

Notions on learning applied to wind turbine development in the Netherlands and Denmark[☆]

Linda M. Kamp*, Ruud E.H.M. Smits, Cornelis D. Andriesse

Department of Innovation Studies, University of Utrecht, P.O. Box 80125, NL 3508 TC, Utrecht, The Netherlands

Abstract

This research investigates how methods of learning influenced the emerging wind power industries in the Netherlands and Denmark. It is found that the manufacturing and implementation successes in Denmark contrast with the relatively poor progress in the Netherlands, and that one of the reasons for this is the contrast in learning mechanisms between the countries. We start from the perspective of innovation systems. Within these systems we place the focus on four types of learning processes: learning by searching, learning by doing, learning by using and learning by interacting. It is concluded that in Denmark, learning by interacting was the most important learning process, while in the Netherlands it was learning by searching. The Dutch wind turbine innovation system was a typical 'science-push' innovation system. The aim was to develop large wind turbines at a fast pace, based on the results of scientific research. Because of the lack of contacts between the researchers and the wind turbine producers, the implementation of the research results was problematic. Contrarily, in Denmark the focus was on knowledge transfer between turbine producers, turbine owners and researchers. In this innovation system, conditions for learning by interacting were optimal. In this way, wind turbines were successfully, though slowly, scaled up and improved.

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1. Introduction

Several Western countries started to develop renewable energy in the 1970s. Reasons were the oil crisis and the Club of Rome report, which warned of imminent shortages of traditional energy sources like oil and gas. The renewable energy source that people had the highest expectations of was wind energy. Two of the countries that were involved in the development of wind energy were the Netherlands and Denmark. Both governments gave active support to this development. Furthermore, both countries have a comparable wind regime. However, the result of the development of wind energy in each country is very different. In the year 2000, Denmark had a flourishing wind turbine industry, that produced wind turbines for the world market. Further-

more, at the end of the year 2000 the cumulative installed capacity of wind turbines in Denmark was 2340 MW and wind turbines produced 15% of the electricity demand. In the Netherlands, the situation was far less rosy. Although 10–15 wind turbine manufacturers were active on the Dutch market at the beginning of the 1980s, in 2000 only one remained. Furthermore, at the end of the year 2000 only 442 MW of wind turbines had been installed in the Netherlands, the target for the year 2000 having been 2000 MW.

This research investigates how methods of learning influenced the emerging wind power industries in the Netherlands and Denmark. It looks into learning processes within the wind turbine innovation system: within companies and organisations, and between companies, organisations and customers. The specific research question is as follows:

To what extent did the learning processes in the Dutch and the Danish wind turbine innovation systems differ in the period 1973–2000 and to what degree can they provide an explanation for the difference in

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*Corresponding author. Tel.: +31-30-2537599; fax: +31-30-2533939.

E-mail address: lm_kamp@hotmail.com (L.M. Kamp).

performance of the Dutch and the Danish wind turbine innovation systems?

2. Methodology

2.1. The case study methodology

We used the case study methodology to answer this question. This is an appropriate research strategy to use when investigating questions of ‘how’ and ‘why’. Furthermore, case studies are a good approach when the researcher has no control over events and is not able to manipulate the relevant behaviour.

2.2. Data collection

To achieve validity in a case study, it is important to use multiple sources of information, such as written documents, from archives or from previous research, and interviews. This implies a complex research process but it is likely to yield better results and improve the quality of the narrative (Yin, 1989).

In our research into the Dutch case we used both written material and interviews. The written material was very varied: we used scientific articles, technical articles, conference proceedings, press releases, policy documents, technical reports, statistics, articles in popular magazines on renewable energy and promotion material from manufacturers. We used this material to obtain an overview of the development of wind turbines in the Netherlands and as a means of checking the data provided via our interviews. For the Danish case, we drew entirely on written material. In the first phase of the research, it appeared that a great deal of academic research had already been done on the development of wind energy in Denmark. Furthermore, a large quantity of literature on the Danish development was available in the Netherlands. Therefore, there was no need to carry out interviews in Denmark.

3. Theory: the innovation system and learning

The concept ‘innovation system’ was developed at the end of the 1980s and the beginning of the 1990s by Freeman (1987), Freeman and Lundvall (1988), Lundvall (1988, 1992) and Nelson (1993, 1994). It starts from the idea that innovations are often developed within systems formed by actors and organisations. Companies, governments, universities, banks, consumers, and other organisations all contribute in a different and interactive way to the innovation process. These actors and organisations, the relationships between them and the institutions influencing them, together form the innovation system (Carlsson et al., 2002).

3.1. The innovation system

Because ‘innovation system’ is such a broad concept, authors can define it differently and stress the element(s) they consider the most important. However, there is a set of characteristics upon which all researchers agree. In a study of a specific innovation system, these characteristics can be used as guidelines to build the theoretical framework. Lundvall summarises them as follows (Lundvall, 1992):

- The *central focus* is on technological innovation but organisational and institutional change are considered important as well.
- Innovation systems in various countries are claimed to be *different*, and it is important to study these differences.
- The viewpoint is *holistic*, in other words, many determinants and their relationships are included in the analysis.
- A *historical perspective* is used. Innovation is seen as an evolutionary and path dependent process. Therefore, innovation can be understood best when the historical development is taken into consideration. Because innovation is path dependent and open ended, it is not possible to define an optimal innovation system. Since the system keeps changing, it is possible that at one moment one system is better suited for stimulating certain technological developments, whereas later on another system performs better.
- Innovation is regarded as an *interactive process*. Firms do not innovate in isolation, but in interaction with other actors. Innovation is influenced not only by the structures and the actors in the system, but also by the interaction between them.
- The importance of *learning*, and especially of *interactive learning*, is stressed. The accumulation of knowledge and skills is considered to be crucial. The focus is on the interactivity between the structures and the actors in the system, and on the learning processes between them.
- There are no straightforward ‘rules’ about how the *boundaries of the system* can be specified; in other words, how to define what belongs to the system and what does not. But, as Lundvall argues (Lundvall, 1992), it might be impossible to identify the boundaries in detail. Therefore, it might be better to try to identify the core elements in innovation systems, and focus on the relations between these (Edquist, 2001). The researcher himself needs to define the boundaries of the system he is studying.
- Innovation systems consist of organisations and institutions on the one hand, and interacting actors on the other hand. Therefore, *a structural view is combined with an actor-oriented view*.

3.2. Learning

An important aspect in the innovation system approach is interactive learning. This is the transfer of knowledge between actors engaged in the innovation process. Lundvall in particular puts interactive learning at the centre of the analysis. While many other researchers concentrate on the influence of institutions on technology development (e.g. Edquist, 1997; Nelson, 1993), Lundvall and his colleagues of Aalborg University focus on the role of interactive learning between the users and producers of technology (Lundvall, 1992).

Like Lundvall, we put learning at the heart of our research. Therefore, we will look more closely at the concept of learning. We will investigate not only interactive learning, but also three other kinds of learning that are important in the innovation process (see a.o. Rosenberg, 1982; Garud, 1997): learning by searching, learning by doing and learning by using.

3.3. Learning by searching

During learning by searching, ‘know-why’ is acquired. Learning by searching is related to the systematic and organised search for new knowledge. It is a broad concept that includes a whole spectrum of activities ranging from basic research to discovering the optimal design characteristics of a product and discovering the design characteristics desired by the market. Synonyms for learning by searching are R&D (research and development) and ‘learning by studying’ (Garud, 1997).

The actors involved in R&D are generally universities, public research organisations or research departments of firms. R&D results are mainly written down in research reports or articles, which means that a great part of the R&D results is in the form of formalised knowledge.

Which (institutional) conditions in the innovation system facilitate learning by searching? On the basis of the innovation literature (see a.o. Andersen and Lundvall, 1988; Nelson and Winter, 1977, 1982; Frenken et al., 1999; Dosi, 1982; Frenken, 2001; Sahal, 1981; Hedberg, 1981; McKelvey, 1997; Carlsson and Jacobsson, 1997), we can list the following:¹

1. the presence of a technological guidepost, guiding the direction for search,
2. the availability of an appropriate scientific theory on the subject, guiding the direction of search,
3. the presence of a technological paradigm, guiding the direction for search,
4. the presence of standards and regulations, guiding the direction for search,
5. an environment that is not (too) hostile,

6. the availability of capital,
7. some level of knowledge and experience in the field of study,
8. the possibility of making mistakes and learning from them
9. the way the ownership of novelties and new knowledge is organised

3.4. Learning by doing

The concept ‘learning by doing’ was introduced by Arrow in 1962. During learning by doing, know-how is acquired. Know-how resides in individuals, organisational routines and manufacturing practices (Garud, 1997). According to Arrow, learning by doing takes place at the manufacturing stage after the product has been designed. Learning at this stage consists of increasing production skills. These skills accumulate with experience in time (Garud, 1997). Through productive processes many problems, faults and bottlenecks are demonstrated and solved. Furthermore, through trial-and-error practical experience is gained on how to produce the technology. This increases the efficiency of production operations (Rosenberg, 1982). An important aspect of learning by doing is the development of ‘rules of thumb’ (Sahal, 1981). Learning by doing generates mainly tacit knowledge.

Which (institutional) conditions in the innovation system facilitate learning by doing? Since this kind of learning originates as a by-product of economic activity in general, we claim that learning by doing always exists. Producing is sufficient to trigger it. This claim is supported by numerous articles about learning curves (see for instance Yelle, 1979; Neij, 1997, 1999; IEA, 2000b). This literature demonstrates that as a result of learning by doing, the price of a product decreases when more products are made. Therefore, the only facilitating condition for learning by doing is the number of products produced.

3.5. Learning by using

Sahal mentions that ‘it is plausible, however, that at least some of the useful know-how is acquired in the *utilisation* of technology’ (Sahal, 1981). He uses the phrase ‘learning via diffusion’, meaning that the increased adoption of a technology leads to improvement in its characteristics. Rosenberg elaborates on this subject and introduces the concept of ‘learning by using’ (Rosenberg, 1982). He writes that learning by using is especially important in connection with products that consist of complex, interdependent components. When these products are used, especially when they are subject to prolonged stress, the outcome of the interaction of the components cannot be precisely predicted by

¹The limited space in this article does not allow us to go into the conditions for learning by searching in detail. For a more elaborate discussion on these conditions, see Kamp (2002).

scientific knowledge or techniques. This interaction can only be assessed after intensive or prolonged use. One of the main purposes of learning by using is to determine the optimal performance characteristics of a durable product since these affect the useful life of the product (Rosenberg, 1982).

The actors involved in learning by using are the users of the technology. Often, these users are firms, like the technology developers. But the users can also be other actors. In the case of wind turbines, the users are the owners of the wind turbines.

Conditions in the innovation system that facilitate learning by using are as follows:

1. The presence of users. This may seem obvious, but it does not have to be. Sometimes, technologies are developed entirely by R&D departments without the involvement of users.
2. The existence of a user group of a minimum size and degree of sophistication. The characteristics of the product under consideration determine the minimum size of the demand and its minimum degree of sophistication (Andersen and Lundvall, 1988).
3. Contacts between the user and the producer to enable the producer to learn from using. We will investigate this below.

3.6. Learning by interacting

As mentioned above, Lundvall places learning in innovation systems at the centre of the analysis. He points specifically to the importance of learning between users and producers. Realising that contacts between users and producers are necessary for successful innovation Andersen and Lundvall introduced the concept of interactive learning, or, in other words, learning by interacting (Andersen and Lundvall, 1988). Their main point is that successful innovation is to a large degree dependent on close and persistent user–producer contacts. The reason is that, particularly in complex innovation processes, firms are hardly ever able to have or develop all the required knowledge and skills in-house. Especially if the required information is tacit and difficult to formalise and communicate more broadly, learning has to occur during direct face-to-face contacts. The more complex the technology, the more one needs to rely on the expertise of others (Lundvall, 1988; Carlsson and Stankiewicz, 1991).

Based on the innovation literature (see a.o. Williams et al., 2000; Dodgson, 1996; Andersen and Lundvall, 1988; Lundvall, 1988, 1992; Nooteboom, 1992, 2001; Grin and Van de Graaf, 1996; Van Est, 1997; Cohendet and Llerena, 1997; Carlsson and Jacobsson, 1997), we

can list the following conditions that facilitate learning by interacting:²

1. mutual interest in the learning process,
2. proximity in the broad sense, including geographical closeness, cognitive closeness, a common language and culture, national standardisation, common codes of conduct, a certain lack of competition and mutual trust between the actors, and congruent frames of meaning regarding the technology,
3. norms of openness and disclosure,
4. the presence of an intermediary if information is not transferred easily or if not all relevant actors cooperate spontaneously.

In the following sections we describe the case studies. In the descriptions we use the wind turbine innovation system as a framework and focus on the nature and intensity of learning processes within this system. To this end, we look for the facilitating conditions that we have identified. In both countries, we distinguish two parallel wind turbine development paths and two accompanying innovation subsystems: the large-scale subsystem and the small-scale subsystem. Within the large-scale subsystems, the emphasis from the 1970s was on the development of large wind turbines, with a power capacity of several megawatts. Within the small-scale subsystems, the emphasis from the 1970s was on the development of smaller wind turbines, with a power capacity of several tens of kilowatts, and on the slow upscaling of these turbines.

4. Wind energy in the Netherlands

4.1. The large-scale wind turbine innovation subsystem

The Dutch NOW programme, the National Research Programme on Wind Energy, started in 1976. Within this programme, subsidies were provided for R&D into the potential of wind energy in the Netherlands and into wind turbine building. The goal of this programme was to develop a significant wind turbine capacity in the Netherlands, consisting of a large number of large wind turbines (Pelser, 1981; BEOP, 1981). As a result of this research programme, two innovation subsystems developed, the large-scale wind turbine innovation subsystem and the small-scale wind turbine innovation subsystem.

In the Dutch large-scale wind turbine innovation subsystem, the paradigm was from the 1970s directed towards building many large wind turbines in the Netherlands. In this subsystem a large amount of

²Again, for a more elaborate discussion on these conditions, see Kamp (2002).

theoretical knowledge on wind turbines was gained during research projects at the Delft and Eindhoven Universities of Technology and at the ECN research centre. This knowledge was merely based on aerodynamic knowledge from the aerospace industry. Design models for wind turbines were developed and more applied research was performed into a.o. structural dynamics and aerodynamics of wind turbines. Slowly, it became clear that wind turbines had their own characteristics and that models and theories from the aerospace industry could not be used without significant adjustment. Furthermore, in the late 1970s and the early 1980s research into tipvanes was performed by the Delft University of Technology. Theoretical research had shown that small vanes on the tips of wind turbine blades could lead to a 60–70% higher energy yield (Van Holten, 1978; BEOP, 1981). Researchers at the Delft University of Technology attempted to build tipvanes that would produce this effect in practice. Disappointingly, they did not succeed. The major part of the knowledge within this subsystem was based on learning by searching.

The knowledge gained was applied to three wind turbine prototypes and two commercial wind turbines. The turbine prototypes that were built were two vertical axis turbines, or VATs, and one horizontal-axis turbine or HAT. Test results were to prove which turbine type was the best in terms of energy yields and efficiency (Pelser, 1981). The first prototype that was built was a vertical-axis wind turbine, or VAT. It was built in the years 1975–1976 by the aeroplane building company Fokker (Pelser, 1981). Other companies involved were the machine building company Stork and the research institute ECN (Sens, 1981). The VAT's rotor diameter was only 5.3 m. It was meant as a scale model. Design parameters for larger models were to be based on the test results of this model. Another goal of the project was to gain operational experience with a VAT turbine (Pelser, 1981). While the VAT turbine was in operation and was being tested, it became evident that building wind turbines was not as easy as expected. Large vibrations occurred in the blades, producing a lot of noise (Dragt, 2000). Because the measurement results were inconclusive, it was decided to build a larger scale model with a 15-m diameter. This turbine was designed by Fokker and built by a number of suppliers³ by order of the Municipal Energy Company Amsterdam (Gemeente Energie Bedrijf Amsterdam, 1982). However, the test results of this turbine were inconclusive as well (Dragt, 2000). This was one of the reasons why no more VAT turbines were built in the Netherlands. The other

reason was that Fokker decided in 1985 to terminate its involvement in wind energy and to give its full attention to its core business: building aeroplanes (Deterink et al., 1997).

In the meantime, a horizontal-axis turbine prototype was built, the HAT-25. This turbine was erected in 1981 at the site of the ECN research institute. It was built by Stork, Fokker, Holec and Rademakers. It had a capacity of 300 kW and a rotor diameter of 25 m. As with the VAT prototypes, the main goal of the HAT-25 project was to obtain measurement results and operational experience (Sens, 1981). The prototype was equipped with two blades and a very advanced regulation system. It could be operated with four regulating procedures (Dekker, 2000; Pelsler, 1981). In this way, it could be tested which regulating procedure functioned best. Measurement results of the turbine were satisfactory and Stork decided to develop a commercial turbine on the basis of the HAT-25 prototype. Of this commercial turbine, called the Newecs-25, three were sold to utilities in the Netherlands and Curaçao.

Within this subsystem, the actors in the manufacturing companies Fokker and Stork and the actors in the research institute and the universities of technology were completely in line with each other: they had the same frame of meaning regarding the technology: their goal was building a large number of large wind turbines, that together would make a significant contribution to the national energy provision (Dekker, 2000; Van Holten, 2000; Pelsler, 1981). This made co-operation and learning by interacting between them very fruitful.

The intended turbine buyers within this subsystem were electricity production companies. The aim was to build large wind power stations, which would deliver electricity to the electricity grid, analogous to other electricity production units, which were also owned by electricity production companies. However, in the design and manufacturing of the wind turbines the aimed buyers were not involved. The design and manufacturing of the wind turbines was an ultimate science-push process: the turbines were developed by large companies and research institutes, based on scientific knowledge.

The electricity production companies were, although they were the intended buyers, not very enthusiastic about wind energy. They were of the opinion that only a maximum capacity of 650 MWe of wind turbines could be fitted into the electricity grid and not the thousands of MWe that ECN and other research institutes mentioned. Some electricity production companies, like that of Zeeland, Schiedam and Curaçao, were willing to try operating a wind turbine. They each bought a Newecs-25 turbine produced by Stork. However, because these turbines were not tested satisfactorily, they had a lot of operational problems (Verbruggen,

³The main suppliers were Polymerin, that built the turbine blades, Brown Boveri, that supplied the electrical installation and regulation, and Visno Machine Fabriek, that delivered the turbine tower and rotor (Gemeente Energie Bedrijf Amsterdam, 1982).

2000). These problems were not good for the electricity sector's opinion of wind energy. Stork also built a horizontal-axis turbine with a capacity of 1 MW and a rotor diameter of 45 m, the Newecs-45 (Hensing and Overbeek, 1985). This turbine was meant as an in-between step towards a 3 MW turbine, which had been calculated to be the most cost-effective turbine (Van Holten, 2000).⁴ Only one Newecs-45 turbine was sold. Like the Newecs-25, it suffered many operational problems (Verbruggen, 2000). Because only a limited number of turbines was built, only limited knowledge was gained by learning by doing and learning by using.

In 1982, at the insistence of the Ministry of Economic Affairs, the SEP (the Co-operation Electricity Production Companies) became involved in the large-scale wind energy subsystem. The SEP agreed to be involved in the development of a pilot wind power station: the Sexbierum wind power station. This time the SEP was very much involved in the design and manufacturing of the wind turbines. Therefore, in this project, the subsystem was complete. The turbines of the wind power station were produced by Holec. The design and building of the wind turbines however entailed a number of problems, resulting in a large delay of the project and in even less enthusiasm about wind energy in the electricity sector (Hutting, 2000; Toussaint, 2000; Verbruggen, 2000).

Because of the many problems, the large financial risks and the small home market, the large companies in the large-scale wind turbine innovation subsystem, Fokker, Stork and Holec, stopped producing wind turbines in the mid-1980s. An important cause of the turbine problems was the lack of learning by using. As was explained in Section 3, in the case of complex installations consisting of many interacting components and functioning in non-stable environments, learning by using is extremely important. Because of the small number of turbines produced, learning by using and learning by interacting with users were limited. The knowledge gained was mainly based on learning by searching. After the mid-1980s, the aim of the Dutch wind energy policy makers was to make this knowledge applicable to the small turbine manufacturers. In this way, in the eyes of the policy makers, the goal of developing a significant wind turbine capacity in the Netherlands could still be reached (NEOM, 1986).

4.2. The small-scale wind turbine innovation subsystem

In the period 1976–1980, about ten small companies in the Netherlands started to manufacture wind

turbines. They became interested in wind turbines because R&D subsidies into wind energy and wind turbines had been made available by the National Research Programme on Wind Energy. The small companies all had different manufacturing histories, like making steel constructions or polyester yachts and manufacturing farming equipment (Stam, 2000; Dutch manufacturers, a.n.).

In the small-scale wind turbine innovation subsystem, the knowledge base was, in contrast with the large-scale wind energy innovation subsystem, learning by doing. By way of trial-and-error, at first small wind turbines were built. These turbines were gradually improved and scaled up. Because the turbines were sold in the vicinity of the manufacturing companies, problems were observed and solved quickly in interaction with the users, enabling the manufacturer to learn from these problems (Boersma, 2000).

In the beginning, the turbine manufacturers encountered many difficulties in building reliable wind turbines. Therefore, ECN set up a test field in 1981. On this test field, the turbines were tested and the manufacturers received indications on what was to be improved in their turbine (Stam et al., 1983). Because of the danger of distortion of competition, ECN was not allowed to give specific indications on how to improve the wind turbines (Stam, 2000). And from each other the turbine manufacturers received no help at all: they considered each other as competitors and were not willing to share any knowledge on how they built wind turbines (Stam, 2000).

Another problem that the Dutch wind turbine manufacturers encountered was the small size of the domestic market. The Dutch market was and remained small because in the Netherlands no investment subsidies were available for wind turbine buyers. Therefore, payback times for wind turbines were large (Werkgroep Duurzaam-energieplan, 1984). Furthermore, wind turbine owners received only small buyback tariffs for the electricity they delivered to the grid. These two factors made buying wind turbines financially not very attractive (Langenbach, 2000; Blok, 2000). The main turbine buyers were renewable energy advocates and farmers (CEA, 1993).

Gradually, the wind turbines became better and larger. However, this process went more slowly in the Netherlands than in Denmark. This caused the inability of the Dutch manufacturers to compete with the Danes on the large Californian market.⁵ This factor, together with the small size of the Dutch market, caused financial problems for the manufacturers in the mid-1980s.

From the mid-1980s wind energy policy started to get involved actively in the activities of the small turbine

⁴A 3 MW turbine was never built in the Netherlands. Only a pre-design study was performed (Kuijs, 1983). Because of the problems with the Newecs-25 and the Newecs-45, the risk of building a 3 MW turbine was considered too high (IEA, 1986).

⁵This market appeared in the early 1980s because large investment subsidies were made available for wind turbine buyers in California.

builders. Because the wind turbine producers in the large-scale wind turbine innovation subsystem had ceased their activities, the small turbine builders were to be responsible for the production of efficient wind turbines that could produce a significant part of the Dutch electricity supply. Therefore, from the mid-1980s on, the research institutes and universities of technologies could only receive R&D subsidies if they made their research results applicable for the small turbine builders (NEOM, 1986). Furthermore, investment subsidies were introduced. This increased the Dutch home market, because utilities started to show an interest in buying wind turbines (IEA, 1987).

From then on, it was actively tried to incorporate the results of learning by searching, in the design and manufacturing process of the small wind turbine builders. Researchers from research institutes and Stork worked together with small wind turbine builders in improving and scaling up their wind turbines. However, this co-operation was sometimes difficult, since the paradigms and the approaches were completely different. This severely limited learning by interacting. The researchers were academic trained science-based thinkers, whereas the manufacturers were ‘builders’ (Boersma, 2000; Verbruggen, 2000).

One manufacturer, Lagerweij, had a different approach. He did not accept direct interference of researchers into his design process, but he did use knowledge obtained by learning by searching by way of personal contacts in Delft and the picking up of their ideas. This resulted in gradual improvements in his small 75 kW/80 kW turbines, for which he used a.o. ideas on flexible components developed at Delft University of Technology (Van Holten, 2000; Boersma, 2000).

The drive towards fast upscaling and the problems involved with incorporated advanced concepts and components in their wind turbines, combined with the small Dutch home market⁶ and the competition from the Danes, who offered better products, resulted in severe difficulties for the Dutch manufacturers in the 1990s. In the year 2000, only one Dutch turbine builder, Lagerweij, remained.

5. Wind energy in Denmark

5.1. The large-scale wind turbine innovation subsystem

In Denmark, as in the Netherlands, a development programme for wind energy was set up in the late 1970s. The main objective was to determine under what circumstances and to what degree wind energy could make a contribution to the Danish electricity supply

⁶As from the 1990s, the small size of the Dutch market was also caused by the siting problems (Wolsink, 1991).

systems (IEA, 1985). The programme was called the Wind Power Programme. Within the programme, the research centre Risø and the Technical University of Denmark were to develop the knowledge needed to build large wind turbines. It was envisaged that large wind turbine parks owned and operated by utilities would be built by a consortium of large Danish firms. The first measurement programme that was carried out was on the Gedser turbine. This wind turbine had been built in the 1950s by the Danish technician Johannes Juul and had proved to work. It had a capacity of 200 kW, a horizontal axis and three blades (Karnøe, 1991). The Danes did not have an aerospace industry, so they could not use knowledge gained in that sector.⁷

In 1977, before the measurement results of the Gedser turbine had become available, it was decided to build two 630 kW turbines on the basis of the specifications of the Gedser turbine, one with a pitch control system, as the Dutch HAT-25 prototype had, and one with a stall control system, as the Gedser turbine had. These two turbines were called the Nibe turbines (Karnøe, 1991). No Danish company was interested in building the Nibe turbines. Therefore, the turbines were procured on a multi-contract basis. Other actors involved were Risø, the Technical University of Denmark and the SEAS utility, which partly financed the wind turbines (Van Est, 1999). So, unlike in the Netherlands, in Denmark the turbine owners were involved from the beginning. Like with the Dutch large wind turbines, there were many problems with the Nibe turbines, e.g. fatigue problems in the blades and problems with the gear box (IEA, 1985).

In the early 1980s, eight more large wind turbines were built: one 265 kW turbine, one 300 kW turbine, five 750 kW turbines and one 2 MW turbine. All these turbines had a pitch control system, because the Nibe turbine with pitch control functioned better than that with stall control (IEA, 1985). Here also, the utilities were involved from the beginning. Apart from the 2 MW turbines, these large turbines were built by the company Danish Wind Technology. This company was established in 1981 by the Danish Ministry of Energy and the SEAS utility (Van Est, 1999).

All wind turbines suffered problems with the blades and the gearboxes (IEA, 1988; IEA, 1990; Heymann, 1998). Building wind turbines proved to be more expensive and risky than expected. Furthermore, no large Danish company appeared to be interested in building large turbines. In the early 1990s, the Danish state sold its shares in Danish wind technology (Karnøe, 1991). By that time, the Danish small-scale wind turbine

⁷As explained in Section 4, this in fact turned out to be an advantage for the Danes. Wind turbines were found to have their own characteristics, and therefore models and theories from the aerospace industry could not be used without significant adjustment.

innovation subsystem had demonstrated its ability to manufacture reliable well-working wind turbines that were far cheaper than the wind turbines developed by the large-scale wind turbine innovation subsystem.

In the Danish large-scale wind turbine innovation subsystem, as in the Dutch, the emphasis was on learning by searching by way of research and measurement programmes. Learning by interacting went better in the Danish large-scale wind turbine innovation subsystem than in the Dutch, because in Denmark the turbine buyers were involved from the beginning and shared the frame of meaning of the research institutes and the turbine producers: building large turbines that could make a significant contribution to the Danish energy supply.

5.2. The small-scale wind turbine innovation subsystem

In Denmark, as in the Netherlands, a small-scale wind turbine innovation subsystem developed as from the late 1970s, which was relatively independent of the wind energy R&D programme set up by the Danish state. The first wind turbine producers in this subsystem were adherents of the grassroots movement and small entrepreneurs. These actors rediscovered the Gedser wind turbine and started developing wind turbines based on this example.

The adherents of the grassroots movement were attracted to the idea of small locally owned and locally governed power production units, instead of large power production units that were centrally owned and centrally governed by the utilities. Furthermore, they saw renewable energy as an absolutely essential substitute for environment-polluting fossil fuels and for the nuclear power plants that were planned by the Danish utilities (Jørgensen and Karnøe, 1995). A famous turbine developed by left-wing oriented people was the Tvind turbine. It was developed by teachers and students of the Tvind school with the help of people with different educational backgrounds. The design, blade profile and calculations were performed with the help of engineers. It had a generating capacity of 2 MW and it performed well, although the frequency of the electricity produced was not stable enough to be fed into the electricity grid (Karnøe, 1991).

By 1978, about ten small wind turbine companies had developed. Many of these had previously manufactured agricultural equipment. Their knowledge was based on the manufacturing of machines, and they learned slowly, by way of trial-and-error, how to manufacture and improve wind turbines (Karnøe and Garud, 2001). They obtained their knowledge from previous wind turbines, like the Gedser and the Tvind turbine, from their own trial-and-error experience in the design and production of wind turbines and from the turbine users, either individually or collectively during the so-called Wind

Meetings.⁸ The turbine companies' design philosophy was to build wind turbines that worked reliably and safely (Karnøe, 1995). They were under pressure to improve their turbines, especially because the performance of their turbines was made public in the magazine *Naturlig Energi*. This magazine was set up by the Danish Windmill Owners Association. In the magazine the performance of the several types of turbines was disclosed. Because they were organised, the users created a strong selection environment for the first Danish turbine builders (Karnøe and Garud, 2001; Heymann, 1998).

All kinds of problems with a.o. rotor speeds, gear boxes, burned out generators, broken yaw systems were handled. Design and construction were based upon trial-and-error and simple rules of thumb (Karnøe, 1995). The manufacturers were used to this way of working and they refrained from taking risks. Gradually, practical and hands-on knowledge about the poorly understood technology accumulated. On the basis of this knowledge, the design rules were gradually improved. Design and development problems stemmed from turbine failures or from construction problems. The failures were often solved by making the turbines more solid, or, in other words, by 'throwing metal on the problem'. This method increased the lifetimes of the Danish wind turbines by limiting aerodynamic loads and preventing dynamic vibrations (Karnøe, 1995).

In 1978, a wind energy department was created at the Risø research centre. Because the research centre had only received financing for 3 years, their strategy was to be of immediate service to the wind turbine manufacturers. If the manufacturers could be convinced of the usefulness of the research Centre, it could in the future get its financing through orders from the manufacturers (Dannemand Andersen, 1993). Therefore, the goal of the members of the research Centre was not to develop the technically best wind turbine, but to develop a wind turbine industry. In this way, a tight network between wind turbine producers, owners and the Risø research centre developed within the small-scale wind turbine innovation subsystem. Because most turbine producers chose to follow the technology guidepost formed by the Gedser turbine, they produced the same turbine type, i.e. a three-bladed stall-regulated wind turbine (Karnøe, 1991). This made the exchange of knowledge very efficient. Therefore, learning by interacting went very well within the subsystem.

Another favourable circumstance was the size of the Danish home market. Already in 1979, investment subsidies were introduced (Van Est, 1999). This made buying a wind turbine far more attractive than in the

⁸During the Wind Meetings, knowledge and experience on wind turbines were shared between wind turbine manufacturers, owners and researchers.

Netherlands. The relatively large home market gave the Danish turbine manufacturers the opportunity to produce a relatively large number of wind turbines and learn by doing during the process. Furthermore, the relatively large user group, which had organised itself in the Windmill Owners Association, was able to act as a strong party during negotiations on buyback tariffs with the utilities.

In the early 1980s, the size of the Danish home market decreased. However, at the same time a very large market arose in California, because large investment subsidies for wind turbine buyers were introduced there (Van Est, 1999). Because the Danes produced relatively good wind turbines and were able to prove this with the statistics in the *Naturlig Energi Magazine*, they were able to capture a large part of the Californian market. In 1985, they sold 2000 wind turbines to California (Karnøe and Garud, 2001). This favoured learning by doing a great deal. However, the demand in California was different from that in Denmark. In California, the buyers wanted larger and more cost-effective wind turbines (Van Est, 1999). This forced the Danes to speed up technology development and to sell turbines that had not yet been thoroughly tested (Karnøe, 1991). This resulted in severe technical problems for the Danish manufacturers.

In 1986 the Californian investment subsidies expired. Exports declined and came to a halt in 1988 (Gipe, 1996). However, the Danish market had started to grow as from 1985. In that year, the utilities had signed a 100-MW agreement, which meant that they had to install 100 MW of wind turbines within the next 5 years (Van Est, 1999). This enabled the Danish turbine manufacturers to make a new start. The Wind Turbine Guarantee Company was set up to guarantee the long-term financing of large export projects (Van Est, 1999). One of the conditions that the manufacturers had to meet in order to qualify for the guarantees was that their turbines had to be approved according to a new, more harsh approval system (Hvidtfelt Nielsen, 2001). The manufacturers were required to lay down their knowledge in a more formalised way (Dannemand Andersen, 1993). Furthermore, they had to scale up and improve their turbines further, because the utilities' demand was for relatively large and cost-effective wind turbines. Turbine design therefore gradually changed from a trial-and-error process to a more R&D-based and formalised process. The role of the Risø research centre also became more formal (Dannemand Andersen, 1993). With the help of Risø, the Danish manufacturers succeeded in meeting the utilities' demand and building up a strong position on the world market.

Learning by interacting between all actors within the subsystem remained very important. Their frames of meaning together evolved from trying to build wind turbines that work to developing large cost-effective

wind turbines based on more formal R&D. Furthermore, because of the continuing large demand, learning by doing and learning by using remained important. Learning by searching gradually gained importance, because design became more and more R&D-based. This co-evolution of knowledge demand and knowledge supply from down-to-earth hands-on knowledge to more formal R&D-based knowledge in Denmark is in large contrast with the Netherlands, where a gap remained between the science-based knowledge supply and the more practical knowledge demand.

6. Conclusions

Our research question was: To what extent did the learning processes in the Dutch and the Danish wind turbine innovation systems differ in the period 1973–2000 and to what degree can they provide an explanation for the difference in performance of the Dutch and the Danish wind turbine innovation systems?

Our answer to this question is as follows.⁹ The Dutch wind turbine innovation system was well suited to support learning by searching. It was a typical 'science-push' innovation system. The wind energy researchers could use an *existing knowledge base* on aerodynamics as a starting point, *R&D subsidies* were provided by the Ministry of Economic Affairs and for a period of 10 years the researchers were *able to make mistakes and learn from them*. Learning by interacting was also supported by the Dutch wind turbine innovation system, but only between the research institutes and the companies that produced large wind turbines. The people in these institutes and companies shared the *same frame of meaning* regarding wind energy, had *all been educated at university level* and *trusted* each other. However, learning by interacting between the turbine producers and the turbine owners was problematic. In the first place, there were *relatively few turbine owners* in the Netherlands, because *investment subsidies* did not become available until 1986. Secondly, the majority of the energy companies, who after 1986 were in most cases the turbine owners, were *not very enthusiastic* about wind energy. This inhibited learning by interacting between the users and the turbine producers. Learning by interacting between the research institutes and the producers of small wind turbines was problematic as well. They did *not share the same frame of meaning* regarding wind energy, had *different educational backgrounds* and did *not trust* each other. Therefore, the results of learning by searching that took place in the

⁹The facilitating and impeding conditions for learning that were present within the wind turbine innovation systems are printed in italics.

research institutes were not converted very well into the development of small wind turbines.

In Denmark, the situation was very different. Learning by searching was supported far less by the innovation system than in the Netherlands. Far fewer *R&D subsidies* were available. However, the other types of learning were supported far better than in the Netherlands. *Investment subsidies* were made available at an early stage, which created a *relatively large user group* from the beginning. This, combined with the fact that the *users organised themselves*, greatly stimulated learning by using and learning by interacting between the turbine users and the turbine producers. These turbine users were mainly farmers and small companies who were in favour of wind energy. This created *trust* and a *joint frame of meaning* with the turbine producers. Whereas in the Netherlands the wind energy innovation system was never very tight, since most turbine users were not deeply involved, in Denmark the links within the innovation system were much *tighter*. Furthermore, the Danish research institute had a good relationship

with the turbine producers. The researchers operated on the *same cognitive level* as the turbine producers and shared the *same frame of meaning* regarding wind energy. In this way, they supported the step-by-step learning and technology development process of the turbine producers. And, to keep up with technology development, the research institute gradually changed the nature of its knowledge supply to the turbine producers. The hands-on knowledge of the 1970s was gradually replaced by more science-based mathematical knowledge. The actors in the Danish wind energy innovation system were *well adjusted to each other and evolved together*, and kept pace with technology development. In our view, far better conditions in the innovation system for learning by interacting between turbine producers, turbine users and the Danish research institute was the main reason for the Danish success. Our main conclusions for each subsystem are summarised in Table 1.

How do our results fit into findings of recent innovation research? First of all, our results emphasise

Table 1
Main conclusions, per subsystem

The Netherlands	Learning by searching	Learning by doing	Learning by using	Learning by interacting
Large-scale subsystem	(+) Existing knowledge base available R&D subsidies available Ability to make mistakes	(-) Very few turbines built	(-) Small user group Intended turbine owners not enthusiastic about wind energy	(-) Turbine producers and users did not share the same frame of meaning regarding wind energy No trust between producers and users
Small-scale subsystem	(+) R&D subsidies available	(-) Not so many turbines built	(-) Relatively few turbine owners because investment subsidies introduced at a late date	(-) Producers and researchers did not share the same frame of meaning regarding wind energy Producers and researchers with different educational backgrounds
Denmark				
Large-scale subsystem	(-) Fewer R&D subsidies available No existing knowledge base available	(-) Very few wind turbines built	(-) Small user group	(+) Trust Joint frame of meaning Tight links between turbine producers, users and researchers Same cognitive level
Small-scale subsystem	(-) Fewer R&D subsidies available	(+) Many wind turbines built	(+) Relatively large user group because investment subsidies introduced early Users organized themselves	(+ +) Trust Joint frame of meaning Tight links between turbine producers, users and researchers Same cognitive level

the usefulness of the innovation systems approach. There is general agreement between innovation researchers that companies do not innovate in isolation. Innovation is a network activity, and the quality of the innovation system is very important for the degree of success of the innovation process (see a.o. Smits, 2002). The differences in the success of the Dutch and the Danish wind turbine innovation systems firmly underline this point. One important conclusion for policy makers is that they in managing present day innovation processes are in need of instruments that support functions operating at system level (Jacobsson and Johnson, 2000; Smits and Kuhlmann, 2002). The cluster approach (OECD, 1999, 2001), the Dutch Programme of Sustainable Technological Development and the German FUTUR programme are early examples of such instruments (Smits and Kuhlmann, 2002). Related to the foregoing is the observation that in the last few decades, innovation researchers have generally agreed that the science- and technology push model, also known as the linear model, is not successful in developing innovations (see for example Nelson and Winter, 1977; Ziman, 2001; Harmsen, 2000). Recent insights from innovation studies point out the numerous and frequent interactions and feedback processes between users and producers in innovation processes (OECD, 1992; Rip and Kemp, 1998; Gibbons et al., 1994). This corresponds to our finding that the Dutch science- and technology push method approach in the case of wind turbine development was not successful, whereas the Danish approach in which also users played an important role from the beginning was far more successful. Furthermore, recent findings in innovation research suggest that it is important for knowledge providers to produce knowledge that meets the demands of the users of the knowledge, the technology developers (Smits, 2002). This also corresponds to our findings. In Denmark, the research institute offered the wind turbine companies the knowledge they needed at that particular moment. In the Netherlands, especially after 1986, the research institutes offered knowledge that was in many cases too scientific for the wind turbine producers. To conclude, as we pointed out in Section 3, the innovation researcher Rosenberg stressed that in the development of technologies like wind turbines that consist of many interacting moving parts and that function in unstable environments, learning by using is very important. This also corresponds to our findings. However, we like to add that—in the development of wind turbines in the Netherlands and Denmark—learning by interacting between the users and the producers is even more important than learning by using.

It would be interesting to investigate whether our conclusion is also applicable to wind turbine innovation systems in other countries. Is learning by interacting the dominant learning process in other countries that have

large wind turbine capacities and thriving wind turbine industries, like Germany and Spain? This would be an interesting topic for further research.

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