2000
14	C.C. Jensen	no data
15	COWI	irrelevant
16	Danfoss	irrelevant
17	Danish Crane Building	1983
18	Dansk Overflade Teknik	2002
19	DEIF	2004
20	DELTA	irrelevant
21	Det Norske Veritas Danmark	no data
22	Deugro Danmark	irrelevant
23	DIAB	2000
24	Difko Invest	2000
25	DONG Energy	1975
26	DS SM	1998
27	Eltronic	irrelevant
28	Fiberline Composites	1979
29	Force Technology	irrelevant
30	Fritz Schur Technical Group	2006
31	FT Technologies	not Danish
32	Gamesa Wind Engineering	not Danish
33	Garrad Hassan and Partners	1984
34	GPV Group	no data
35	Green Wind Energy	2002
36	Haco	no data
37	Helens Ror	no data

38	Hempel	1980
39	Hendricks Industries	1980
40	Hydra-Grene	no data
41	Jorgensen og Otoft	no data
42	JSB Plast	1988
43	Jupiter Composites	no data
44	K.P. Komponenter	no data
45	kk-electronic	1978
46	Klingspor	no data
47	KR Wind	2002
48	Krangarden	1979
49	Lincoln Danmark	no data
50	LM Glasfiber	1978
51	Mita-Technik	1983
52	Monofiber	irrelevant
53	Niebuhr Tandjulsfabrik	no data
54	Nissens	no data
55	Oiltech	irrelevant
56	Orga Aviation	2003
57	Parker Hannifin Danmark	not Danish
58	Peter Madsen rederi	irrelevant
59	PMC Technology	no data
60	Prodan	no data
61	Ramboll Danmark	1986
62	Reichhold Danmark	irrelevant
63	Ribe Maskinfabrik	no data
64	Sandvik	no data
65	Scanpocon	irrelevant
66	Schaeffler Danmark	irrelevant
67	Schneider Electric	no data
68	Siemens Wind power	1980
69	Sika Danmark	irrelevant
70	Skagen Sandblaseri & Skibs service	1994
71	SKF Danmark	irrelevant
72	Steel Team	no data
73	Suzlon Energy	1995
74	Svendborg Brakes	1989
75	Technologisk Institut	1975
76	Teknatex	no data
77	Tibnor	irrelevant
78	Vattenfall	1996
79	Vestas	1979
80	Vest-Fiber	1999
81	Welcon	no data

No data = *no data found on the start of wind power related activity*
Irrelevant = *a too small affiliation to the wind power industry*
Not Danish = *no substantial activities in Denmark*

Table 35 Development of Entrepreneurial Activity for wind power in Denmark

Year	Number of installed wind turbines per year	Standar-dised value	Start-ups	Shake-out in 1985	Cumu-lative	Standar-dised value	Average value of standar-dised values	Final value
1973	0	0	0		0	0	0	0
1974	1	0.0013263	0		0	0	0.0006631	0.00075
1975	1	0.0013263	2		2	0.0689655	0.0351459	0.03997
1976	1	0.0013263	1		3	0.1034483	0.0523873	0.05958
1977	2	0.0026525	1		4	0.137931	0.0702918	0.07994
1978	11	0.0145889	2		6	0.2068966	0.1107427	0.12594
1979	10	0.0132626	3		9	0.3103448	0.1618037	0.18401
1980	45	0.0596817	3		12	0.4137931	0.2367374	0.26923
1981	96	0.127321	1		13	0.4482759	0.2877984	0.3273
1982	95	0.1259947	0		13	0.4482759	0.2871353	0.32655
1983	75	0.0994695	2		15	0.5172414	0.3083554	0.35068
1984	102	0.1352785	1		16	0.5517241	0.3435013	0.39065
1985	390	0.5172414	0	-8	8	0.2758621	0.3965517	0.45098
1986	308	0.4084881	1		9	0.3103448	0.3594164	0.40875
1987	339	0.4496021	0		9	0.3103448	0.3799735	0.43213
1988	484	0.6419098	2		11	0.3793103	0.5106101	0.58069
1989	328	0.4350133	1		12	0.4137931	0.4244032	0.48265
1990	379	0.5026525	0		12	0.4137931	0.4582228	0.52112
1991	348	0.4615385	0		12	0.4137931	0.4376658	0.49774
1992	203	0.2692308	0		12	0.4137931	0.3415119	0.38839
1993	128	0.1697613	0		12	0.4137931	0.2917772	0.33183
1994	143	0.1896552	1		13	0.4482759	0.3189655	0.36275
1995	170	0.2254642	1		14	0.4827586	0.3541114	0.40272
1996	431	0.571618	1		15	0.5172414	0.5444297	0.61916
1997	569	0.7546419	0		15	0.5172414	0.6359416	0.72323
1998	495	0.6564987	1		16	0.5517241	0.6041114	0.68703
1999	469	0.6220159	2		18	0.6206897	0.6213528	0.70664
2000	754	1	4		22	0.7586207	0.8793103	1
2001	130	0.1724138	1		23	0.7931034	0.4827586	0.54902
2002	373	0.494695	3		26	0.8965517	0.6956233	0.7911
2003	124	0.1644562	1		27	0.9310345	0.5477454	0.62293
2004	14	0.0185676	1		28	0.9655172	0.4920424	0.55958
2005	18	0.0238727	0		28	0.9655172	0.494695	0.56259
2006	10	0.0132626	1		29	1	0.5066313	0.57617
2007	12	0.0159151	0		29	1	0.5079576	0.57768
2008	51	0.0676393	0		29	1	0.5338196	0.60709

Appendix XX Data sources, calculations and final values for Knowledge Development for wind power in Denmark; and argumentation on the importance of this function.

This function is measured with the following dimensions and indicators:

- National size of Wind Power R&D: measured by the funds spent in the following programmes / by the following agencies: the Energy Technology Development and Demonstration Programme (EUDP); the Danish Energy Research Programme (EFP), Public Service Obligation (PSO) and the Programme Commission on Energy and Environment (ENMI). The funds also include own investments from the research institutes that have conducted the research. These data were provided by Risø (2009a). For all 228 projects the allocated funds were divided over the years the project ran. Then, for all years the budgets for wind power research were summed. This database however only included data for the research since 1996.

The funds available to wind power research before this period were gathered by literature research and some additional calculations. The first substantial fund to wind power research was provided in the Marshall funds after World War II. 300,000 DKK were allocated for the development of the Gedser turbine. The Wind Power Programme was developed after the first oil crisis and in Phase 1 (1977-1980) 35 million DKK was spent on mainly large-scale wind turbine research and includes the establishment of the Risø Test and Research Centre. This is 8,75 million per year. In Phase 2 (1981-1984) 35.4 million DKK was spent, so another 8.85 million DKK per year (Kamp, 2002). In the period 1985-1990 115 million DKK was spent on the research and development of the Masnedo and Tjaereborg turbines (Kamp, 2002): this is 19.16 million DKK per year.

- Publications (indicator 1): in Scopus by Danish organisations on wind power. Scopus is a global academic database of articles. In this database a search was conducted with the search terms wind or offshore power plants or windfarm or windmill in the titles, abstracts or keywords of an article. It was restricted to the following research institutes: Risø National Laboratory, Danmarks Tekniske Universitet, Danmarks Miljøundersøgelser, Kobenhavns Universitet and Dong Energy AS, which also has an R&D department. This resulted in 991 hits in total (Scopus, 2009c). The results are sorted per year and one year more was extracted, to correct for the lag in time between knowledge production and publication date.
- Publications (indicator 2): by Risø and the Danish Technical University on wind power. These two research institutes are the largest Danish producers of publications on wind energy. In the database of Risø all publications of Risø and the Danish Technical University are stored and to correct for any missing data in Scopus from these two important players, Risø's database is also used. This search is further revealing in that it also includes articles in Danish. The search terms were wind or vind or vindenergi or wind plus power. The results (Risø, 2009b) were counted and sorted per year. One year is extracted from the publications year to compensate for lags in time, as explained previously.

Since there are now two indicators for publications, the weight factor of public budgets spent on R&D is two, so that both indicators have the same impact on the final value for each year.

In both The Netherlands and Denmark Knowledge Development was of a good level in the emerging innovation system of wind power. However, the Danish structure of knowledge infrastructure was very different from the Dutch one (Kamp, 2002). Smit *et al.* (2007) concluded that the Danish knowledge structure for wind was very different from the British system. Klaassen *et al.* (2005) explain the differences between Denmark, Germany and the United Kingdom in R&D impact on innovation. All these studies point out success factors on why the Danish knowledge structure was better than in the other countries in reaching a successful development of a wind power innovation system.

According to all authors the successful development of R&D started with the Wind Power Programme of 1978, where 5.5 million DKK was granted to the establishment of the Risø Test Station. The self-enforced link of Risø with turbine producers had successful Knowledge Development as a result. It appeared to be a fruitful strategy and the Risø Test Station would be the centre of the wind power hub for the coming decennia. It formed an important source of trust and stability of the industry (Buen, 2007). The start of Knowledge Development is thus determined to be in 1978, with the decision that the Risø together with the Technical University of Denmark in Copenhagen would were to develop the knowledge needed to manufacture large scale wind turbines (Kamp, 2008).

The value of Risø for the industry is visible both in the small-scale and the large-scale turbine industry. The first installed wind turbines were very unreliable and therefore commercially unattractive. The large-scale turbines had problems with fatigue in the blades and failures of gear boxes. The manufacturers of components cooperated in research with each other and Risø to solve these problems (Kamp *et al.*, 2004). The focus was on learning by searching, but manufacturers were actively involved so that effective learning by interacting also took place (Kamp *et al.*, 2004).

The importance of Knowledge Development for the success of wind power is considered of *high* level: although there was little need for fundamental R&D, applied knowledge production was crucial for

the development of wind turbines. This was produced to a large extent with the help of manufacturers and users.

Table 36 Data on Knowledge Development on wind power in Denmark

Year	Public budgets spent on wind power R&D in DKK	Standar-dised value (weight = 2)	Publications in Scopus by Danish organisations -1 year	Standar-dised value	Pubications by Risø and Danish Technical University - 1 year	Standar-dised value	Avarage of standar-dised values	Final value
1970			0	0			0	0
1971			1	0.006803	2	0.024096	0.0154496	0.0206
1972			1	0.006803	1	0.012048	0.0094255	0.01257
1973			0	0	0	0	0	0
1974			0	0	0	0	0	0
1975			0	0	2	0.024096	0.0120482	0.01606
1976			3	0.020408	0	0	0.0102041	0.01361
1977	8750	0.106684	3	0.020408	2	0.024096	0.0644681	0.08596
1978	8750	0.106684	4	0.027211	2	0.024096	0.0661688	0.08823
1979	8750	0.106684	1	0.006803	4	0.048193	0.0670908	0.08945
1980	8750	0.106684	9	0.061224	2	0.024096	0.0746722	0.09956
1981	8850	0.107903	5	0.034014	2	0.024096	0.0684791	0.09131
1982	8850	0.107903	5	0.034014	1	0.012048	0.065467	0.08729
1983	8850	0.107903	11	0.07483	3	0.036145	0.0816952	0.10893
1984	8850	0.107903	14	0.095238	0	0	0.0777611	0.10368
1985	19160	0.233607	7	0.047619	1	0.012048	0.1317204	0.17563
1986	19160	0.233607	3	0.020408	4	0.048193	0.1339539	0.17861
1987	19160	0.233607	10	0.068027	1	0.012048	0.1368225	0.18243
1988	19160	0.233607	7	0.047619	2	0.024096	0.1347325	0.17964
1989	19160	0.233607	11	0.07483	3	0.036145	0.1445473	0.19273
1990	19160	0.233607	8	0.054422	7	0.084337	0.1514934	0.20199
1991			16	0.108844	15	0.180723	0.1447832	0.19304
1992			9	0.061224	5	0.060241	0.0607327	0.08098
1993			13	0.088435	6	0.072289	0.0803623	0.10715
1994	0	0	11	0.07483	12	0.144578	0.0731361	0.09751
1995	26	0.000313	24	0.163265	81	0.975904	0.3798273	0.50644
1996	19131	0.23325	30	0.204082	83	1	0.4176452	0.55686
1997	30269	0.369053	43	0.292517	62	0.746988	0.4444028	0.59254
1998	43856	0.534715	34	0.231293	74	0.891566	0.548072	0.73076
1999	50475	0.61542	44	0.29932	52	0.626506	0.5391663	0.71889
2000	56451	0.688277	44	0.29932	68	0.819277	0.6237875	0.83172
2001	66064	0.805477	35	0.238095	36	0.433735	0.5706958	0.76093
2002	54102	0.659636	66	0.44898	63	0.759036	0.6318217	0.84243
2003	51428	0.62703	81	0.55102	60	0.722892	0.631993	0.84266
2004	57342	0.699134	88	0.598639	48	0.578313	0.6438052	0.85841
2005	70047	0.854046	87	0.591837	47	0.566265	0.7165483	0.9554
2006	82018	1	147	1			0.75	1
2007	74499	0.908325	100	0.680272			0.6242307	0.83231
2008	76773	0.936054					0.468027	0.62404

Appendix XXI Data sources, calculations and final values for Knowledge Diffusion for wind power in Denmark; and argumentation on the importance of this function

This function is measured with the following indicators:

- Conference papers (indicator 1): as found by a Scopus database search on the terms 'wind power' 'wind energy' or 'offshore power' in title, keywords or abstract. Only conference papers were selected, which will indirectly indicate when conferences on wind power had place. The articles were sorted per year (Scopus search, 2009f).

- Conference papers (indicator 2): as found in the publications database by Risø and the Danish Technical University (Risø, 2009c). These two research institutes are the most important on wind power technology in Denmark. These results should have the same trend as the previous indicator, but since the database is more complete it compensates for eventual missed trends from the first indicator.
- Cooperation with European partners. This is measured by the number of partners involved in Framework Programme (FP) projects on wind power by the European Commission. The data for FP5 and FP6 (1999-2006) was complete and accessed via a database delivered by Technopolis (2008). Data for wind power projects before 1999 was not publicly available and a compensation value was calculated based on general information on R&D funds from the European Commission to renewable energy and wind power technology. This calculation method is explained in Appendix VII.

Table 37 Knowledge Diffusion of wind power in Denmark

Year	LN conference papers by Danish organisations	Standardised value	Conference papers by Risø and DTU	Standardised value	FP5 and FP6 projects on wind (*1000 euro)	Coorection value for pre-FP 5 research	Standardised value	Average of standardised values	Final value
1979						0	0	0	0
1980						0.125	0.0007716	0.0007716	0.00113
1981						0.125	0.0007716	0.0007716	0.00113
1982						0.125	0.0007716	0.0007716	0.00113
1983	1	0.012658				0.125	0.0007716	0.0067149	0.0098
1984	3	0.037975				0	0	0.0189873	0.02771
1985	10	0.126582				0.25	0.0015432	0.0640627	0.09351
1986	1	0.012658				0.25	0.0015432	0.0071007	0.01036
1987	0	0				0.25	0.0015432	0.0007716	0.00113
1988	2	0.025316				0.25	0.0015432	0.0134298	0.0196
1989	1	0.012658				0.1875	0.0011574	0.0069078	0.01008
1990	2	0.025316				0.5625	0.0034722	0.0143943	0.02101
1991	1	0.012658	30	0.291262		0.875	0.0054012	0.1031072	0.1505
1992	2	0.025316	30	0.291262		0.75	0.0046296	0.1070694	0.15628
1993	2	0.025316	24	0.23301		1.6875	0.0104167	0.0895809	0.13076
1994	5	0.063291	22	0.213592		1.375	0.0084877	0.0951237	0.13885
1995	3	0.037975	45	0.436893		2.375	0.0146605	0.1631761	0.23818
1996	1	0.012658	77	0.747573		2.375	0.0146605	0.2582972	0.37702
1997	4	0.050633	94	0.912621		2.375	0.0146605	0.3259716	0.4758
1998	8	0.101266	31	0.300971		13.25	0.0817901	0.1613423	0.2355
1999	2	0.025316	103	1	1	12	0.0740741	0.3664635	0.53491
2000	7	0.088608	41	0.398058	20	12	0.1234568	0.2033742	0.29685
2001	4	0.050633	98	0.951456	93	12	0.5740741	0.5253878	0.76688
2002	9	0.113924	76	0.737864	125	12	0.7716049	0.541131	0.78986
2003	11	0.139241	73	0.708738	162		1	0.6159928	0.89913
2004	25	0.316456	71	0.68932	149		0.9197531	0.6418431	0.93686
2005	28	0.35443	31	0.300971	80		0.4938272	0.3830761	0.55915
2006	26	0.329114	82	0.796117	76		0.4691358	0.5314554	0.77573
2007	79	1			60		0.3703704	0.6851852	1
2008	26	0.329114			60		0.3703704	0.3497421	0.5105

As already discussed in the previous subsection on Knowledge Development, there was a lot of effective cooperation between various actors of the wind power innovation system in order to produce knowledge on better manufactured wind power turbines. This learning by interacting occurred between university, research institutes, component suppliers, project operators and turbine manufacturers and is considered crucial to the success of the Danish Wind Power industry (Smit *et al.*, 2007). Also other authors (o.a. Buen and Kamp) recognize this crucial importance of research consortia with a strong focus on strengthening of the whole industry. Besides these strong research networks, Kamp (2008) also recognizes the annual Wind Meetings organized by Risø which were open for all international interested players in the industry, as a valuable source of Knowledge Diffusion.

There is no ambiguity found on the *high* importance and influence of Knowledge Diffusion on the success of wind power in comparison to other countries that did not have such strong cooperation, and therefore failed in establishing a strong technological innovation system.

Appendix XXII Data sources, calculations and final values for Guidance of the Search for wind power in Denmark; and argumentation on the importance of this function

The function is measured by two dimensions and their indicators:

- Public awareness: measured as media attention to wind power issues. Newspaper articles were found and counted via Lexis Nexis, an international newspaper archive. The search terms were vindenergi and vind and the selected papers Borgen and Politiken, because they had the earliest articles available. This resulted in 784 articles (Lexis Nexis, 2009b). Unfortunately they only supply Danish newspaper articles since 1996. No Danish newspapers were found that have free digital access to their news paper archive with articles published earlier than 1996. Therefore this indicator has no data in the period before 1996.
- Governmental awareness: this is measured by the presence and influence of a green party. In Denmark there was no typical green party. The party that has the most support for green policy is the Socialistisk Folkeparti (SF). Their ideology is described as 'democratic socialism and red-green politics' (SF, 2009). This party has never been in the office and therefore political awareness has a maximum value of 0.5. To bring some nuance to their relative influence, the best results of the elections to SF (i.e. 14.6% of the votes in 1987) get a value of 0.5 and all other percentages of the votes are standardised to the 0.5 scale relative to the 14.6% of the votes that has the 0.5 value.

The average values are not standardised to the 0-1 scale, because then the impression might be that there were moments with very high guidance, while in fact the government had never had a very green character, because the red-green party was never in the office. This lack of governmental awareness (historical activity) is thus covered by not scaling up to 1. The results of the analysis are as follows.

Tranæs (1996) wrote on the history of the creation of the wind power industry and the difficulties the industry had to deal with to start. One of the main issues was the lack of interest from public authorities and their behaviour to stop wind industry growth in the 1970s. This illustrates the lack of governmental awareness and support to the advantages of wind power.
In the historic outlines of the development of the Danish wind power industry, often the presence of strong grassroots in the Danish society are mentioned. Heymann (1998) evidently links this circumstance to success of renewable energy. Besides this societal basis, the authorities have also been helpful in providing the right policy instruments.

Buen (2006: 3893) explains the importance of public and political guidance for the establishment of the technological innovation system as follows:

> *"The oil crisis in 1973-74 had made people understand the need for domestic energy production. Partly as a result of the strong anti-nuclear sentiment, a left-wing government came into office in the late 1970s. Unemployment was rising rapidly. This enabled the let-wing government to link wind power development to industrial development, employment and export revenues. This secured agreement across party lines in line with Denmark's consensus-based tradition. The second oil embargo in 1980-81 threatened Denmark's balance of payment due to its continued dependence on imported petroleum products, and created a benign climate for government intervention. Two increasingly strong industrial organizations, the Danish Wind Turbine Owners Association and the Danish Wind turbine Manufacturers Association, coordinated their lobbying efforts.*
> *Policy instruments could not have been upheld and would not have had the effect on innovation, niche market commercialization and diffusion, had it not been for this conducive context."*

The left-wing government would be in office until 2001. Their continuity in policy making for the establishment of a strong wind power industry, together with a common grassroots support, would serve successful development of the industry for more than 20 years. With the entrance of a right-wing government in 2001, many support schemes were stopped or decreased by large steps and a large decrease in installed turbines had place. For offshore wind turbines, none have been installed between 2003 and 2006 (Smit *et al.*, 2007). The importance of this function is thus considered *high* to the success of the industry.

Table 38 Guidance of the Search of wind power in Denmark

Year	Percentage of the votes	Value for political awareness (max 0.5 for 1987 - devide by 29.2)	Number of newspaper articles on wind energy	Standar-dised value	Average
1970	6.1	0.20890411			0.2089041
1971	9.1	0.311643836			0.3116438
1972	9.1	0.311643836			0.3116438
1973	6	0.205479452			0.2054795
1974	6	0.205479452			0.2054795
1975	5	0.171232877			0.1712329
1976	5	0.171232877			0.1712329
1977	3.9	0.133561644			0.1335616
1978	3.9	0.133561644			0.1335616
1979	5.9	0.202054795			0.2020548
1980	5.9	0.202054795			0.2020548
1981	11.3	0.386986301			0.3869863
1982	11.3	0.386986301			0.3869863
1983	11.3	0.386986301			0.3869863
1984	11.5	0.393835616			0.3938356
1985	11.5	0.393835616			0.3938356
1986	11.5	0.393835616			0.3938356
1987	14.6	0.5			0.5
1988	14.6	0.5			0.5
1989	14.6	0.5			0.5
1990	8.3	0.284246575			0.2842466
1991	8.3	0.284246575			0.2842466
1992	8.3	0.284246575			0.2842466
1993	8.3	0.284246575			0.2842466
1994	7.3	0.25			0.25
1995	7.3	0.25			0.25
1996	7.3	0.25			0.25
1997	7.3	0.25	24	0.126316	0.1881579
1998	7.6	0.260273973	37	0.194737	0.2275054
1999	7.6	0.260273973	24	0.126316	0.1932949
2000	7.6	0.260273973	43	0.226316	0.2432949
2001	6.4	0.219178082	51	0.268421	0.2437996
2002	6.4	0.219178082	42	0.221053	0.2201154
2003	6.4	0.219178082	41	0.215789	0.2174838
2004	6.4	0.219178082	53	0.278947	0.2490627
2005	6	0.205479452	69	0.363158	0.2843187
2006	6	0.205479452	69	0.363158	0.2843187
2007	13	0.445205479	141	0.742105	0.5936554
2008	13	0.445205479	190	1	0.7226027

Appendix XXIII Data sources, calculations and final values for Market Formation for wind power in Denmark; and argumentation on the importance of this function

The indicators that lead to the development of Market Formation are based on literature search on market creating policy instruments. First, for general understanding of the evolution of policy instruments to stimulate wind power an overview of the outcomes of the literature study is presented. Afterwards, Buen (2006) is cited for his explanation of these policy changes.

Before any legislation: ownership was mostly by enthusiastic private investors (Tranæs, 1996).

1978: the residency criterion is introduced for guild memberships: one has to live within a distance of 3 kilometres (Tranæs, 1996).

1979: introduction of a 30% investment subsidy (Kamp, 2002). Users had to comply with three conditions to receive the subsidy, of which one was that they have to live within 3 kilometres from the windmill. Also, the windmill had to be approved by the Test and Research Centre (Risø); and only private buyers were eligible for the subsidy (Kamp, 2002).

1985: members should live within the same borough plus 10 extra kilometres, which results in 3-20 boroughs in an area of electricity supply. Also a consumption criterion was introduced: a maximum share of the member's own consumption plus 35%, with a minimum share based on consumption of 6,000 kWh. This maximum was introduced on request of large power companies (Tranæs, 1996).

1981: The Energiplan 1981 stated that 60,000 small wind turbines were to be placed before the year 2000 (Buen, 2006).

1982: The investment subsidy is decreased to 20% (Buen, 2006).

1984: A 10-year agreement between the government and power companies that the latter should connect all approved windmills to the electricity grid. Also, they had to offer an electricity price of 85% of the market price to guild members. According to Buen (2006) this really triggered Market Formation.

1985-1987: The investment subsidy was reduced to 15% in 1985 and 10% in 1987. Also the criteria were tightened and subsidies on windmill farms were abandoned (Buen, 2006).

1986-1990-1994: as an offer to the consumption criterion that was introduced after pressure of the power companies, the utilities were forced to erect two times (between 1986-1990 and 1991-1994) 100 MW of windmills. This also created demand for turbine or component manufacturers (Tranæs, 1996).

1989: removal of the investment subsidy. According to Kamp (2002) this removal explains the decrease in installed wind turbines, although the 2 times 100 MW agreements would stimulate the installation of wind turbines (Buen, 2006). Both trends more or less neutralized each other.

1990: Energi 2000 is a long-term energy plan from the government, in which an extra 1500 MW of wind power was to be installed before 2005 (Buen, 2006).

1992: in the Law for Wind Turbines both the criterion of residence and consumption were extended. Guild member could live within the same or the neighbouring borough to where the windmill stands. It meant that guild member could be collected from 3-5 boroughs. The consumption shares were increased to a minimum of 9,000 kWh or your own consumption plus 50% (Tranæs, 1996).

1992: although power companies have not succeeded in installing 100 MW in 1990, they did so in 1992. Also the second term was fulfilled in 1996 instead of 1994. Despite the unwillingness of the Danish power companies to install windmills, in these days the German and Chinese markets grew, which resulted in continued activity of Danish manufacturers (Buen, 2006).

1994 and 1996: less tight conditions to invest tax-free in wind turbines for individuals (Buen, 2006).

1996: broader regulation states that every person who works in a firm, owns real estate or lives in a house in a borough, can have shares in a wind turbines up to 30,000 kWh (Tranæs, 1996).

1996: the governments sets the goal with the power companies to install 200 MW of wind mills on mainland before the year 2000 (Buen, 2006).

1996: The Energi 2000 plan is followed up by Energi 21: now the government changed the previous goal and wants to install 4000 MW offshore wind power before 2030 (Buen, 2006).

1998: power companies and the government agree to install 750 MW of wind turbines offshore (Buen, 2006).

2000: the planning rules for the placement of wind turbines were tightened and a new and tighter price regime for the installation of turbines started (Buen, 2006).
2001: no restrictions in membership and ownership of wind turbines. Only the first 3000 DKK income are tax-free. On all other revenues a tax of 60% is to be paid. This instrument stimulates shared ownership of wind turbines (Buen, 2006).
2001: a repowering scheme was initiated which aimed at replacing old wind turbines instead of placing new ones all the time, which worked out successfully (Buen, 2006).

Buen (2006: 3891) summarizes the development in Market Formation policy as follows:

> *"In general, policy instruments to stimulate wind power and wind industry development in Denmark have been gradually —if not always smoothly— removed in line with cost reductions and maturity of the industry. We have seen that investment subsidies were gradually removed towards the end of the 1980s; that production subsidies (deduction of electricity and/or carbon tax) were maintained from the early 1980s until 2000; that guaranteed grid connection and a specified feed-in-tariff have been maintained almost until present; and that the scope for tax exemptions related to co-operative or individual wind turbine ownership has been gradually increased from the early 1980s until present.*
> *Danish policy is also strongly characterized by long-term agreements between the government and power companies; similar agreements between power companies, producers and users; as well as long-term energy-environmental policy objectives."*

The information on the policy instruments is transcribed into historical activity values by the following ways:

- Investment subsidies: these are presented as percentages of the investment costs of wind turbines that are covered for by the government. Then, the highest of these subsidies (i.e. 30% from 1979-1981) got the value 1, and all other investment subsidies are calculated relative to this on the 0-1 scale.
- Power companies demand: this is the wind turbine capacity that the power companies were forced to establish. These targets were often for 4-5 years, and therefore these targets are expressed as an average installed capacity per year. The highest average installed capacity by power companies got the value 1 (i.e. 100 MW / year in 2001-2007) and all other data for installed capacity are calculated relative to that on the 0-1 scale.
- The residency criterion is expressed in the number of kilometres that the guild member had to live from the wind turbine. The consumption criterion is expressed as the minimum power in kWh that a guild member could use. These two indicators are combined into one value 'combined relative value guild criteria' where the most favourable circumstances got the value 1 (i.e. no residency criterion and the largest consumption minimum in the years since 2001) and all other circumstances are valued relative to that. This resulted in a scale with 0.2 steps, where the least favourable criteria got the value 0.2 and each step that the criteria became better, the value was increased by 0.2.
- Electricity payback price or feed-in tariffs. Just like the guild membership criteria, this indicator cannot easily be translated to a 0-1 scale. Therefore an ordinary scale is composed which has the following scales: R = reduction on the electricity price (value is 0.8), LF = low feed-in tariffs (value is 0.4), RF = regular feed-in tariff (value is 0.6) and HF = high feed-in tariff (value is 1). The exact feed-in tariff legislation and the reasoning behind these ordinary values can be read in the next paragraphs.

Finally the average was taken of the values of these four policy instrument indicators, and a final value was calculated by rescaling this average to the 0-1 scale.

Feed-in tariff legislation 1984-2009

Wind turbines connected to the grid from 1 January 2005
Plant owners are responsible for the sale of production on the electricity market and for related costs. There is a fixed premium of 10 øre/kWh for 20 years and an allowance of 2.3 øre/kWh for offset costs etc. Permits for the establishment of offshore wind farms are subject to decision by the Minister of Transport and Energy after tendering or application.
This is considered a relatively low feed-in tariff.

Wind turbines connected to the grid 2003-2004

Plant owners are responsible for the sale of production on the electricity market and for related costs. A premium up to 10 øre/kWh for 20 years is available. The premium is regulated in accordance with the market price, as the total of the two must not exceed 36 øre/kWh. There is also an allowance of 2.3 øre/kWh for offset costs etc.
This is considered a regular feed-in tariff.

Turbines connected to the grid 2000-2002
The system operator will sell the production on the spot market and the subsidy together with the market price will ensure a tariff of 43 øre/kWh for 22,000 full load hours for turbines on land and 10 years for offshore turbines. Once full load hours are used up, turbine owners are responsible for the sale of production on the electricity market and for related costs. A premium up to 10 øre/kWh until the turbine is 20 years old is available. The premium is regulated in accordance with the market price, as the total of the two must not exceed 36 øre/kWh. There is also an allowance of 2.3 øre/kWh for offset costs etc.
This is considered a relatively high feed-in tariff.

Turbines bought prior to the end of 1999
The system operator will sell the production on the spot market and subsidy together with the market price will ensure a tariff of 60 øre/kWh until full load hours are used up and subsequently 43 øre/kWh until the turbine is 10 years old. Full load hour allowance is 25,000 hours for turbines of 200 kW or less, 15,000 hours for turbines of 201-599 kW and 12,000 hours for turbines of 600 kW and over. If the turbine is more than 10 years old but has not used its full load allowance up yet, it is eligible for a premium of 27 øre/kWh with a ceiling of 60 øre/kWh for the total of the market price and the premium. When the turbine is over 10 years old and its full load allowance is used up, the owner is responsible for sale of production on the electricity market and related costs. A premium up to 10 øre/kWh until the turbine is 20 years old is available. The premium is regulated in accordance with the market price, as the total of the two must not exceed 36 øre/kWh. There is also an allowance of 2.3 øre/kWh for offset costs etc.

Source: Energistirelsen, 2009

Table 39 Market Formation of wind power in Denmark

Year	Investment subsidy	Value	Power companies demand (MW/year)	Value	Residency criterion for guild members (km)	Consumption minimum for guild members (kWh)	Combined relative value for guild criteria	Electricity price / feed-in tariffs	Value	Average value	Final value
1977	0	0		0			0		0	0	0
1978	0	0		0	3		0.2		0	0.05	0.06667
1979	30%	1		0	3		0.2		0	0.3	0.4
1980	30%	1		0	3		0.2		0	0.3	0.4
1981	30%	1		0	3		0.2		0	0.3	0.4
1982	20%	0.66		0	3		0.2		0	0.215	0.28667
1983	20%	0.66		0	3		0.2		0	0.215	0.28667
1984	20%	0.66		0	3		0.2	R	0.8	0.415	0.55333
1985	15%	0.5		0	10	6000	0.4	R	0.8	0.425	0.56667
1986	15%	0.5	20	0.25	10	6000	0.4	R	0.8	0.4875	0.65
1987	10%	0.33	20	0.25	10	6000	0.4	R	0.8	0.445	0.59333
1988	10%	0.33	20	0.25	10	6000	0.4	R	0.8	0.445	0.59333
1989	10%	0.33	20	0.25	10	6000	0.4	R	0.8	0.445	0.59333
1990	0	0	20	0.25	10	6000	0.4	R	0.8	0.3625	0.48333
1991	0	0	20	0.25	10	6000	0.4	R	0.8	0.3625	0.48333
1992	0	0	20	0.25	20	9000	0.6	R	0.8	0.4125	0.55
1993	0	0	20	0.25	20	9000	0.6	R	0.8	0.4125	0.55
1994	0	0	20	0.25	20	9000	0.6	R	0.8	0.4125	0.55
1995	0	0	20	0.25	20	9000	0.6	R	0.8	0.4125	0.55
1996	0	0	20	0.25	50	30000	0.8	R	0.8	0.4625	0.61667
1997	0	0	50	0.5	50	30000	0.8	R	0.8	0.525	0.7
1998	0	0	50	0.5	50	30000	0.8	R	0.8	0.525	0.7
1999	0	0	50	0.5	50	30000	0.8	R	0.8	0.525	0.7
2000	0	0	50	0.5	50	30000	0.8	HF	1	0.575	0.76667
2001	0	0	100	1	none, 3000 DKK tax-free		1	HF	1	0.75	1
2002	0	0	100	1	idem		1	HF	1	0.75	1
2003	0	0	100	1	idem		1	RF	0.6	0.65	0.86667
2004	0	0	100	1	idem		1	RF	0.6	0.65	0.86667
2005	0	0	100	1	idem		1	LF	0.4	0.6	0.8
2006	0	0	100	1	idem		1	LF	0.4	0.6	0.8
2007	0	0	100	1	idem		1	LF	0.4	0.6	0.8
2008	0	0	50	0.5	idem		1	LF	0.4	0.475	0.63333

Also for Market Formation the authors agree on the direct effect of investment subsidies since 1979 on the development of the industry. It is also seen as a good explanation for differences in success of wind power between countries. Kamp (2008: 289) explains this as follows:

> *"This [investment subsidies] helped the formation of a relatively large home market at an early phase. Because this market was relatively large, it could organize itself better than the Dutch home market and could therefore negotiate better payback tariffs with the utilities."*

Also Klaassen (2005: 229) considers the "*investment subsidies between 1979 and 1989 instrumental in achieving such a rapid expansion of the capacity*".
The Danish also experienced the disadvantages of vanishing support schemes. When in 1982 the investment subsidies started to decrease to 0 in 1989, the start of a shake-out had occurred. However, this decreasing home market demand was compensated by large export opportunities in California. In the beginning of the 1980s almost all produced turbines went to California, because attractive tax incentives there triggered the investments in wind power. Yet, also this market disappeared when in 1986 the tax credit by the US federal government and California were abandoned (Buen, 2006). The market revived again in 1996-97 when Denmark first eased the residency criterion, then forced higher demand from the utilities and finally in 2000 also high feed-in tariffs were introduced (see historical activity analysis, for more detail).
The influence of each measure to increase or decrease demand had direct effects on the production and installed capacity of wind turbines. Therefore, the importance of Market Formation on the success of wind power is considered *high*. The take-off of this function is chosen as 1979, the year the 30% investment subsidies were introduced.

Appendix XXIV Data sources, calculations and final values for Resource Mobilisation for wind power in Denmark; and argumentation on the importance of this function

This function is composed of one value. That is the financial resources allocated by the government, research institutes and firms for research, development and demonstration (RD&D) of wind power. The government have allocated the largest share of these resources, especially in the first years. The data is based on literature study and database analyses and have the same input data as the indicator 'national budgets spent on RD&D' from the function Knowledge Development (Kamp, 2002 and Risø, 2009: see paragraph on Knowledge Development). The difference is that for this function the resources are not spread over the years that the research had place, but that they are put at the year previous to the year that the research has started. In this way, the resources were mobilized first at once and knowledge was created later gradually.

Table 40 Resource Mobilisation for wind power in Denmark

Year	Financial resources for RD&D projects, in 1000 DKK	Resources mobilization: the allocated resources minus 1 year	Standardised value
1976		35000	0.366411574
1977	35000		0
1978			0
1979		35400	0.370599135
1980	35400		0
1981			0
1982			0
1983		11500	0.120392374
1984	115000		0
1985			0
1986			0
1987			0
1988			0
1989			0
1990			0
1991			0
1992			0
1993		0	0
1994	0	231	0.002418316
1995	231	37879	0.396551544
1996	37879	33294	0.348551627
1997	33294	93985	0.983919766
1998	93985	42710	0.44712681
1999	42710	60402	0.632342626
2000	60402	57570	0.602694695
2001	57570	47256	0.494718439
2002	47256	49864	0.522021336
2003	49864	74124	0.775996901
2004	74124	95521	1
2005	95521	86215	0.902576397
2006	86215	54436	0.569885156
2007	54436	93278	0.976518253
2008	93278	1762	0.018446206

Kamp (2008) in her comparative study of Denmark and The Netherlands finds that both countries scored sufficiently on the availability of resources, but that the way these funds were spent differed on a crucial point. The Dutch allocated it to only R&D subsidies until 1992, while the Danish spent it on both R&D and market stimulating instruments from an early phase on. The availability of these market subsidies resulted in a relatively large home market, which again made more resources available. She (2008: 289) concludes that "*R&D subsidies alone proved to be unable to develop a wind power innovation system.*"
The spending on the wind power industry was however of a rather discontinuous character, with changing policy and profiting parties of the funds. Also, besides Kamp none of the authors argues that financial resources are one of the main success factors.
The function is given a value of *medium* importance to the success of the industry. Its presence is crucial, but it more serves as a precondition than as a directly stimulating factor, and should be allocated to both R&D and Market Formation activities.

Appendix XXV Data sources, calculations and final values for Lobby Activity and Creation of Legitimacy for wind power in Denmark; and argumentation on the importance of this function

For this function two dimensions are studied and each has various indicators:

- Active lobby groups: by literature study (Tranæs, 1996; Kamp, 2002) the most important lobby groups for renewable energy and wind power are identified. Each year that this organisation was in place 0.1 point was awarded to this organisation. The following relevant lobby groups were identified:
    - OAA – 1974: Organization for Information on Nuclear Power, later known as the Movement on Energy and Environment (in Danish the OOA), which was mainly an anti-nuclear movement, but now also has the objective to increase research in alternative forms of energy and the drawing-up of long term energy policy, being socially and ecologically justifiable (OAA, 2009).
    - OVE – 1975: Danish Organization for Sustainable Energy (in Danish OVE). OVE's aim is "*to work for a resource and environment conscious energy policy through grassroots initiatives to reach 100% renewable energy supply in Denmark by 2030.*" (OVE, 2009).
    - DWTOA – 1978: formerly known as the Danish Wind Power Stations (Danske Vindkraftvaerker) and later as the Danish Wind Turbine Owners Association. The number of members was 6,000 in 2006, existing of single wind turbine owners, cooperatives and interested people. By taking also the members of the cooperatives into account, the DWTOA represents about 60,000 people wind turbine owners (DWTOA, 2009). The DWTOA also published the *Naturlig Energi*, a monthly magazine with the performance of different types of turbines. This magazine was an important trigger for technological competition among producers (Kamp, 2002).
    - DWTMA / DWIA – 1981: Danish Wind Turbine Manufacturers Association, later known as the Danish Wind Industry Association. Today they claim to represent 99.9% of Danish wind turbine manufacturing measured in MW and more than 200 companies. They also publish various articles and are engaged in advocacy (DWIA, 2009).
    - EWEA – 1982: the European Wind Energy Association. They have various activities, among which the annual European Wind Energy Conference (EWEC) with about 6,000 participants and the bi-annual European Offshore Conference (EOC – 2,000 participants) are well known. (EWEA, 2009).

An interesting example of the goals of such a lobby group is a paragraph from the opening speech of the Danish Wind Power Stations (later DWTOA). The first chairman formulated the main objectives, challenges and goals as presented in Box 4.

- Events creating legitimacy: by literature search the following events were identified that could possibly create legitimacy for the cause of renewable energy or wind power.
    - Oil crises of 1973 and 1979.
    - Chernobyl disaster in 1986.
    - Lobbying activities at the end of the 1980s and beginning of the 1990s by the DWTOA and the DWIA, resulting in the Wind Power Act and Wind Power Programme in 1992 (Tranæs, 1996; Kamp, 2008).

The power from the DWTOA is acknowledged by Kamp (2002). She says that their power was that they negotiated collectively for all users with the utilities. When the utilities were obligated to pay feed-in tariffs to the electricity producers, the DWTOA negotiated for the highest tariffs for its members. Because the wind turbine owners were organised in this way they were more powerful in the negotiations than the single turbine owners in The Netherlands, explaining partially the success of the industry in Denmark (Kamp, 2002).

Box 4 A fragment of the opening speech of the foundation of the Danske Vindkraftvaerker

> "Knowing that our energy stocks of coal, oil, gas and uranium are limited we are surprised that since the first energy crisis in 1973, nothing really effective has been done to initiate relevant research and to sort out legislation related to renewable energy… It puzzles me that the state energetically talks about and plans energy only related to coal, oil, gas and uranium. Only in passing remarks is the energy from the wind and sun mentioned, knowing well that the first mentioned energy sources are limited, whereas the wind and sun are inexhaustible. It also surprises me that the energy planners when talking about coal, oil, gas and uranium minimize the irreparable pollution connected to the use of these materials. I am thinking of the dangers in connection with carbon dioxide, sulphur, lead, and radiation. Is disaster necessary to open our eyes to the fact that these substances firstly are a health hazard, and that secondly their availability is very limited?" (Tranaes, 1996:3)

The phrases quoted in the subsection on Guidance of the Search (Buen, 2006: 3891) clearly explain how legitimacy was created in the 1970s after the oil crises and anti-nuclear movements. Also, the combined efforts of two large lobby groups, the DWTOA and the DWMA, are said to have had impact on the speeding up of policy making of the left-wing parliament (Buen, 2006).

Kamp (2008) found that such lobby activities were larger in Denmark compared to The Netherlands and may therefore explain success. The Danish turbine owners were organized better, and had better bargaining positions. Furthermore, the resistance of Danish people against turbines was lower than the Dutch, who were afraid of danger to the birds and the negative effects on the landscape (Kamp, 2008).

However, the other authors do not give many credits to the influence of lobby organizations in later phases, or other forms of legitimacy creating events or groups. Although other authors may not emphasize the crucial importance to success of this function, the research of and discussion with Linda Kamp shows that is was an enabling factor that had paved the way for further development, and therefore it is given the value of *medium* importance for the success of wind power in Denmark.

Table 41 Lobby Activity and Creation of Legitimacy of wind power in Denmark

	Active lobby organisations					Major lobbying events				Total lobbying activity (if more than 1, than 1)
Year	OOA	OVE	DWTOA	DWTMA / WPIO	EWEA	Improving market circum-stances	Chernobyl catastrophe	Lobbying for Law for Wind Turbines	Oil Crises	
1970										0
1971										0
1972										0
1973									0.5	0.5
1974	0.1									0.1
1975	0.1	0.1								0.2
1976	0.1	0.1								0.2
1977	0.1	0.1								0.2
1978	0.1	0.1	0.1							0.3
1979	0.1	0.1	0.1						0.5	0.8
1980	0.1	0.1	0.1							0.3
1981	0.1	0.1	0.1	0.1						0.4
1982	0.1	0.1	0.1	0.1	0.1					0.5
1983	0.1	0.1	0.1	0.1	0.1					0.5
1984	0.1	0.1	0.1	0.1	0.1					0.5
1985	0.1	0.1	0.1	0.1	0.1					0.5
1986	0.1	0.1	0.1	0.1	0.1	0.5	0.5			1
1987	0.1	0.1	0.1	0.1	0.1	0.5				1
1988	0.1	0.1	0.1	0.1	0.1	0.5				1
1989	0.1	0.1	0.1	0.1	0.1					0.5
1990	0.1	0.1	0.1	0.1	0.1					0.5
1991	0.1	0.1	0.1	0.1	0.1			0.5		1
1992	0.1	0.1	0.1	0.1	0.1			0.5		1
1993	0.1	0.1	0.1	0.1	0.1					0.5
1994	0.1	0.1	0.1	0.1	0.1					0.5
1995	0.1	0.1	0.1	0.1	0.1					0.5
1996	0.1	0.1	0.1	0.1	0.1					0.5
1997	0.1	0.1	0.1	0.1	0.1					0.5
1998	0.1	0.1	0.1	0.1	0.1					0.5
1999	0.1	0.1	0.1	0.1	0.1					0.5
2000	0.1	0.1	0.1	0.1	0.1					0.5
2001	0.1	0.1	0.1	0.1	0.1					0.5
2002	0.1	0.1	0.1	0.1	0.1					0.5
2003	0.1	0.1	0.1	0.1	0.1					0.5
2004	0.1	0.1	0.1	0.1	0.1					0.5
2005	0.1	0.1	0.1	0.1	0.1					0.5
2006	0.1	0.1	0.1	0.1	0.1					0.5
2007	0.1	0.1	0.1	0.1	0.1					0.5
2008	0.1	0.1	0.1	0.1	0.1					0.5