The Emergence of a Growth Industry: A Comparative Analysis of the German, Dutch and Swedish Wind Turbine Industries*

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Abstract

The objective of this paper is to compare the evolution of the wind turbine industry in Germany, the Netherlands and Sweden. Four factors stand out in explaining the relative success of the German industry: (1) creation of variety in an early phase, (2) establishment of legitimacy of wind energy, (3) the employment of advanced market creation policies in a later phase and (4) the use of industrial policy to favour the domestic industry. Implications for policy include fostering legitimacy for the new technology and creating powerful, predictable and persistent economic incentives.

Key words: wind energy, innovation system, industrial dynamics, policy, functional analysis

1. Introduction

In recent years, the 'innovation system' perspective has obtained increased legitimacy as a way of analysing industrial development. For such a system to support the growth of an industry, a number of functions have to be served within it, e.g. the supply of resources. We suggest that we can evaluate the performance of an innovation system by assessing its 'functionality', i.e. how well these functions are served. The analytical objective of the paper is to develop a framework that enables us to make such an assessment in different phases in the evolution of an industry.

We apply this framework to a cross-country comparative analysis of the evolution of the wind turbine industry in Germany, the Netherlands and Sweden over a period of about twenty years.

The wind turbine industry is a non-high tech growth industry (Jacobsson and Johnson, 2000), in which the knowledge base is mechanical and electrical engineering mixed with software and aerodynamics. Since its inception, it has been dominated by Danish firms, which currently supply about 44 percent of the world sales (BTM Consult, 2000).

Other countries have also tried to develop a wind turbine industry, but with varying success. *Sweden* developed very large turbines in the early 1980s, but a domestic industry never quite materialised in spite of a substantial government R&D programme. Today, there are a few Swedish firms at the tail of the global industry. In *the Netherlands*, a range of firms entered the industry in the 1970s. At the end of the 1980s, the Dutch industry was relatively advanced, but today there is only one Dutch-owned firm left, which accounted for less than 1 percent of the world sales in 1999 (BTM Consult, 2000). *Germany* shared the Swedish emphasis on large wind turbines in the early 1980s, but in the mid-1980s a set of firms supplying smaller turbines emerged. These firms now constitute the nucleus of the German industry, which grew phenomenally in the 1990s and is now the second largest industry in the world. The four largest German firms accounted for approximately 27 percent of the world sales in 1999.[1] The empirical objective of this paper is to analyse the evolution of the wind turbine industry in these countries and to explain their relative success and failure in terms of the functionality of their respective innovation systems.

The paper is structured as follows. In section 2, we present our analytical framework. Section 3 contains a brief description of the technology and of the market for wind turbines. In section 4, we describe the development of the wind turbine industries in the three countries by mapping the functional pattern of their respective innovation system. In section 5 the three cases are compared and some policy implications are discussed.

2. Analytical framework

As is argued in an expanding literature on innovation systems, the innovation and diffusion process is both an individual and collective act. The determinants of industrial development and growth are not only found within individual firms; firms are embedded in innovation systems that aid and constrain the individual actors within them.

The innovation system approaches share an understanding of a set of basic functions that are necessary for an innovation system to work (Johnson, 1998). Earlier, we have suggested that a technology or product specific innovation system may be described and analysed in terms of its ‘functional pattern’, i.e. in terms of how these functions are served (e.g. Johnson and Jacobsson (2000)). The pattern stems from the character of, and interaction between, the components of an innovation system, i.e. actors, networks and institutions (Carlsson and Stankiewicz, 1995), which may be specific to one innovation system or ‘shared’ by a number of different systems.

The first, and maybe most obvious, function of an innovation system is to *create 'new' knowledge*. [2] This function may also be viewed as an overall goal of a system since an

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[1] These firms and their market shares are Enercon (12 percent), Nordex (7.8 per cent), Tacke (5 percent) and Dewind (1.5 percent) (BTM Consult, 2000). Tacke is now owned by a US corporation, but develops and produces its turbines in Germany. Nordex was originally Danish, but is now owned by a German firm and develops its turbines in Germany.

[2] This and the following paragraphs constitute a synthesis of a large body of literature and are largely based on Johnson (1998). For detailed references, see Johnson and Jacobsson (1999).

innovation system may be defined in terms of knowledge generation, diffusion and utilisation (Carlsson and Stankiewicz, 1995).

A second function is to *guide the direction of the search process* of the suppliers of technology and customers, i.e. to influence the direction in which actors deploy their resources. This function includes providing recognition of a growth potential (e.g. in terms of identifying technological opportunities), which is closely connected to the legitimacy that a new technology has in the eyes of various actors. The function also includes guidance with respect to both technological choice (i.e. the choice of specific design configurations), and market choice. Individual actors may be guided by inducement mechanisms such as the identification of problems of a technical nature, changing factor prices, the formation of standards or regulation and relationships to competent customers, or by various policy interventions. This is, of course, a particularly important function in the process of forming a new industry.

A third function is to *supply resources*, i.e. capital, competence and other resources. Capital is partly needed to distribute risks and may, sometimes, come with competence, for instance in the form of venture capital. Competence refers to a whole range of competencies, including technological competencies.

A fourth function is to facilitate the creation of *positive external economies* in the form of an exchange of information, knowledge and visions. Indeed, this function lies at the heart of the systemic approach to innovation and involves the formation of networks and meeting places and, perhaps, changes in culture.

A fifth function is to *facilitate the formation of markets*. Markets do not necessarily emerge in a spontaneous fashion, but may need to be created. Firms need to make investments of various types in order both to identify and to reach new customers. Governments may need to improve social acceptance by legitimising the new technology or removing legislative obstacles.

The functions are not, of course, independent of one another, and a change in one function may, thus, lead to changes in other functions. For instance, the creation of an initial market may act as an inducement mechanism for new entrants that bring new resources to the industry. The linkages between functions may also be circular, which may set in motion a virtuous circle. For instance, the resources brought into the industry by a new entrant may be used to develop the market further.

The framework provides us with a tool for analysing the dynamics of an innovation system. In addition to studying evolutionary processes in terms of changes in entries and exits, network formation, institutional adaptation etc., attention can be paid to the way in which the functional pattern of an innovation system evolves and what drives its evolution.

The framework also allows us to evaluate an innovation system in terms of the way it supports the development of an industry. Since all the functions need to be served for a new industry to evolve and perform well, we suggest that a particular innovation system may be evaluated in terms of its ‘functionality’, i.e. in terms of *how well* the functions are served within that system.

What ‘well served’ means is to be expected to differ depending on what particular stage of evolution an industry is in (Utterback and Afuah, 1998). Several cyclical models of product/industry development have been developed in order to capture regularities in the evolution process (e.g. Utterback and Suarez, 1993; Tushman, Anderson and O'Reilly, 1997). These models are based on the idea that most (if not all) products or industries go through identifiable phases which differ in terms of the character of technical change, the patterns of entry/exit and the rate of market growth. The number of phases differs between models, but it is usually possible to differentiate two main phases.

The first is one of experimentation with frequent entries and exits, many different competing technological alternatives and a small market (Nelson, 1994; Utterback and Suarez, 1993). The outcome of the competition is highly uncertain both in terms of which alternative(s) will be the winner (Nelson, 1994) and in terms of industry leadership. Innovators compete as much against market scepticism as against rivals (Utterback, 1994).

The second is characterised by market growth (Utterback, 1994), fewer new entrants (Utterback and Suarez, 1993) and, possibly, a shake-out of firms. In some of the literature, the transition from the first phase to the second is driven by the emergence of a ‘dominant design’. The selection of that design results in a change in the nature of technical change from radical product innovation to process innovation and incremental product innovation (Utterback, 1994).

We have chosen not emphasise the concept of dominant design for two reasons. First, a shift between the phases may occur in the absence of a clear dominant design. A dominant design might, indeed, occur as a result of a large-scale diffusion rather than cause it. Second, and more important, even if a dominant design does emerge, the ‘radicalness’ of technical change does not necessarily have to decrease. Technological discontinuities may very well occur within the frames of a dominant design (Hidefjäll, 1997) and, hence, a technology-driven turbulence may continue to exist even after the selection of the dominant design (Ehrnberg and Jacobsson, 1997, Tushman, Anderson and O’Reilly, 1997).

In view of the different characteristics of the two phases, the functions clearly have different roles to play in the two phases. Whereas the discussion below is not exhaustive, we point to some main differences between the phases in terms of these roles.

In the first phase, the key words are experimentation and the generation of variety. A necessary condition for this to occur is that the direction of search of new or established firms is guided towards the new product. Due to the need for legitimacy for the new technology, it may be especially important that the entry of respectable actors is stimulated. The creation of variety is, however, central and the system needs to ensure the creation of new knowledge within different technological approaches. This may involve the entry of firms from different backgrounds and the provision of special incentives for experimentation, e.g. in the form of resources.

The system must also facilitate the creation of external economies, e.g. via problem-solving networks in the form of user-supplier links. A necessary condition for these links to form and for new firms to enter is, of course, that markets are open to new sources of supply (Nelson, 1994) or that new (niche) markets are identified and stimulated.

In the second phase, the key words are diffusion and firm expansion. The system needs to support a shift towards cost reduction. This is, in part, achieved by exploiting economies of scale. The system must, thus, identify and facilitate the formation of mass markets. At the same time, it needs to prevail in its support of a variety of actors and technologies. Continued legitimacy contributes to actor variety and firm growth, since it guides the direction of search of firms and attracts private capital that supply firms with resources. Such resources are necessary for firm expansion and technology development, including development required to handle technological discontinuities within the frame of a dominant design.

In short, the 'functionality' of an innovation system may be assessed in terms of how it supports firm entry, variety and the formation of niche markets in the first phase, and market expansion and the supply of resources to exploit that market in the second phase. In order to make such an assessment, we need to analyse the dynamics of the innovation system by mapping the evolution of the functional pattern. This will be done in section 4. Before that we will outline some key features of two phases in the wind turbine industry in the next section.

3. Salient features of the two phases in the wind turbine industry

In the wind turbine industry, we can identify two phases that correspond to the ones described above. The first is characterised by substantial technological variety (and uncertainty), underdevelopment of the market and entry of many firms. The second is characterised by a considerable turbulence, driven by rapid growth in the market and an up-scaling of the turbines (corresponding to a set of minor technological discontinuities), as well as by many exits but also some new entrants, including some larger firms. In this, as well as in the subsequent section, we will therefore distinguish between a phase of experimentation (roughly 1975-1989) and one of turbulence and growth (roughly 1990-1999).

3.1 The phase of experimentation

In the 1970s and early 1980s, there was a large number of fundamentally different designs: horizontal- and vertical-axis turbines,[3] turbines of varying sizes (5 kW to 3 MW) and turbines with different number of blades (one to four). Firms with a broad range of backgrounds (shipbuilding, gearboxes, agriculture machinery, aerospace, etc.) experimented with a variety of approaches, bringing their specific competences to the industry.

The market developed quite slowly during the 1980s; even in the peak year of the Californian 'boom'[4] in the mid-1980s, only 420 MW[5] were installed (see figure 3.1).

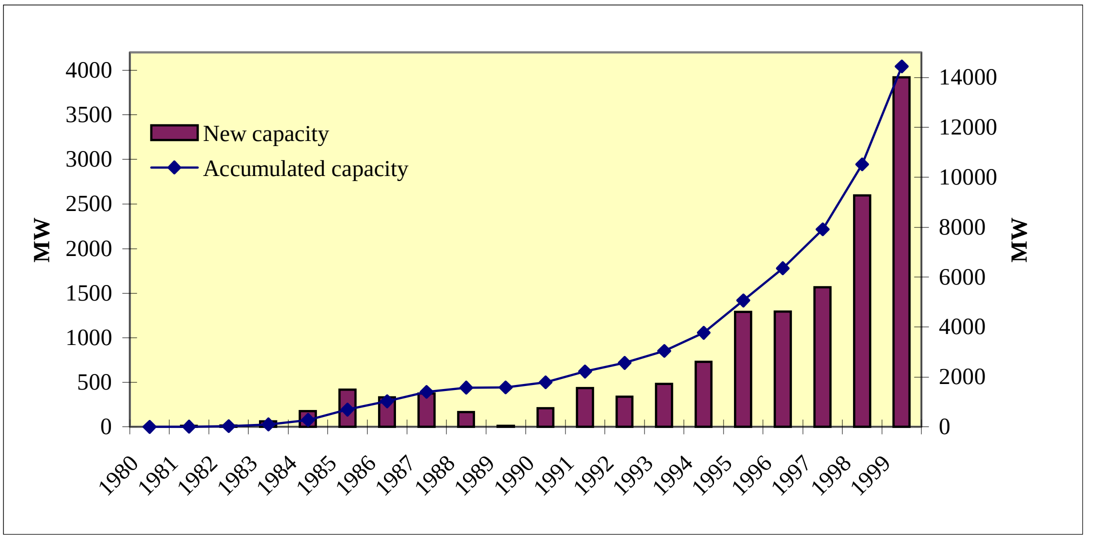

Figure 3.1: Global wind turbine installations 1980-1999 (Sources: 1980-90 Kåberger (1997); 1991-93 European Commission (1997), volume 5, table 2.2; 1994-99 BTM Consult (2000), table 2-1

In the late 1970s and early 1980s, large firms such as MBB and SAAB entered the industry on the basis of government contracts to develop MW turbines. Most of these firms left in the 1980s or early 1990s, mainly because of the non-viability of MW turbines at that time. In parallel, many smaller firms entered, either as entrepreneurial start-ups or as a result of

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[3] The difference between horizontal-axis and vertical-axis turbines lies in the orientation of the axis of rotation – horizontal with respect to the ground (and roughly parallel to the wind stream) vs. vertical with respect to the ground (and roughly perpendicular to the wind stream).

[4] This 'boom' was driven by tax incentives and involved the setting up of many thousands of wind turbines.

[5] MW stands for megawatt, which is a unit for power. Wind turbines are usually classified by their rated power, i.e. the maximum power that the turbines may produce.

the diversification by mechanical engineering firms. These firms focused on smaller turbines and came from, e.g., Denmark, Holland and Germany. In Denmark as many as 26 firms had sold more than three turbines in the 1980s (Karnoe, 1991, appendix 2, table 2.2.). In Germany, 13 firms were active in the 1980s[6] (elaboration on Durstewitz (2000)). In the Netherlands, 15-20 firms entered the field in the late 1970s and early 1980s (elaboration on Verbong (2000)).[7]

3.2 The phase of turbulence and growth

The horizontal-axis three-bladed design was selected from among the many alternatives.[8] A technology driven competition continued, however. First, three alternative horizontal designs competed throughout the 1990s.[9] Second, the commercial turbines greatly increased in size. This was especially apparent in Germany, where the average size of newly installed turbines increased from perhaps 50 kW in the mid-1980s to roughly 185 kW in 1992 (BTM Consult, 1999, table 2-3) and over 900 kW in 1999 (BWE, 2000).[10]

In the mid-1990s, a very rapid market growth began. Indeed, the average annual market growth in terms of installed capacity was 38 percent during the 1990s (see figure 3.1). The leading markets were Germany (with a growth of 4,336 MW in 1992-1999), followed by Spain (1,796 MW) and the USA (1,348 MW) (European Commission, 1997, volume 5, table 2.2; BTM Consult, 1999, table 2.2; BTM Consult, 2000, table-2-6).

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[6] In this case, we included all German firms that had sold a turbine on the German market.

[7] In 1989, the German and the Dutch industry supplied in the order of 10 MW each (elaboration on Durstewitz (2000) and IEA (1997a)), which may be compared with the Danish industry, which supplied about 130 MW (Hantsch, 1998). NB: The supply and installation of turbines does not always take place in the same year.

[8] The horizontal axis design has historically been equipped with one, two or three blades. However, the one-bladed design was never successful and from around 1990, the two-bladed design lost ground for aesthetic reasons, leaving the three-bladed design as the dominant one. However, as late as around 1990 the vertical axis design was seen as one of four competing designs (Karnoe, 1991).

[9] The first design is the 'Danish stall' design, which combines stall control, constant rotation speed and an asynchronous generator. Stall control is a way of power control in which the aerodynamic design of the blades causes the lift to decrease and the drag to increase above a certain wind speed, thus limiting the power output of the turbine. The stall-control is now giving way to pitch control, which constitutes the second design. In pitch control, the blades are rotated in their longitudinal axis above a certain wind speed, which limits the power output of the turbine to its rated value. The third design involves the use of pitch control, variable rotation speed and a synchronous generator. In addition, there are semi-variable designs and a couple of other power-control principles, e.g. the 'active stall' control.

[10] There is reason to believe that the further up-scaling will lead to a preference for the third design approach as the pitch and variable speed features make it easier to handle large aerodynamic forces and to monitor and control the turbines (van Kuik, 2000). The German industry, which is leading the up-scaling process, is now shifting towards this design principle (Müller, 1999; Hansen, 1999).

A process of concentration and growth in the size of the firms took place. Some firms grew organically, whereas other firms grew by mergers and/or acquisitions.[11] The rapid growth in the market also led to more entries, primarily in Germany and Spain. Among these were both entrepreneurial firms and large firms that entered the industry by acquiring small, established firms.

4. Development of a wind power industry in Germany, the Netherlands and Sweden

In this section, we will map the functional pattern of German, Dutch and Swedish innovations systems in the two phases.

4.1 The phase of experimentation

4.1.1 The German case

In the German case, the key function in this phase was 'Guide the direction of search' (see figure 4.1). This function was initially influenced by an R&D policy, which via the function 'Supply resources' induced a search in many directions. Even though the projects aiming at developing MW turbines received much international attention,[12] this R&D programme was large enough to finance most projects applied for and flexible enough to finance most types of projects (Windheim, 2000a). In the period 1977-1991, about 46 R&D projects were granted to as many as 19 industrial firms and a range of academic organisations for the development or testing of small (e.g. 10 kW) to medium sized (e.g. 200-400 kW) turbines (elaboration on Windheim (2000b)).[13] Both horizontal- and vertical-axis turbines received support, as did turbines with different numbers of blades. These experiments stimulated the creation of variety through an influence on the function 'Create new knowledge'.

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[11] The German market leader Enercon and the Danish firm Vestas are examples of organic growth, whereas the Danish firm NEG Micon is an example of growth by mergers and acquisitions.

[12] The most prominent was the Growian machine, developed by MAN, erected in 1982 and dismantled in 1987 (Gipe, 1995).

[13] The numbers exclude funding given for the purpose of demonstrating wind turbines. In addition, there was support for projects that could benefit all sizes of turbines.

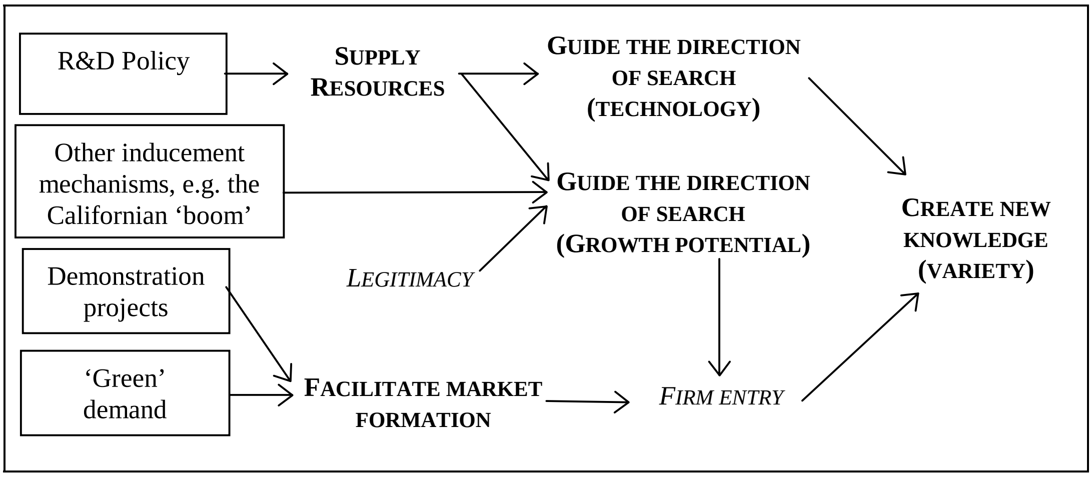

Figure 4.1: The German innovation system in the phase of experimentation.

Some of this new knowledge was also exploited commercially by German suppliers, beginning in 1984 when MAN sold a 20 kW turbine. Another thirteen German firms sold turbines in the 1980s, and eleven of these firms still existed in 1989 (elaboration on Durstewitz (2000)).[14]

A condition for the firm participation in turbine development and production, within and outside the R&D programme, was an early legitimacy to wind turbines. The legitimacy was due partly to a political consensus on the benefits of wind power,[15] and induced firms to begin a search towards wind turbines.

Given the legitimacy, firms were induced to enter for a number of reasons. Of course, the resources provided by the R&D programme made the area seem attractive. Moreover, in several cases the firms' existing markets were in recession at the same time as the Californian boom, and the expansion of the Danish wind turbine industry sent clear signals about the attractiveness of the wind turbine market (Tacke, 2000; Schult and Bargel, 2000). The new entrants were also induced by emerging local niche markets, supported by the function 'Facilitate market formation', which was served by two mechanisms. First, the green movement in Germany was strong, which led to the emergence of a 'green' demand from some utilities. As there were as many as 800 different utilities in Germany, there was

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[14] We approximate entry with the year of the first sales and exit as the year of the last sales.

[15] This consensus was particularly clear after the Chernobyl accident (Molly, 1999).

ample room for diverse opinions with regards to technology choice (Reeker, 1999).[16] There was also an early niche of environmentally concerned farmers (Schult and Bargel, 2000; Tacke, 2000). Second, the federal R&D policy subsidised investment in wind turbines in a number of demonstration programmes (Hemmelskamp, 1998). At least fourteen German suppliers of turbines received funding for 124 turbines in the period 1983-1991 (elaboration on Windheim (2000b)).[17]

However, the domestic market still remained weak throughout the experimental phase. For instance, in 1986 and 1987, when seven new German firms entered the industry, only 15 and 44 turbines were sold respectively (elaboration on Durstewitz (2000)) and the total installed power was just 19 MW by the end of 1989 (see table 4.1).

Together with the R&D policy, the large number of entries nevertheless contributed to the broad range of experiments undertaken and the consequent accumulation of knowledge and competence. Indeed, the diversity in experiments undertaken is the main characteristic of this early phase in Germany.

TABLE 4.1: *The German market for wind turbines 1982-89*.

	NUMBER OF NEW TURBINES	ACCUMULATED NUMBER OF TURBINES	NEW POWER CAPACITY (MW)	ACCUMULATED POWER CAPACITY (MW)
1982	1	1	0.02	0.02
1983	1	2	0.06	0.08
1984	4	6	0.10	0.18
1985	12	18	0.24	0.42
1986	15	33	0.52	0.94
1987	44	77	1.94	2.88
1988	61	138	4.99	7.87
1989	87	225	11.8	19.67

Source: Elaboration on Durstewitz (2000).

4.1.2 The Dutch case

In the Dutch case, the first phase consists of two, quite different, sub-phases partly running in parallel.

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[16] Several people we interviewed claimed that the Green movement reached the Universities of Technology (Fachhochschule) and that some of the engineers who graduated began to develop wind turbines, both as suppliers and customers.

[17] According to Hemmelskamp (1998), 214 turbines were supported.

The outcome of the first of these sub-phases was similar to that of the first phase in Germany, although the functional pattern of the innovation system was somewhat different (see figure 4.2).

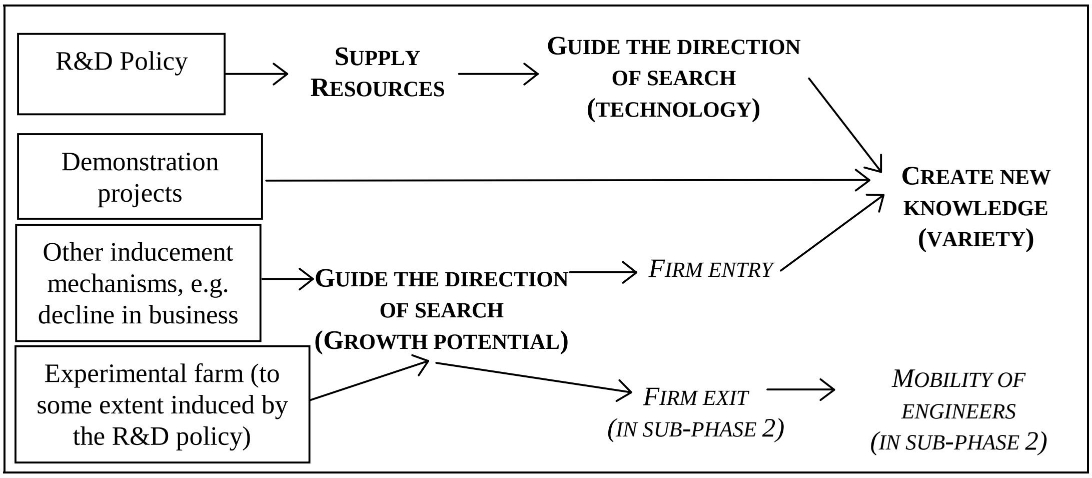

Figure 4.2: The Dutch innovation system in the first sub-phase of the phase of experimentation.

In the late 1970s and early 1980s, a multitude of firms entered and experimented with various designs, thus influencing the function ‘Create new knowledge’ in such a way that variety was created. Most of the firms were driven by the decline in their original business (van Holten, 2000). The first commercial turbines were erected in 1980, and in the mid-1980s, there were 15-20 firms developing or producing a large variety of turbines (mostly 10-80 kW).

The function ‘Create new knowledge’ was also influenced by two government-financed wind energy programmes. Within these programmes, the development of a large variety of turbine types was supported. Basic research and development of larger turbines was conducted at the Dutch energy research institute (ECN) and the technical universities, sometimes in co-operation with the larger industrial firms. In addition, the development activities of the emerging wind turbine industry were funded; all types of turbines could receive support (Janssen and Westra, 2000; Versteegh, 2000), with roughly half of the investment cost. This was, of course, very important, especially for the smaller firms

(Versteegh, 2000).[18] Thus, the function 'Guide the direction of search' was influenced, via the function 'Supply resources', so that variety was created and sustained. There were also some other mechanisms serving the function 'Create new knowledge'. Firms could get free help with testing their turbines at a test field run by ECN (Janssen and Westra, 2000; van Holten, 2000) and there were also some small demonstration projects, in which new prototypes and turbines in new applications were supported, e.g. by fiscal incentives ('t Hooft, 2000).

On the market side, the influence on the function 'Facilitate market formation' appears to have been much weaker than in Germany; the green demand was not so strong and the interest from the utilities was weak. However, in 1982 some electricity producers decided to build an experimental wind farm with 300 kW turbines (Kuipers, 2000a). Half of the planned cost of 50 MNLG was provided by the wind energy programme ('t Hooft, 2000). However, although the stated objectives were achieved,[19] there were problems with the turbines; when they were put into operation, many components failed (IEA, 1991) and in the longer run, the maintenance cost turned out to be too high to keep the turbines in operation (Kuipers, 2000b).[20] The primary impact on the industry structure was that two large firms left the wind turbine industry.[21]

When the efforts of the larger firms faded, some of their R&D people moved to the smaller firms (van Holten, 2000; van Kuik, 2000). The mobility in the labour market also increased as people from research institutes and universities went to the industry (Versteegh, 2000). This mobility later proved to be important for the choice of technology in these firms (see below).

[18] The second programme even had as an explicit goal to involve the Dutch industry in the development and production of wind turbines (van Holten, 2000; Verbong, 1999).

[19] One of the objectives of the experimental farm was to develop further wind turbine technology and to optimise the application of wind turbines (Kuipers, 1986). Other objectives were to study the aerodynamic effects of putting many turbines close together (Kuipers, 2000a) and to study the social and environmental aspects of the farm (Kuipers, 2000b).

[20] As one of the objectives was to develop further wind turbine technology, a new prototype was developed and installed in the farm. However, this meant that there was no room for gradual improvements and this may have contributed to the turbine problems, although they were probably also caused by the supplier's lack of experience.

[21] One was Stork FDO that lost its enthusiasm for wind turbines partly as a result of competing for the contract without getting it (Verbruggen, 1999). The other was the supplier, Polenko/Holec, that after the turbine problems decided that wind turbines was not a core business (van Kuik, 1999).

In the second sub-phase, the situation changed substantially (see figure 4.3).

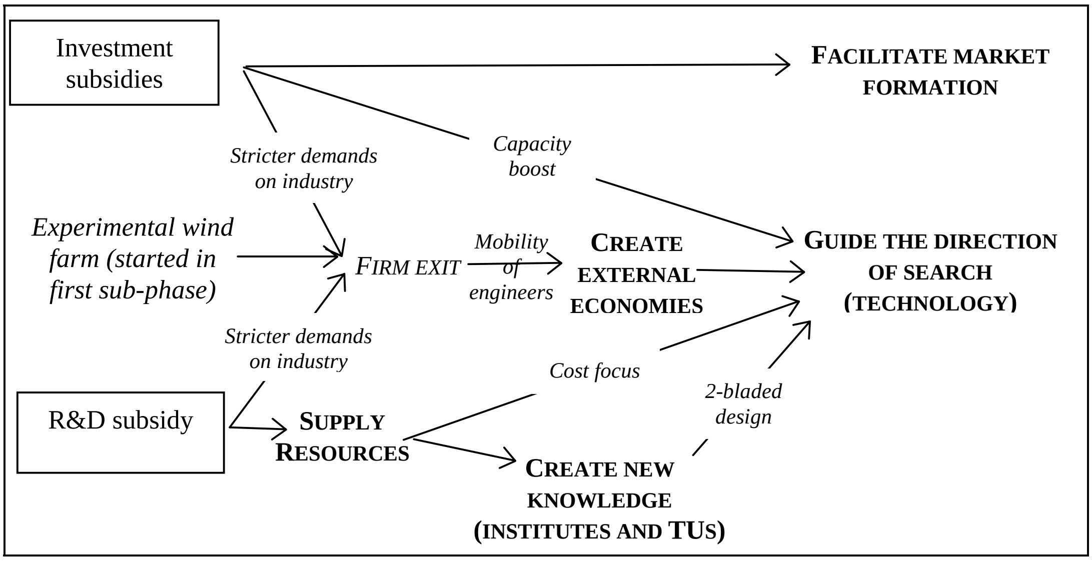

Figure 4.3: The Dutch innovation system in the second part of the first phase.

The political interest in wind was revived by an energy price crisis in 1984 ('t Hooft, 2000) and an official goal of 1,000 MW by the year 2000 was set in 1985. As the demand was still weak, one of the primary government goals was to influence the function 'Facilitate market formation'. For this purpose, another programme was introduced in which an investment subsidy was awarded to utilities and independent customers (Carlman, 1990; 't Hooft, 2000). This resulted in a small market expansion (see table 4.2). The majority of the turbines were Dutch, even though it was not required by the programme ('t Hooft, 2000).

TABLE 4.2: *Installed capacity in the Netherlands 1980-1989*.

	NEW POWER CAPACITY (MW)	ACCUMULATED POWER CAPACITY (MW)
1980		0.02[a]
1981	0.38	0.4[a]
1982	1.1	1.5[a]
1983	1.7	3.2[a]
1984	0.5	3.7[a]
1985	1.8	5.5[a]
1986	1.5	7[b]
1987	9	16[b]
1988	6	22[b]
1989	11	33[b]

Sources: Elaboration on:
[a] *Kamp (1999)*
[b] *IEA (1997a)*

The programme also influenced the function 'Guide the direction of search' in three ways with respect to technology choice. First, the design of the investment subsidy made some firms 'boost' the generator of the turbines in order to maximise the subsidy for their customers (Gipe, 1995; 't Hooft, 2000).[22] Some of the Dutch turbines that were developed were, therefore, not cost competitive internationally. Second, the programme's focus on finding a breakthrough in cost-effectiveness was one of the reasons why some of the Dutch firms developed two-bladed turbines.[23] The programme contained an R&D subsidy for which only firms that aimed at developing cheaper turbines were eligible.[24] When the firms sought for cost-effective designs, they were directed towards the two-bladed design by the researchers in engineering firms, institutes and technical universities ('t Hooft, 2000).[25] In part, this was probably made possible by the mobility of engineers (see above), which influenced the function 'Create External Economies', increasing the receiver competence of the firms.[26] Third, the focus on cost-effectiveness also drove firms to develop relatively large turbines since these were considered to be better in this sense ('t Hooft, 2000).[27]

The programme also involved stricter demands on the firms; instead of supporting basically all firms, project proposals were evaluated and ranked more systematically ('t Hooft, 2000) and firms were, thus, more obviously made to compete for funding. The selection pressure increased and many firms left the industry (Verbong, 1999). In 1988, only seven Dutch firms had certified turbines, which was a prerequisite for obtaining building permits and investment subsidies, and these firms were also the only firms that had received funding for turbine developments (Hack and de Bruijne, 1988).[28] The experiences in relation to the

[22] The customer received an amount of money per kW installed (up to a maximum amount). The customer, thus, got more support for a turbine with a large generator than for a turbine with a smaller generator.

[23] For example, Newinco introduced its first two-bladed design in 1989 (Versteegh, 2000). Another firm, Lagerwey, actually had two-bladed turbines from the very beginning.

[24] The firms had to state how they could contribute to the aims of the programme (the installation of 150 MW, a cost-effective wind turbine and a self-supporting industry in the period 1986-90) in order to receive the 70 percent subsidy for their development costs (Hack and de Bruijne, 1988).

[25] From the very beginning, the Dutch researchers focused their research on the two-bladed design (van Holten, 2000; van Kuik, 2000; Versteegh, 2000). It was, and still is, claimed to be less expensive than the three-bladed.

[26] Several of our interviewees have stated that the competence gap between, e.g., ECN and the firms had been much too large for firms to adopt the research results earlier.

[27] The development of larger turbines was probably also a 'natural' choice for the firms that saw utilities as their main customers.

[28] A seventh firm, Stork, had certification for its NEWECS turbines (Hack and de Bruijne, 1988), but at this time it had already left the wind turbine industry and was concentrating on providing engineering consultant services.

experimental wind farm (see above) further induced firm exit. At the end of the phase, the industry consisted of one firm in the category below 100 kW and four firms in the category 200-500 kW[29] (de Bruijne, 1990).[30]

In summary, the result of the second sub-phase was a growing domestic market, the selection of a number of firms and the choice of an, by international standards, quite unusual dominant design. Thus, at a time when the German industry was still in a phase of variety creation, the Dutch industry had taken its first step into a phase of market growth and selection, both in terms of technology choice and commercial success.

4.1.3 The Swedish case

In Sweden, an R&D policy provided substantial influence on the function 'Supply resources' until the mid-1980s. It began in 1975, when Saab received funding for the design of a 60 kW experimental turbine (DFE, 1979). In 1977, a more substantial R&D programme for wind energy was initiated, 105 million SEK over a period of three years (Carlman, 1990).[31] Until 1979, Sweden spent more government money on wind energy R&D than either Germany or the Netherlands, and the Dutch accumulated R&D funding did not reach the Swedish level until 1985 (IEA, 1997b).

However, the supply of resources influenced the function 'Guide the direction of search' in such a way that the function 'Create new knowledge' was restricted to very large turbines. The aim of the programme was to develop 2-3 MW turbines and there was no support for small or medium-sized turbines. Two full-scale MW turbines were erected in 1982 and 1983 respectively, one by a shipyard and one by a mechanical engineering firm (which later became part of Kvaerner Turbin) (Göransson, 1998). Much due to these turbines, Sweden was considered to be one of the leading countries in wind energy at this time (Carlman, 1990).

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[29] However, one of these firms seems to have been active on paper only.

[30] There were probably also some manufacturers of small (<50 kW) turbines.

[31] The political force behind this programme, as well as its 1981 follow-up, was the Centre party. The Centre party, which is a non-socialist party, has always been the main political force in favour of renewables, whereas the other parties, with the exception of the Communist party, have had either a cool or a very hostile attitude. For more details, see Carlman (1990).

Apart from the government funding, which induced a few large firms to enter the wind turbine industry, there was hardly any positive influence on the function 'Guide the direction of search' (in terms of growth potential). The local market was close to non-existent since there was hardly any positive influence on the function 'Facilitate market formation', such as demonstration programmes or 'green' demand.[32] The lack of demand was further aggravated by the fact that several new nuclear power plants were taken into operation after the referendum, which led to an expansion in the supply of electricity and low prices. More importantly, neither the market growth in the 1980s in California and Denmark, nor recessions in other areas led to a search into wind turbines, presumably due to the lack of legitimacy of the technology.

This lack of legitimacy had its roots in the Swedish nuclear power issue, which had been discussed since the early 1970s and which led to a referendum in 1980 after the Harrisburg accident. It was decided that the Swedish nuclear époque was to end in 2010, but the issue has still not been settled. The energy-intensive industry, the capital goods industry and the two dominant utilities formed a powerful alliance to stop the threat of nuclear power being dismantled.[33] In the other camp, the anti-nuclear power movement referred to the results of the referendum and demanded the dismantling of the first nuclear power station.

The Social Democrats in power had considerable problems to balance the demands of the two camps, which led to an uncertainty with regards to policy and an associated lack of predictability of the conditions in the energy field (Göransson, 1998). Over time, a 'nuclear power trauma' emerged, which reduced all energy issues to one: the issue of whether or not to dismantle the Swedish nuclear power plants. In the very heated debate, renewable energy technology was seen only as a substitute for nuclear power.[34] Consequently, an interest in, for example, wind power was automatically assumed to involve an anti-nuclear stance and, thus, a 'betrayal' of Swedish industry, which enjoyed the benefits of cheap nuclear power.

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[32]As late as in 1992, there were only 39 turbines in Sweden (BTM, 1998, table 2-5).

[33] These actors had successfully worked together earlier to develop a good infrastructure to provide industry and consumers with cheap electricity (Kaiser, 1992).

[34] This also influenced the function 'Guide the direction of search'. Since renewable energy technologies were measured against the yardstick of a nuclear power plant by the utilities, the subsequent technology choice in renewables was biased in favour of large sizes, the only technology which could have an impact on the power balance in the short and medium term (Johnson and Jacobsson, 1999).

Thus, it was not surprising that few industrial actors wanted to be associated with wind power and, obviously, it did not gain any legitimacy either in the eyes of the capital goods industry or among potential industrial users.

In 1985, the new Social Democratic government drastically reduced the level of ambition in the wind energy programme (Carlman, 1990). The few existing firms were severely constrained, as they needed subsidies to sell their turbines (as did all other large turbines in this period).[35]

In the parliament, there were, however, several demands made for government financed or subsidised demonstration plants, both in 1985 by the Centre party and in 1986 by an expert group (Carlman, 1990). The responses to the latter proposal were typical for the 'trauma': The federation of industries was critical; the farmer's association wanted demonstration plants for small turbines and an environmental group wanted an expansion of both small and large turbines (Carlman, 1990). This group also suggested the implementation of measures to ensure easy grid connection for the turbines. In 1989, the Centre party argued that the utilities should be obliged to accept electricity from wind turbines and that there should be a guaranteed minimum price (Carlman, 1990).[36] None of these suggestions were, implemented and the market for wind turbines developed very slowly. In 1990, there were fewer than 30 commercial turbines (Carlman, 1990) and a total stock of 4.4 MW (Elforsk, 1996).

The Swedish industry was still almost non-existent, even though a small mechanical engineering firm entered the industry and Kvaerner took up its work on large turbines again when approached by the German firm MBB (Göransson, 1998).[37] The former firm supplied three 250 kW turbines, which were the first medium-scale turbines ever built by a Swedish firm.[38]

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[35] For example, Kvaerner's preparations for a series production of 2 MW turbines were never realised.

[36] As we will see, these were key features of the German Electricity Feed-in Law to come a year later.

[37] A 3 MW turbine was developed partly with support from the Swedish wind energy programme and Vattenfall and was erected in 1992 (Göransson, 1998).

[38] The entry of this firm, Zephyr, was induced by the municipal utility, which had an ambition to develop a 'green profile' (Svensson, 1998).

Hence, in a phase when Germany and the Netherlands developed a lot of knowledge and a set of industrial firms with experience in building a few hundred turbines, Sweden's main strength lay in designing very large turbines for which there was no market at that time.

4.2 The phase of turbulence and growth

4.2.1 The German case

In the second phase, the German case was characterised by virtuous circles, in which the functions influenced each other in a self-reinforcing process (see figure 4.4). These circles were initially induced by measures affecting the price of wind electricity, which influenced the function 'Facilitate market formation' and led to a rapid market expansion.

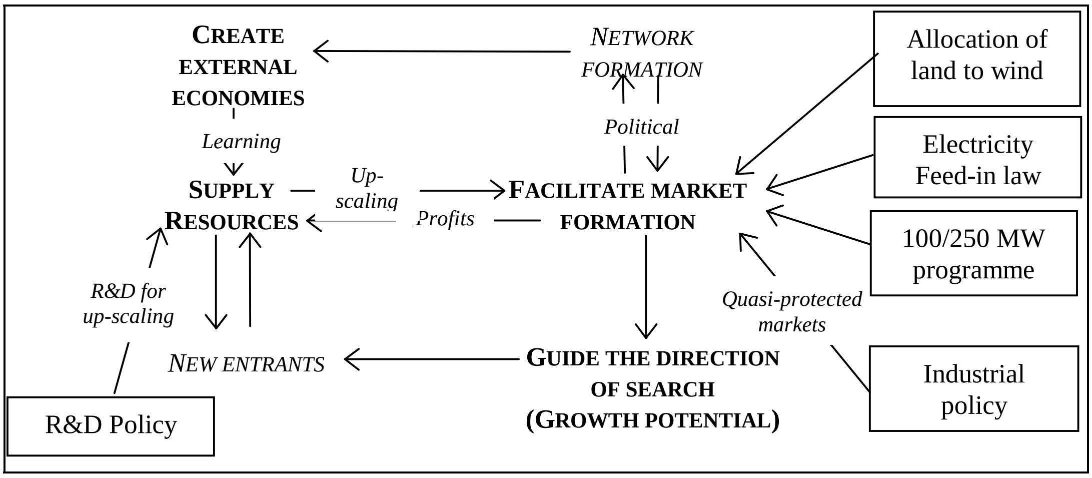

Figure 4.4: The German innovation system in the phase of turbulence and growth.

The first measure was a federal combined market stimulation and scientific programme, which was initiated in 1989. This programme initially aimed at installing 100 MW of wind power – a huge figure compared to the stock of 19 MW in 1989 – and was later expanded to 250 MW. The programme mainly involved a guaranteed payment per kWh electricity produced.[39] The bulk of the sales within the programme took place 1990-1995 and the programme accounted for most of the close to 60 MW that were sold in the years 1990-1992 (ISET, 1999b, table 3).

[39] In addition, private operators, e.g. farmers, had the possibility to obtain an investment subsidy (Durstewitz, 2000a).

The second measure, the Electricity Feed-in Law (EFL), came into force in 1991.[40] It required utilities to accept electricity delivered to the grid by independent wind turbines and to pay 90 percent of the average consumer electricity price. The payment stipulated by the EFL was put on top of the 100/250 MW programme subsidy as well as of various state programmes (DEWI, 1998), which resulted in very high payments.

The powerful combination of market stimulation measures resulted in an 'unimaginable'[41] market expansion from about 12 MW in 1989 to close on 490 MW in 1995 (BWE, 2000). Since the payment was based on a law and not a temporary programme, the income generated from wind turbines was both high and predictable, which greatly reduced the risks associated with investment. Farmers, private individuals and firms had a clear economic incentive to invest in wind turbines and, as a consequence, private capital was mobilised on a large scale.

Not surprisingly, some of the economic benefits spilled over to the suppliers in the form of high prices, which through the function 'Supply resources' induced product development, in particular in terms of the up-scaling of turbines (Molly, 1999). One of the reasons for the rapid up-scaling during the 1990s was the allocation of land to wind turbines stipulated by the federal government in 1997; if the states did not designate areas for the erection of wind turbines, operators would be free to erect them anywhere. As the land available for wind turbines became more restricted, the demand for larger turbines increased.[42]

The function 'Supply resources' was also served by the federal R&D programme, which continued to co-finance the industry's development work. For example, some of the early entrants received funding to design medium-sized and large turbines (500 kW, 750 kW and 1 MW), which helped them to up-scale their turbines further. Resources were also provided by some of the new entrants, which were induced by the market expansion (Molly, 1999).[43]

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[40] The Law was backed by all parties in the parliament (Ahmels, 1999).

[41] This was the word used by a central person in the evolution of the German wind turbine industry and market.

[42] Moreover, new firms emerged, specialising in erecting and managing wind parks, primarily built with larger turbines, which further stimulated the fast market growth.

[43] As many as 16 German firms started to sell turbines on the German market in the period 1990-1993, although most of them stopped soon thereafter (elaboration on Durstewitz (2000)). Later, two large corporations, Enron and Balke-Dürr, acquired the firms Tacke and Nordex, providing the capital they needed to participate in the race towards larger turbines.

Aided by industrial policies at federal and state levels, German suppliers managed to capture a significant part of the expanding market. An umbrella of implicit and explicit federal and state policies created a temporary quasi-protected market and German firms were able to increase their supply to the German market from 62 turbines (9 MW) in 1989 to 719 turbines (325 MW) in 1995 (elaboration on Durstewitz (2000)). Thus, these policies may be said to have influenced the function 'Facilitate market formation' to the advantage of the German suppliers.

First, an industrial policy element seems to have been present in the 100/250 MW programme. Projects were selected so that there was a wide range of experiments in terms of different applications (state and operator) and types of turbines. Due to this selection process and the large number of applications – as many as 8,000 applications were received and only 1,500 granted (Windheim, 2000a) – there were ample opportunities to manipulate the selection of projects so as to favour German industry (Hoppe-Kilpper, 2000; Molly, 1999; Ahmels, 1999).[44] Moreover, since a ceiling of 40 turbines was set on the sales of each turbine category (DEWI, 1998),[45] small firms were able to benefit from the programme (the ceiling was, of course, only relevant to the large and dominant firms). This also worked in favour of the German firms since they were relatively small, especially in comparison with the Danish market leaders. Yet, the dominant Danish industry was not locked out of the market entirely since it was neither possible, due to EU regulations, nor seen as desirable as the benefits of competition would be reduced (Hoppe-Kilpper, 2000).[46] Eventually, the Danish industry received about 35 percent of the projects, the Dutch (Lagerwey) about 7 percent and the German industry the remaining 57 percent (more than 700 turbines) (elaboration on ISET (1999b), table 11).[47]

[44] The programme was especially significant for the present German market leader, Enercon. In 1990-92, between 40 and 50 percent of Enercon's turbines were sold within the programme (elaboration on Durstewitz (2000)). Interestingly, the high share was reached before Enercon developed the E40 model, which used a unique technology and therefore could be assumed to constitute a special 'type'. In total, Enercon sold 325 turbines within the 250 MW programme, which represented about 45 per cent of the total sales by German firms. Other firms which benefited greatly were Tacke, Husumer, Seewind and Ventis (which later spun off the fast growing Dewind).

[45] The ceiling probably became higher as the programme changed from 100 to 250 MW.

[46] The former CEO of Vestas, Finn Hansen recalled however that the Danish firms found the German market difficult to penetrate but never understood why (Hansen, 1999)

[47] This is based on information on the firms that had installed more than 40 wind turbines by 1998. Thus, the tail of German firms, which sold fewer units, has been left out. Therefore, the share of German firms is slightly underestimated. As earlier, we have treated Nordex as a German firm.

Second, at the state level there were explicit or implicit policies to foster a local turbine industry. For instance, at the end of the 1980s Tacke benefitted when Nordrhein-Westphalen created a programme where one of Tacke's turbines was the only one eligible for a 50 percent investment support (Tacke, 2000).[48] Other firms had close local user-supplier relationships. For example, Enercon sold its first units of an early turbine to local utilities (Reeker, 1999) and Husumer experienced that there were strong local biases in the choice of supplier (Schult and Bargel, 2000).

The growing strength of the suppliers and users allowed for the formation of two types of powerful networks. First, it led to the emergence of learning networks via the function 'Create external economies'. These developed primarily between wind turbine suppliers and local component suppliers due to the need to adapt the turbine components to the particular needs of each turbine producer.[49] The benefits of learning also spilled over to new entrants, since they influenced the function 'Supply resources'; subsequent entrants could rely on a complete infrastructure.[50] Indeed, some new entrants were able to work as design firms, i.e. without the production of components or in-house assembly (Mayer and Delabar, 2000), which made it possible for them to minimise capital investments.[51] Second, political networks were formed between competitors with a common interest in influencing the institutional framework to the benefit of the whole industry. These networks were manifested in an active industry association that enrolled both turbine suppliers and turbine owners,[52] and proved to be of great importance during the ensuing battle over the feed-in law.

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[48] This program was seen as a second start for the firm, which later grew to be the second largest in Germany. The CEO considered this programme only next to their earlier California participation in importance to the development of the firm.

[49] Relationships to customers seem to be of less importance, which is not surprising since most of the customers have been farmers. Some larger customers are, however of importance today for feed-back. (Hansen, 1999).

[50] Today, the supplier industry is well developed in Germany and several of the interviewees emphasised the importance of having access to this industry locally.

[51] Other parts of the infrastructure were set up as well, for example the German wind energy institute (DEWI), which is an organisation that bridges industry with customers and government (Molly, 1999), and wind turbine test sites, which have been of great importance for the turbine manufactures (Windheim, 2000a).

[52] In addition, it collaborated with other industry associations in the renewable field in an umbrella organisation which had 8,000 members in 1999 (Ahmels, 1999).

At the time of the design of the EFL, neither the opponents nor the proponents of wind power could have imagined the scale of the diffusion that ensued (Ahmels, 1999). However, in the mid-1990s the rapid diffusion of wind turbines led to a response from the larger utilities. Intense discussion and lobbying followed, which reintroduced substantial uncertainty and the market stagnated. In 1997, a select committee with 15 members of parliament was responsible for investigating whether or not the law should be amended. In the end, the wind turbine lobby won the political battle, although it was a close call; in the select committee, the proponents of a continued law won the vote by eight to seven (Ahmels, 1999). This was largely a result of the rapid diffusion of wind turbines in the first half of the 1990s and the associated growth of the German industry, which made it possible to add economic arguments to environmental ones in favour of wind energy. Additionally, the utilities did not get support from any of the political parties (Molly, 1999). Indeed, as one CDU member of the industry said, " In this matter we collaborate with both the Greens and the Communists". Nor did the German federation of industries (VDMA) choose to support the power companies when they opposed the EFL (Tacke, 2000).

In conclusion, the market formation set in motion a set of virtuous circles, which resulted in the German industry narrowing the gap to the Danes considerably. Today, there are at least nine German firms active in the industry.[53] Yet, this evolution would hardly have been possible without the phase of extensive experimentation in the 1980s, which led to the emergence of a German wind turbine industry strong enough to respond to the effects of the function 'Facilitate market formation'.

4.2.2 The Dutch Case

In the Dutch case, the virtuous circles of market growth, increased industry resources and growing political strength did not appear for two main reasons: The domestic market did not develop as expected and the Dutch industry failed to exploit the growing German market (see figure 4.5).

[53] Enercon, Tacke (bought by Enron), Dewind, Husumer (recently bought by Jacobs), Jacobs Energy, Fuhrländer, WTN, Frisia and Seewind; these firms sold at least one turbine on the German market in 1999. There may also be other firms operating, selling very small turbines or selling only abroad.

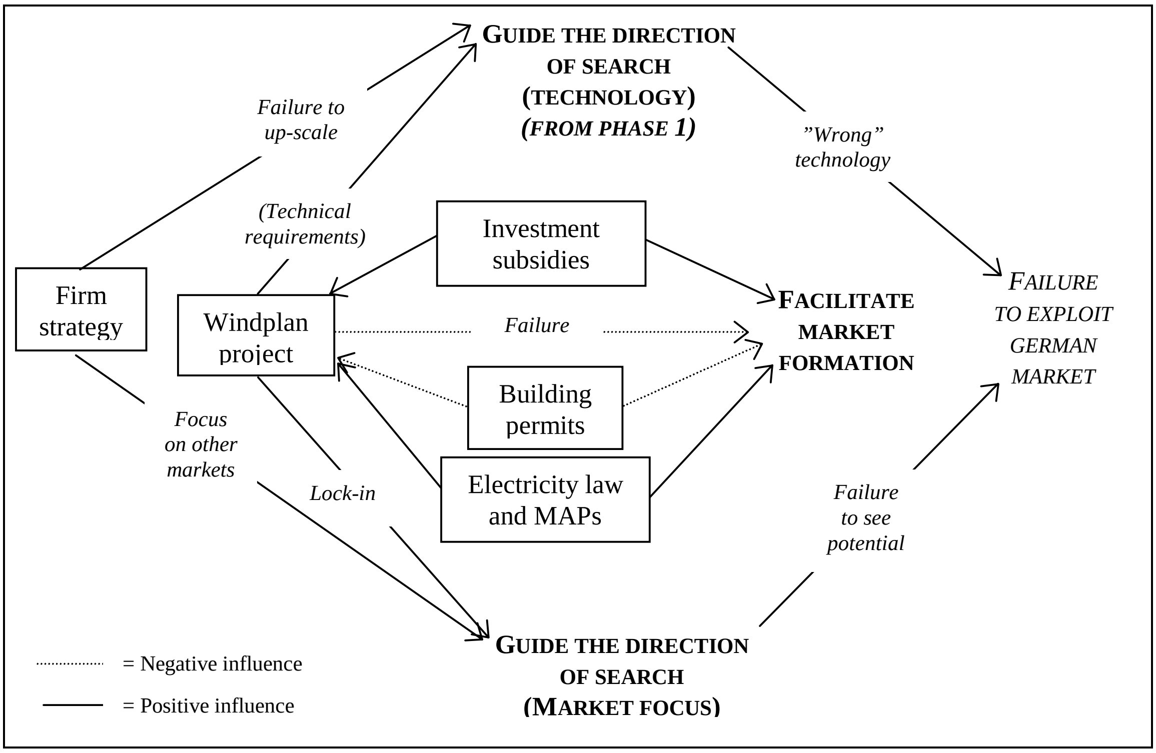

Figure 4.5: The Dutch innovation system in the second phase.

In 1990, the total installed capacity was less than 50 MW and the Dutch goal of 1,000 MW in 2000 was still far away. The government tried to influence the function 'Facilitate market formation' through continued investment subsidies (Verbong, 1999; Wolsink, 1996), but it did not have the intended effect. One of the reasons for this was the problem of finding sites for the turbines. The population density is very high and the building permit procedure was slow and time-consuming (Gipe, 1995; 't Hooft, 2000).[54]

However, at the end of the 1980s a new electricity law created a demand for wind energy. The law separated electricity production from electricity distribution (Verbong, 1999) and the electricity distributors could not produce or import electricity with the exception of electricity produced by renewable energy technology (Kip, 1999).[55] Moreover, the distributors were allowed to finance their investment in renewable energy technology via a new electricity tax (Wolsink, 1996).

[54] Obtaining building permits for wind turbines involve changing the zone plans of the municipalities and applying for a building permit. Both these decisions may be appealed at numerous levels and in total, a normal project takes over five years to complete. (Janssen and Westra, 2000; 't Hooft, 2000).

[55] The electricity distributors saw wind power as an opportunity to strengthen their bargaining power in relation to the large electricity producers and improve their environmental image (Verbong, 1999).

Since the distributors believed that co-ordinating their investments in wind energy would result in better and cheaper turbines, they formed the Windplan foundation aiming at installing 250 MW over a five-year period (Kuipers, 2000a). Compared to the market size at this time, the promised 50 MW per year during five years was a lot and the hopes on the Windplan project were high.[56] The Dutch firm Newinco/Nedwind started to deliver turbines, but the project was quite suddenly abandoned in 1993 (Verbong, 1999). The primary reason was that the electricity distributors started to question the benefit of joint procurement; they believed that they could get lower prices and better guarantees if they bought the turbines themselves (Kuipers, 2000a). Another reason was the problem to obtain building permits described above (Janssen and Westra, 2000; Kuipers, 2000a; Wolsink, 1996), which had the same effect on the Windplan members as on other customers.

The central authorities did, however, make an attempt to solve the building permit issue. They made an agreement with some of the provincial authorities about how to distribute the 1,000 MW (Kuipers, 1991). However, neither central nor provincial authorities had any real decisive power over building and environmental permits – these were obtained from the local authorities, and they were not included in the agreement (Janssen and Westra, 2000; Kip, 1999) and had no real interest in complying with the agreement.[57] Thus, the building permit issue continued to block the function 'Facilitate market formation'.

In spite of the problems with the Windplan project and the building permits, the Dutch investment subsidy was withdrawn in 1996 (Novem, 1999; 't Hooft, 2000).[58] A couple of other measures were implemented to support wind power: tax schemes designed to support environmental investments in general (Novem, 1999) and, later, a new electricity law, which specified the share of the utilities' electricity sales that had to come from renewable

[56] This was also a lot more than the German 100 MW programme, which was initiated at about the same time (at that time it was not yet clear that it would be extended to 250 MW).

[57] There were few benefits and many disadvantages associated with wind energy for local communities (van Kuik, 2000). In addition, the central government was fairly arrogant towards them, which made them unenthusiastic (Kip, 1999).

[58] Ironically enough, this caused the market to 'boom' in 1995, much due to the perceived uncertain future for wind power in the Netherlands (IEA, 1998).

energy sources.[59] The result of these measures was not, however, very impressive. After 1995, the market stayed at a stable level of 40-50 MW per year and in 1999 the total installed capacity was still nowhere near the goal of 1,000 MW.

One reason why more powerful measures were not used to facilitate the market formation seems to have been that wind power was not really an important political issue (Janssen and Westra, 2000). For example, it is in principle possible for the government or parliament to impose directives for land usage on the local authorities in cases of 'national interest', but wind power has not been considered sufficiently important to get that kind of support ('t Hooft, 2000).

The second reason for the lack of virtuous circles in the Dutch case was that the Dutch industry failed to exploit the German market, which started to expand a few years prior to the failure of the Windplan project.[60] There were two primary causes of this failure.

First, some of the Dutch turbines turned out not to be in demand on the German market due to an 'inappropriate' choice of technology. During the second phase, a change to only three-bladed turbines was dictated by the German market ('t Hooft, 2000; van Kuik, 2000) and there was not yet any demand for large turbines. However, as mentioned earlier, most Dutch turbines were two-bladed and quite large. In addition, some claim that although the requirements of the Windplan project were technically feasible, they were not commercially feasible with respect to other markets.[61] Thus, the requirements may have influenced the function 'Guide the direction of search' in terms of technology choice even further away from the demands of the international (including the German) market.

Second, and probably more important, the function 'Guide the direction of search' in terms of market focus steered the firms away from the German market so that they failed to see

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[59] It also included a 'green labelling' system where every kWh of electricity produced from renewable energy sources got a label that may be bought and sold (van Zanten, 1999).

[60] The exception was Lagerwey, which entered the German market and was fairly successful initially, largely because it had a niche market (in the farmers) and a good reputation. However, when the rapid up-scaling begun, Lagerwey's managers made the strategic mistake of ignoring it (Boursma, 1999) and Lagerwey quickly lost its market position.

[61] There are some contradictory statements on this issue – some claim that the turbines developed were not that different from what was already commercially available, whereas others claim that the turbines were very different from other turbines and that they were too advanced to be in demand in other markets.

and to react upon its potential. The function was influenced in part by the strategic choices made by the firms and in part by the Windplan project. Both Nedwind and Windmaster put their 'export bets' partly (if not mostly) on the North American and Indian market. They also invested a lot of time and effort in the Windplan project answering the tender and developing new turbines and had, therefore, less management time and resources to develop other markets.[62] Indeed, the promise of the Windplan project probably made it seem unnecessary to look for opportunities elsewhere. Even though over 90 percent of the first 75 MW to be built were reserved for Dutch firms,[63] a large number of foreign firms answered the tender (Kuipers, 2000a). This clearly indicates that the Dutch market was perceived as very interesting for the future.[64] In this perspective, the choice of the Dutch firms to concentrate on their home market is not so difficult to understand.

Without access to a booming market and the associated economic benefits, the Dutch firms had neither the resources to develop their technology fast enough to keep up with the German suppliers nor the political strength to influence the vital building permit issue. Thus, most of the industry stagnated and failed. In 1998, Windmaster went bankrupt and was acquired by Lagerwey. Nedwind also got into trouble and was acquired by NEG Micon. Lagerwey is now the only large Dutch wind turbine firm left.

4.2.3 The Swedish case

In Sweden, there continued to be R&D support for the development of Swedish turbines, which was now carried out mainly in three firms: Kvaerner Turbin, Zephyr and Nordic Windpower.[65] However, the firms had to co-finance the projects to a larger extent than before (Göransson, 1998) and the technology had to be 'new' in order for the firms to receive support (Svensson, 1998).[66]

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[62] Of course, when Newinco/Nedwind was chosen as the only supplier (Kuipers, 2000a) it was quite natural for it to concentrate its efforts even more on this project.

[63] In order to receive investment subsidies within the frames of the wind energy programme, Windplan was required by the Ministry of Economic Affairs to buy a large part of the turbines from Dutch producers (Kuipers, 2000a).

[64] One of the interviewees even stated that "at that time, no firm could afford to not be part of the project".

[65] Nordic Wind Power was founded in 1990. Its turbines (a 400 kW turbine and a 1 MW turbine) have an unusual design; the turbine is significantly lighter than other turbines and is, therefore, expected to be cheaper.

[66] For example, the firm Zephyr had to continue to develop its second turbine by expanding the wing by 2 meters in order to fulfil the conditions for receiving subsidies for technical development work. As a result, the turbine failed (Svensson, 1998).

It was also difficult for the firms to find venture capital or other partners that could co-finance technology and market development. [67] One reason for the difficulties was that the deregulation of the electricity market changed the status of Vattenfall so that it had to reduce its role as a development partner (Averstad, 1998), a role that had been of importance to several Swedish wind turbine firms. Most importantly, however, potential industrial partners were not interested, which was clearly associated with the 'nuclear power trauma'. As one CEO explains: "There was mental resistance to wind power".

Thus, there was a lack of resources, which was troublesome for all firms; the smaller firms had very weak resource bases and wind turbines were not a prioritised part of the larger Kvaerner corporation. The lack of resources severely constrained the firms, as they needed reference installations to gain creditability in the market and to get enough 'staying power' to challenge the Danish suppliers with their early mover advantages.

The function 'Facilitate market formation' was influenced somewhat by policy measures. A market expansion programme in the form of an investment subsidy was started in 1991 (Averstad, 1998). It was supplemented by an environmental bonus in 1994, and from 1996 utilities were required to buy the wind power produced by independent producers (Averstad, 1998). Although these inducement mechanisms were much weaker than in Germany and Denmark, the market began to expand. The diffusion could have been much faster, though, had there been fewer problems in securing building permits (Grahn, 1998).

However, in sharp contrast to the German and Dutch cases, the phase of experimentation did not lead to the development of a strong Swedish industry with response capacity. In addition, there were no mechanisms that favoured Swedish suppliers.[68] Without a quasi-protected local market, development partners and legitimacy, no virtuous circles were set in motion and the market was handed over almost completely to Danish suppliers.

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[67] For example, it took the founder of a new firm, Nordic Windpower, five years to find a first customer and initial financing. After that, it took eight more years of search before NWP received risk capital from three venture capital firms. (Bergqvist, 1998).

[68] In fact, the Swedish rules for the investment subsidies worked more in favour of the Danish suppliers. The turbines had to be certified in order to receive investment subsidies, and since there was no certification authority in Sweden, it was decided that turbines that were certified in Denmark would automatically be certified in Sweden as well (Svensson, 1998).

The remaining industry now consists mainly of two firms: Nordic Wind Power and ScanWind, which is a Swedish-Norwegian spin-off of Kvaerner's wind turbine activities.[69] Although both these firms have some experience in large turbines, they are up against Danish and German firms that are now mass-producing 1.5 MW turbines and that are in the process of designing much larger turbines (5 MW). The risk is therefore obvious that Sweden will end up without any firm in this growth industry.[70]

5. Conclusions: Why does performance differ and what implications can we draw for policy?

The objectives of this paper were to develop an analytical framework and to use this framework to explain the performance of the wind turbine industry in three countries.

The analytical framework is based on an innovation system approach in which the system is analysed in terms of its 'functional pattern'. With this framework, we can scrutinise, for instance, the direction of search of various actors, the subsequent type and variety of knowledge generated and the resources supplied to exploit that variety. We can analyse in both static and dynamic terms, i.e. how these functional patterns evolve. In section four, we outlined such patterns in the three countries studied.

Looking at the patterns through the 'filter' of life cycle models allowed us also to assess the 'functionality' of the innovation systems i.e. *how well* the functions were performed. We argued in section 2 that the meaning of functionality would be expected to differ between phase in the evolution of an industry. In an early phase, functionality may be assessed by analysing how the innovation system supports firm entry, the formation of niche markets and the creation of variety, whereas in a later phase, the emphasis is shifted to mass market formation and resource supply to exploit that market.

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[69] After some economic problems, Kvaerner decided to discontinue its wind turbine activities and some of its employees then founded a new firm (Energimagasinet, 2000). Zephyr left the industry in 1998, due to problems in keeping up with the international trends in size of the turbines, which in turn was much due to lack of resources.

[70] However, ABB recently announced the launching of a new wind turbine, Windformer, which is claimed to have a 20 percent higher power output than conventional technology (Köhler, 2000). The experience, resources and legitimacy of such a large actor may very well result in a new chance for the Swedish wind turbine industry. In addition, there are a few producers of very small turbines.

We suggest that it is useful to analyse the functionality of the German, Dutch and Swedish innovation systems under four headings: (1) variety creation in the first phase, (2) legitimacy of wind energy, (3) market formation in the second phase and (4) the use of industrial policy.

(i) *Variety*

In an early period of an industry's evolution, as that of wind turbines in the 1980s, technological uncertainty is high and industry needs to place its bets widely in terms of experimenting with a variety of designs.

This was done in Germany as well as in Holland through several mechanisms. In both countries, R&D policy encouraged a broad range of technical experiments and some of the resulting turbines were exploited commercially on the market. In Germany, but not in the Netherlands, the Californian and Danish 'booms' and the formation of niche markets were clear inducement mechanisms for firm entry. In addition, some German and Dutch firms responded to the decline in their original business by entering the wind turbine industry. So, at the end of the 1980s, a large number of actors, firms and universities had developed and tried out a range of different designs. Many failed, but this is a necessary ingredient in the formation of a new industry.

In Sweden, the picture was very different. Policy guided the firms in one direction only – MW sized turbines. A couple of these turbines were erected, but apart from that there was hardly any local demand. Nor were any Swedish firms stimulated to enter by the Californian/Danish experience. Only one firm supplying smaller turbines entered at the end of the decade.

Whereas both Germany and the Netherlands managed to create variety both in terms of the knowledge generated and in terms of the actors exploiting it, the Swedish knowledge was, thus, limited to larger turbines and to mainly one firm, Kvaerner. The functionality of the German and Dutch innovation systems was, thus, far superior to that of the Swedish in this respect.

(ii) *Legitimacy*

A key feature in the process of generating variety in Germany and the Netherlands was the early legitimacy of wind turbines. Already in the 1980s, there was a political consensus that wind turbines should be supported and it was legitimate for private capital to exploit wind turbine technology. The legitimacy meant that firms responded to various stimuli, e.g. the Californian ‘boom’, R&D programmes etc., by diversifying into wind turbines or by starting a new firm. Without these entrants, the variety in terms of knowledge generated would, of course, have been much less.

In Sweden, wind turbines lacked legitimacy. This meant that Swedish firms responded differently to the very same stimuli that made some German firms move into the wind turbine industry. The Danish and Californian experiences simply passed by most of Swedish industry. Due to the ‘nuclear trauma’ and the associated lack of legitimacy, the few individuals and firms who saw a future in wind turbines faced severe limitations in terms of access to resources (capital), partners, markets and government support (apart from R&D funding to MW turbines). This meant that the very considerable competence built up by government R&D programmes, some of which could have been exploited for smaller turbines, came to little use. Thus, legitimacy is a key concept in an explanation of why the German and Dutch innovation systems had a superior functionality in terms of variety creation in the first phase.

(iii) *Market formation*

The legitimacy of wind turbine technology in Germany also meant that there was little opposition to creating a market formation programme. The 250 MW programme and the initial formulation of the Electricity Feed-in Law (EFL) met little or no opposition from the proponents of centralised power production. The market expansion that followed on these programmes set in motion virtuous circles where the variety generated in the first phase was exploited.

When the debate over the EFL started in the mid-1990s, it took place in a context where the initial legitimacy appears to have been strengthened, in part by the growing economic importance and political strength of the wind turbine industry. The legitimate nature of wind energy meant that the ‘battle’ over the EFL was won by the infant German wind turbine industry and, as a result, market formation continued to be the driving force in a set of virtuous circles.

In the Netherlands, the local industry[71] was locked into a local market that did not grow very fast in the 1990s. The Windplan project of the early 1990s kept the Dutch firms largely focused on the local market and the Dutch turbines were not in demand abroad due to an inappropriate choice of technology. The Windplan project failed, in part because the siting issue was not resolved. No virtuous circles were put in motion and the initial variety was not exploited. We interpret the failure to solve the siting issue as a failure to develop further the initially reasonably strong legitimacy. The central government did not take adequate steps to overrule the local governments which controlled the planning process.

In Sweden, although the market developed in the 1990s, virtuous circles for a Swedish wind turbine industry were not started simply because it was too weak to respond to the growing demand. Unlike in Germany and the Netherlands, there was an absence of an initial variety from which winners could be selected.

Thus, in the second phase, the functionality of the German innovation system was superior to that of the Dutch in that a larger market was formed and, through virtuous circles, more resources were supplied to the industry. Underlying the greater functionality of the German innovation system was, however, a greater legitimacy.

(iv) *Industrial policy*

In the first half of the 1990s, the German industry was aided by industrial policies at the federal and state levels that created a ‘quasi protected’ market and a German market share of more than 50 percent, which is especially remarkable considering the otherwise dominant position of the Danish industry. This was clearly of vital importance to the ability of infant German industry to benefit from the powerful market formation locally.

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[71] The exception was Lagerway.

In the Dutch case, there were also some elements of industrial policy. For example, more than 90 percent of the initial order of 75 MW in the Wind Plan project was awarded to Dutch firms. However, since the market never really materialised, the protectionist element had instead the effect of locking the firms to the local market.

In Sweden, energy policy never really had an industrial policy element. When the market expanded in the 1990s, no efforts were made to foster a local industry and the few firms that had entered the industry had almost no chance to be part of a virtuous circle of market expansion and increase in the supply of resources flowing into the industry.

There are a number of lessons for policy. First, when the technological uncertainty is large, as in the case of wind turbines in the first phase, diversity must be fostered. The Swedish R&D policy only financed MW turbines whereas the German and Dutch stimulated knowledge creation with respect to both small and large turbines. Diversity in design developments may have to continue to be supported for a lengthy period. Take for example the two-bladed turbine. It was, and still is, considered to be better than the three-bladed in terms of economic performance, and at the end of the 1980s almost half of the turbines on the German market were two-bladed. Yet, the two-bladed design was defeated by the three-bladed on the German market only a few years later.

Second, the creation of variety is closely connected to the number of actors within a field since these may bring different types of visions, competencies and complementary assets to the new industry. It is, therefore, central to guide the direction of search of a variety of firms towards the new field. The guidance may, as we have seen in our cases, come in many different forms and may be case-specific. Therefore, we will limit this discussion to what we believe is its most important aspect, i.e. legitimacy.

As evident in the three cases, it is vital that legitimacy is created for the new technology or industry. Without legitimacy, private capital will not flow into the industry and without an industry active on the political arena it will be difficult to remove institutional blocking mechanisms, as in the Dutch case of building permits, or to get institutional inducement mechanisms, as the present German version of the feed-in-law, in place. Thus, even if a number of support systems are implemented, a poor legitimacy will obstruct the evolution of virtuous circle of resource supply, market development and firm growth. Legitimising a new technology may, therefore, be a key policy objective.

The third lesson is that the exploitation of variety is strongly associated with the creation of powerful, predictable and persistent economic incentives, which was evident in the German case. Powerful incentives create the profitability needed to attract private investors. Predictability reduces the uncertainty for the actors involved, and persistent policies are required since the development of an industry takes time – the German economic incentives have been in place for ten years and are only now beginning to bear fruit.

Fourth, it is not the volume of resources supplied in government policy programmes that matter, but how the funds are used to generate a self-reinforcing process. As we have seen, a large government financed R&D programme was not enough to create a successful Swedish industry. In contrast to the Swedish case, policy agents[72] need to be concerned with all the required functions of an emerging system, and to intervene, if necessary, to support those functions that are relatively poorly served (or not served at all).

How to do this is, however, by no means self-evident. First, each function may be served in several different ways.[73] For example, resources may be supplied through a number of sources (e.g. government programmes, private investors and venture capital firms) to different recipients (e.g. suppliers or buyers) and in a variety of forms (e.g. subsidies and loans). Thus, a well functioning system may, presumably, not come about in one way alone, as illustrated in the phase of experimentation where Germany and the Netherlands managed to create variety in quite different ways.

Second, in some cases a number of different mechanisms are needed in order for a function to be served. Take the example of the function ‘Facilitate market formation’. The Dutch experience shows there is more to it than relative prices and financial incentives; the early investment subsidies clearly had limited effect due to the problems of obtaining building

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[72] These include not only government bodies but all types of actors who have an interest in influencing the functionality of a system.

[73] See Rickne (2000) for an analysis of the relations between actors and functions in the case of biomaterials.

permits. Likewise, the German 'boom' was not created by financial incentives alone; it took a combination of investment subsidies, legislation, legitimacy and industrial policy to start and to maintain the virtuous circle that eventually made the German market the fastest-growing in the world. This means that policy makers may have to work with a number of mechanisms simultaneously.

Third, due to the systemic character of industrial development, it may be impossible for one function to be served unless other functions are served as well. For example, some knowledge can only be created through a process of learning-by-using, which requires a market. The presence of a market may also be necessary for the direction of search of industrial actors to be guided towards a new technology. Policy makers therefore need to consider and understand the interdependencies between the various functions.

These features make it difficult to know how to influence a particular function as well as to predict the outcome of an intervention. We will illustrate this with market formation programmes in Germany and Holland. At about the same time, around 1989, Germany and the Netherlands designed market formation programmes of similar sizes. Clearly, nobody could have foreseen the formidable success of the German programme in creating a market (and indirectly influencing functions), nor the failure of the Dutch. Had instead the Dutch been successful with their programme (as many Dutch and foreign firms expected them to be) and the German programme failed (something which was entirely conceivable), the Dutch may today had been the ones catching up with the Danes.[74] Indeed, for an observer in the late 1980s, the Dutch industry must have seemed as likely to succeed as the German (if not more). This should make us humble with respect to our ability to control the sequences of events leading to the growth of new industries.

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[74] For instance, who could have foreseen that by the time the EFL was questioned, the wind turbine industry would have the lobbying strength to counteract the resistance? How could one have foreseen that the Dutch government would not succeed to solve the siting problem or that the electricity suppliers would suddenly decide not to go through with the Windplan project?

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