4 Wind energy in Denmark

4.1 Introduction

4.1.1 Poul la Cour and F.L. Smidth

Denmark’s experience with wind turbines that produce electricity started before 1973. The Danish physics professor and wind pioneer Poul la Cour began experimenting with wind generated electricity in 1891 (Gipe, 1995). La Cour was a very versatile scientist, who combined knowledge obtained from machine construction, electrical engineering and aerodynamics with craft pragmatism (Heymann, 1995). Around 1903, he developed the 'Klapsejler', a simple, robust and reliable windmill that produced direct current electricity (Heymann, 1998). This windmill helped introduce electricity into Denmark’s countryside and helped Denmark overcome severe fossil fuel shortages during the Second World War. La Cour saw electricity as a progressive force in the restructuring of society. He was engaged in several activities for public enlightenment (Jørgensen and Karnøe, 1995). In order to solve the problem of the intermittent nature of the wind, he combined wind turbines with storage of electrical energy by way of batteries and by separating water. With financial support from the Danish government, he improved the aerodynamic design of the blades and designed a wind turbine with two, three or four narrow blades.

During the Second World War, another type of windmill was built: F.L. Smidth’s more modern Aeromotor. Smidth used the experience he had gained by working with concrete while building concrete wind turbine towers. He used knowledge from the rapidly advancing field of aerodynamics to develop modern airfoils for the turbine blades. The laminated wooden blades of the turbine were coned towards the tower (Gipe, 1995). The wind turbine’s maximum capacity was 70 kW. It was designed with two or three blades and various overspeed regulations: pitch, variable rotor speed and brake flaps on the blades (Karnøe, 1991). Smidth developed and manufactured 60 Aeromotors. Because the wooden blades were failure-prone, the maintenance costs of these wind turbines were high (Jørgensen and Karnøe, 1995). After the Second World War, the small decentralised windmills that produced direct current were quickly replaced by large, centralised, power plants that produced alternating current from fossil fuels.
4.1.2 Johannes Juul

In the 1940s, the Danish technician Johannes Juul began to develop wind turbines that produced alternating current that could be connected to the electricity grid. According to Juul, the wind turbines could reduce Denmark’s dependence on fossil fuel imports. Juul, an electrician, started his wind turbine activities after his retirement. Before that, he had worked at the SEAS utility in Sealand, building and maintaining electrical installations and developing new electrical devices. In 1947, by order of the SEAS utility, he started to research wind power (Heymann, 1998). SEAS let Juul start this research because it faced an energy shortage in the late 1940s (Jørgensen and Karnøe, 1995). Juul received considerable support for his design and development work not only from SEAS, but also from the Association of Danish Utility Companies (Heymann, 1999).

In 1948, Juul built a wind tunnel which he used for testing blade profiles and rotor designs. In 1949, he built his first small, 15 kW wind turbine with an 8 metre rotor diameter (Gipe, 1995; Hvidtfelt Nielsen, 1999). This wind turbine was equipped with a rotor that had two rigid blades facing down-wind and with passive yaw control. It produced AC electricity and was connected to the SEAS electricity grid. Power output was controlled mainly by stalling and by additional air brakes at the pitchable blade tips (Heymann, 1998; Karnøe, 1991). The construction was very stiff. The turbine was called the wind motor.

By operating and testing the wind motor, Juul gained a great deal of knowledge, which was essential for the development of his wind turbine design. However, after three months of operation, one of the blades broke as a result of fatigue. Juul solved the problem by fitting new blades and placing additional small rods between the blades. After another four months of testing, another blade bent from fatigue. Juul inserted more rods for further blade support. He concluded that equipping the wind turbine with three blades, joined by rods would reduce the fatigue even further. He realised that the down-wind position of the rotor combined with insufficient yaw caused unwanted vibrations in the turbine. Therefore, he moved the rotor to the up-wind position and added active yaw control, which proved to be a superior solution (Heymann, 1998).

In 1952, Juul built a somewhat larger, 40 kW wind turbine with an up-wind three-bladed rotor and active yaw control. This turbine was a modified Smidth turbine (Gipe, 1995). Because it operated satisfactorily, Juul felt encouraged to take another step: in 1956 near Gedser on the island of Falster he built a larger, 100 kW wind turbine, and later enlarged it to a 200 kW turbine with a 24 meter rotor. The turbine
was built with 300,000 DKK support from the Marshall plan (Jørgensen and Karnøe, 1995). In the manufacturing process Juul was assisted by the technical staff of the SEAS utility (Hvidtfelt Nielsen, 1999).

Juul equipped the Gedser turbine with design features that he had developed while operating his previous wind turbines: a concrete tower, three blades rigidly fixed to the hub and supported by several rods, stall control combined with passive pitchable blade tips, an up-wind rotor, and active yaw control. As an extra overspeed precaution, the turbine was fitted with a mechanical brake in the generator shaft (Hvidtfelt Nielsen, 1999). The turbine blades were made of wood covered with aluminium plates (Jørgensen and Karnøe, 1995). He used this simple material, because of shortages of materials like glass fibre (Karnøe, 1991). Juul’s design calculations were very basic and simple, but they worked. The main design criteria were simplicity, security and low cost (Heymann, 1998). Juul had taken over these criteria from La Cour’s windmills, which he had seen when he was very young (Karnøe, 1991). These criteria were to be the basis for the success of the Danish wind turbine manufacturers two decades later.

The test operation period of the Gedser turbine lasted from 1957 until 1967. In this period, the turbine worked reliably. It produced 2.2 million kWh and was capable of producing 350,000 kWh annually (Gipe, 1995). However, by 1962, the SEAS utility had concluded, on the basis of economic calculations, that the wind turbine was unable to compete with fossil fuels. SEAS based its conclusions on the Windpower Commission’s 28 view that the cost-effectiveness of wind turbines should be calculated not from the value of the electricity they produced, but from the amount of fossil fuel saved in the power stations (Jørgensen and Karnøe, 1995). Although the Gedser turbine was a success from a technical point of view, operation was stopped for economic reasons (Heymann, 1998; Hvidtfelt Nielsen, 1999). The costs of the electricity produced by the Gedser turbine were two times higher than they were allowed to be for profitable operation (Heymann, 1995).

4.1.3 The oil crisis

The 1973 oil crisis both in the Netherlands and in Denmark triggered the development of new activities in the field of wind energy. In contrast to the Netherlands, Denmark had no fossil fuel resources of its own. Therefore, Denmark was even more dependent on other countries for the provision of energy. In 1973, about 94% of the country’s energy supply consisted of imported oil; the remaining 6% consisted of foreign solid fuels, like coal (Heymann, 1998; Hvidtfelt Nielsen, 2001).

28 This commission was founded in 1950 to support and supervise Juul’s efforts (Heymann, 1999).
Both in the Netherlands and in Denmark we can distinguish two different wind turbine development paths after 1973: large-scale and small-scale. Both development paths had their own innovation subsystem. In part A of this chapter, we will describe the developments within the large-scale wind turbine innovation subsystem. In part B, we will describe the developments within the small-scale wind turbine innovation subsystem. Since these descriptions are based merely on secondary material, they will be less elaborate than those in the previous chapter. General conclusions about both subsystems will be drawn in Chapter 5.

**Part A: The large-scale wind turbine innovation subsystem**

**4.2 1975 - 1976**

After the 1973 oil crisis, the Danish Academy for Technical Science did some research into the possibilities for wind energy in Denmark. In 1975, the conclusions of this research were published: wind resources were plentiful and about 50 million DKK would be enough to establish a technology base to start the production of wind turbines (Karnøe, 1991). In about 10-15 years these wind turbines would be able to provide 10% of the energy needed in Denmark, at competitive prices. No reserve capacity would be needed if only 10% of the energy or less was provided by wind turbines. If the percentage increased, a small amount of reserve capacity would be needed to provide energy when there was no wind blowing (Karnøe, 1991; Gipe, 1995).

**4.3 1977 - 1980**

**4.3.1 The Wind Power Programme**

The conclusions of the investigations of the Danish Academy for Technical Science resulted in the setting up of a Danish development programme for wind energy in 1977. The main objective was to determine under what circumstances and to what degree wind energy could make a contribution to the Danish electricity supply system (IEA, 1985). Within the programme, called the Wind Power Programme, the research organisation Risø National Laboratory and the Technical University of Denmark were to develop the knowledge needed to build large wind turbines (Van Est, 1999). It was envisaged that large wind turbine parks owned and operated by utilities would be built by a consortium of large Danish firms. The Federal Wind Energy Programme in the United States served as an R&D model for the Wind Power Programme (Van Est,
1997). Like the Federal Wind Energy Programme, the Danish programme relied on scientific knowledge and the efforts of large industrial firms (Van Est, 1999).

The first phase of this development programme lasted from 1977 till 1980 and had a budget of 35 million DKK. Of this budget, 82% went towards the development of large wind turbines and 18% towards the development of small wind turbines (see part B of this chapter) (Karnøe, 1991). In the first phase of the Wind Power Programme, a new measurement programme was carried out on the 20-year-old Gedser wind turbine. This was done in co-operation with the United States Ministry of Energy. The fact that the Gedser turbine was the only wind turbine in the world with such a large capacity, and had been in operation without technical problems for 10 years made both the Danes and the Americans very interested in performing measurements on that turbine. In 1977 the Gedser turbine was restored and put into test operation until March 1979, with positive results (Heymann, 1998).

In 1977, a Danish delegation visited the United States. The official objectives of this visit were threefold (Van Est, 1999):
- to keep abreast of the American research plans
- to maintain and extend the contact between the American and Danish Wind Power Programmes
- to discuss the Danish-American co-operation in the Gedser measurement programme.

However, a fourth, more practical objective was perhaps even more important: the delegates wanted to buy a ready-made rotor, or, if that turned out to be impossible, a calculation method to construct a Danish rotor (Van Est, 1999). They did not achieve this fourth objective. The large American companies engaged in wind energy, e.g. Hamilton-Standard, were not interested in selling technological know-how. They were willing to export glass fibre reinforced polyester rotor blades, but their price was so high that the Danish delegation could not afford to buy them (Karnøe, 1998; Van Est, 1999). This forced the Danes to start developing their own modern wind turbine blades. The challenge was taken up by the Risø research institute. Like the Dutch research institute ECN, Risø was set up in the 1950s as a nuclear energy research institute and had not gained any experience in the field of wind energy before the 1970s.

After the Gedser measurement programmes, the American and Danish large turbine development programmes started to follow different paths. Whereas the Americans chose to elaborate on the scientifically more elegant design concept of the German Hütter, the Danes decided to take the main features of over Juul’s design.
Besides setting up wind turbine R&D, the Wind Power Programme aimed to set up a complete wind turbine innovation system. Since the utilities were foreseen to be the future buyers of the wind turbines, they were directly involved in the management of the Wind Power Programme. The programme was co-ordinated by the joint research institutes of the Danish Utilities, DEFU (Van Est, 1997; IEA, 1985).

4.3.2 The Nibe wind turbines

In 1977, before the test results for the Gedser wind turbine became available, it was decided to build two prototype wind turbines at Nibe in northern Jutland. These wind turbines were to have three blades, an up-wind rotor of 40 metres, an active yaw system and a power capacity of 630 kW. The large upscaling step from 200 kW and 630 kW clearly reveals the idea that wind turbine technology would be very straightforward and that only large wind turbines would be able to make a significant contribution to the country’s energy provision. The goal was to develop and produce on the basis of the Nibe turbines 500 to 600 large wind turbines with power capacities between 500 kW and 1 MW, from 1985 until 1990 (Karnøe, 1991).

Because of limited financial resources, the turbine rotor blades were not made entirely of glass fibre reinforced polyester. Instead, a hybrid structure was chosen, consisting of both steel and glass fibre reinforced polyester. The main difference between both Nibe wind turbines was the power control system: the Nibe A turbine had a stall-controlled rotor, like the Gedser turbine, whereas the Nibe B turbine had pitch control. Alle turbine components were manufactured in Denmark. The blades of the two turbines were designed at Risø, and the rest of the design work was done in the Department of Fluid Mechanics at the Technical University of Denmark (Van Est, 1997). The turbines were financed partly by the Ministry of Energy and partly by the utility SEAS (Karnøe, 1991).

No Danish company was interested in building the Nibe prototype. Therefore, the turbines were procured on a multi-contract basis. A range of companies with different technical skills were contracted. Sometimes, e.g. in the case of the 20 metre long blades, it was difficult to find a Danish company with the right expertise. Companies that built turbine components include (Karnøe, 1991):
- F.L. Smidth from Copenhagen, which built the gear of the Nibe B
- Thrige Titan from Odense, which built the generator and the electrical system
- Frichs from Århus, which constructed most of the machine parts

The Nibe A turbine was connected to the electricity grid in September 1979, the Nibe B turbine in August 1980 (IEA, 1984). In the first few months, the trials revealed a large number of problems, so the trial period was extended from days to months. The
most serious problem was metal fatigue in the steel parts of the rotor blades (Van Est, 1999).

4.3.3 The large-scale wind turbine innovation subsystem in 1977-1980

In this period, the large-scale wind turbine innovation subsystem was set up in Denmark. All important actors were represented within this subsystem:
- the Ministry of Energy, which set up the Wind Power Programme in co-operation with the Danish utilities
- the utilities, which were the foreseen wind turbine buyers and had a very large say in the Wind Power Programme. SEAS, the Jutland utility was even more involved, since it partly financed the Nibe turbines.
- several large companies, each providing a part of the Nibe wind turbines
- the research institutes Risø and the Institute for Fluid Mechanics at the Danish Technical University, which designed the Nibe turbines
- intermediary organisations, which provided the funding

Figure 4.1 depicts the large-scale wind turbine innovation subsystem in this period.

Figure 4.1: The large-scale wind turbine innovation subsystem in the period 1977-1980.

In this figure, as in the innovation subsystem figures in the previous chapter, the boxes represent actors. The straight lines between the boxes indicate learning processes between actors, whereas the dotted lines between the boxes indicate subsidy flows. The thickness of the bold lines indicates the importance of the interactive
learning processes. The italics in the boxes represent the learning processes of the actors. An \((s)\) means learning by searching, a \((d)\) means learning by doing and a \((u)\) means learning by using.

### 4.3.4 Conclusion

Let us look at the learning processes within the Danish large-scale wind turbine innovation system in this period. Learning by searching was the most important form of learning. Within the Wind Power Programme, much research was done into the possibilities for wind energy in Denmark. Furthermore, the research institutes designed the Nibe turbines on the basis of learning by searching. While the Nibe turbines were being built and the turbines were coming into operation, learning by doing and learning by using began. Learning by using was done only by one utility: SEAS. Because the utilities were very much involved in the Wind Power Programme, they were more co-operative and more on the same line with the other actors involved than in the Netherlands. They facilitated learning by interacting between the utilities and the other actors. The companies building components of the Nibe turbines, regarded this project as a one-only project and not as the start of further activities in wind turbine development. Therefore, the companies were less integrated into the large-scale subsystem than in the Netherlands and learning by interacting was more difficult. All actors within the subsystem shared the same paradigm: to make possible the installation of a large number of large wind turbines within the Danish electricity grid.

### 4.4 1981-1985

#### 4.4.1 Danish Wind Technology

In 1981, the official goal was formulated: by the year 2005 10% of Danish electricity consumption was to be supplied by wind energy. This implied a total of 1,500 MW of installed turbine capacity (Karnøe, 1991).

However, it had become clear that no large Danish company was interested in developing large wind turbines. The above mentioned consortium that built the Nibe turbines showed little interest in building other large wind turbines. Therefore, in December 1981 the Danish Ministry of Energy, together with the SEAS utility, established the wind turbine company Danish Wind Technology (Dansk Vindteknik A/S) (Van Est, 1999). This company was to develop and market large wind turbines based on the research results from the Wind Power Programme.
illustrates the science-push paradigm within the Danish large-scale wind turbine innovation subsystem.

Up till 1984, the accumulated costs of the Wind Power Programme were 70.5 million DKK. Of this amount, the utility had contributed 11.5 million DKK, and the United States Department of Energy had contributed about 1 million DKK because it co-sponsored the Gedser measurement programme (IEA, 1985). During this period and the previous period, the main achievement of the Wind Power Programme was the development of the Nibe wind turbines. Furthermore, theoretical investigations e.g. site evaluations, grid integration investigations and offshore feasibility studies, were performed (IEA, 1985). A wind atlas was made, in which the Danish wind resources throughout the country were described (IEA, 1986). Technology development, and especially R&D into the reduction of material fatigue in wind turbines and the reduction of installation costs, was considered to be the most important aspect of the Wind Power Programme (IEA, 1986).

4.4.2 The Nibe turbines

From the beginning, there were many problems with the Nibe turbines, the major one being metal fatigue in the blades. The turbines were often out of operation. From November 1983 until 1984, the Nibe A turbine was out of operation due to problems with the gear box, the bolts in the blades and metal fatigue in the blades. Because wake and stall measurements were considered more important than electricity production, it was decided that in the following years the turbine would only operate if measurements were to be made (IEA, 1985). From 1983 until 1991, the Nibe A turbine only operated for a few hours (IEA, 1992).

The Nibe B was out of service during most of 1983 because of various fatigue problems in the blades. In January 1984, three new laminated wooden blades were installed on Nibe B. In the rest of the year 1984, its availability was higher than ever before, namely 86% (IEA, 1985). The pitch-controlled Nibe B turbine outperformed Nibe A, having completed more than 18,000 hours of operation by the autumn of 1988 (Heymann, 1998).

4.4.3 Other wind turbines

In 1984, ELKRAFT ordered the construction of five 750 kW turbines and ELSAM the construction of a very large 2 MW turbine. Both the 750 kW turbines and the 2 MW turbine were scaled-up versions of the Nibe B pitch-controlled wind turbine. The better performance of the Nibe B turbine was the reason for this choice, although it was more difficult to manufacture a turbine with pitch regulation than with stall
regulation. Both the 750 kW turbines and the 2 MW turbine will be described in the following section (IEA, 1985).

Furthermore, in 1982 Danish Wind Technology built a 265 kW wind turbine at Koldby in Jutland and in 1983 developed an updated version of that machine at Nibe with a 300 kW generator, (IEA, 1985). Unlike the Nibe turbines and the below described 750 kW and 2 MW turbines, which were all up-wind wind turbines, these new turbines were down-wind machines (IEA, 1985).

### 4.4.4 The large-scale wind turbine innovation subsystem in 1981-1985

In this period all important actors were represented within the subsystem:

- the Ministry of Energy, which had set up the Wind Power Programme together with the utilities and had partly financed the large wind turbines
- the utilities, which had a very large say in the Wind Power Programme. Both ELKRAFT and ELSAM became actively involved in this period, ordering the building of wind turbines in their area.
- the newly established company Danish Wind Technology, established by the utilities and the Ministry of Energy. However, still no large Danish firm was interested in developing and building large wind turbines.
- the research institute Risø and the Institute for Fluid Mechanics at the Danish Technical University, which designed the large wind turbines
- intermediary organisations, which provided the funding

The large-scale wind turbine innovation subsystem in the period 1981-1985 is represented in figure 4.2.

### 4.4.5 Conclusion

What can be said about the learning processes in this period? Learning by searching, performed by Risø and the Danish Technical University, remained important. It was seen as the basis of the development of large wind turbines. Learning by doing and learning by using gained in importance, since the Nibe turbines had been in operation for a number of years. Wind turbines turned out to be more difficult to operate than expected, mainly because of material fatigue problems. Since the relations with the utilities were still good and more utilities became involved in the large-scale wind turbine subsystem in this period, learning by interacting between the utilities and the other actors became more important. In addition, a wind turbine manufacturer was established in this period: Danish Wind Technology. This company was well integrated into the subsystem, since it had been set up by the utilities and the Ministry of Energy. Therefore, learning by interacting between this company and the other actors went very well.
4.5 1986 - 1991

4.5.1 The Masnedø turbines

In spite of large technical problems with the Nibe turbines, particularly with the turbine blades, the utilities decided, at the insistence of the Ministry of Energy, to continue the wind turbine development programme. In 1984 the utility ELKRAFT had ordered the newly established company Danish Wind Technology in 1984 to build five 750 kW wind turbines with technology close to that used in the Nibe B turbine (IEA, 1985; Van Est, 1999). The five 750 kW turbines were erected on the isle of Masnedø. One of the lessons learnt from the Nibe turbines was that blade problems in a large-scale turbine could be avoided if the blades were homogenous. Therefore, the 40 metre long blades of the Masnedø turbines, called Windane 40, were made entirely of glass fibre reinforced polyester (IEA, 1985). The power system was regulated by pitch control (IEA, 1986).

The theoretical part of the design process for these turbines, as for the Nibe turbines, was performed by the Institute for Fluid Mechanics at the Danish Technical University in Copenhagen. The institute performed calculations and developed
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models. Danish Wind Technology built the turbines and the blades. The research institute Risø performed measurements. In this way, theory and practice were completely separate (Karnøe, 1991).

The total project cost about 50 million DKK and was financed by ELSAM, the European Union and the Danish government (IEA, 1986). The construction of the five Masnedø turbines started in March 1985 (IEA, 1986). In January 1987, the turbines came into operation. It was not long until numerous problems arose. On October 12, 1987, one turbine burned down completely when it caught fire due to overheating (IEA, 1988). The cause was a defective circuit breaker which did not cut off the power supply to the 750 kW generator when the rotor came to a standstill. The generator that was still loaded then overheated and burst into flames (IEA, 1988). The turbine was rebuilt and was put into operation again in 1990 (IEA, 1991).

Other problems like material fatigue and the rupture of a shaft in the gearbox and other gearbox problems forced the engineers in 1988 to limit the maximum power output to 450 kW (Heymann, 1998; IEA, 1989). In 1989 and 1990, all Masnedø turbines were equipped with new gearboxes (IEA, 1990; IEA, 1991). Furthermore, soon after commissioning had begun, surface cracks appeared on a number of turbine blades. Two of the turbines were equipped with wooden blades, technically similar to those of the Nibe B turbine. The remaining three turbines were provided with new fibre glass blades during 1991.

4.5.2 The Tjæreborg turbine

Another Danish utility, ELSAM, went even further and built an even larger turbine: a 2 MW wind turbine, at Tjæreborg near Esbjerg. This turbine was an upscaled version of the Nibe B turbine with a rotor diameter of 60 metres (IEA, 1988). As in the case of the Nibe turbines, no Danish manufacturer showed any interest in building a prototype of that size. Therefore, the Tjæreborg turbine was also procured on a multi-contract basis (Van Est, 1999). The wind turbine cost about 65 million DKK and was financed by ELSAM, the European Union and the Danish government (Jørgensen and Karnøe, 1995; IEA, 1986). It had a three-bladed up-wind rotor with a 61-metre diameter and was pitch-controlled, like Nibe B. The blades of the Tjæreborg turbine, like those of the Masnedø turbines, were made completely of glass fibre reinforced polyester. Each weighed eight tonnes (IEA, 1988).

The Tjæreborg turbine was manufactured between 1986 and 1988 and officially inaugurated in June 1988 (IEA, 1989). Despite initial problems, the turbine performed better than its predecessors, but like theirs, its economic performance was
disappointing (Heymann, 1998). In August 1989, the gearbox failed seriously because the main gear wheel fractured. It was replaced in 1990 (IEA, 1990).

4.5.3 Other wind turbines

At the end of 1985, three upscaled Koldby wind turbines, with a rotor diameter of 31 metres and a generating capacity of 300 kW and called Windane 31, were ordered to be built at Hundested on the north coast of Sealand. A modified version of these turbines was installed in 1985 on Langeland by FYNSVÆRKET, the utility on Funen (IEA, 1986). Although built to produce electricity, an additional goal was to compare the costs of Windane 31 with those of the other wind turbines with different generating capacities. In this way, it was hoped that within the Wind Power Programme the optimum turbine size and the optimum price could be determined (IEA, 1986).

In 1989, ELKRAFT started designing a 50 metre diameter, 1 MW prototype turbine with variable rotor speed and blades that could operate in both the pitch and the stall control modes. The prototype was scheduled to be commissioned in mid-1991 (IEA, 1990). It was put into operation at Avedøre, near Copenhagen, in December 1993 (IEA, 1994).

4.5.4 The end of the Wind Power Programme

Around 1990, the large-scale testing and demonstration programmes were abolished. The Danish state sold its shares in Danish Wind Technology (Karnøe, 1991). Apparently, large Danish companies were not interested in taking the risk of developing large wind turbines. By that time, the small-scale wind turbine innovation subsystem had demonstrated its ability to manufacture reliable well-working wind turbines that were far cheaper than the wind turbines developed within the Wind Power Programme. This subsystem will be described in part B of this chapter. The Nibe turbines were taken over by ELSAM in 1988 and resumed operation after an overhaul. The Nibe A turbine was equipped with fully pitchable blades, like the Nibe B turbine (IEA, 1988). The Nibe B was provided with a new gearbox (IEA, 1990). The performance of the Nibe turbines remained inferior to that of smaller commercially manufactured Danish wind turbines (Heymann, 1998).

4.5.5 The large-scale wind turbine innovation subsystem in 1986-1990

Within this subsystem, all important actors were represented:
- the Ministry of Energy, which was responsible for the Wind Power Programme in co-operation with the Danish utilities
the utilities, which were the owners of the large wind turbine and had a very large say in the Wind Power Programme. SEAS, the Jutland utility was even more involved, since it partly financed the Nibe turbines.

- the company Danish Wind Technology, established by the utilities and the Ministry of Energy, which built most of the large wind turbines. Furthermore, a number of companies were involved in building parts of the Tjæreborg wind turbine. However, still no Danish firm was interested in developing and building large wind turbines.

- the research institutes Risø and the Institute for Fluid Mechanics at the Danish Technical University, which designed the large wind turbines

- intermediary organisations, which organised the funding

The large-scale wind turbine innovation subsystem in the period 1986-1990 is depicted in Figure 4.3.

![Figure 4.3: The large-scale wind turbine innovation subsystem in the period 1986-1991.](image)

Around 1990, the large-scale wind turbine innovation system fell apart. The Danish Wind Power Programme was terminated. Still no large Danish company had shown any interest in developing large numbers of large wind turbines. The state sold its share in the company Danish Wind Technology, which meant that the company ceased to exist. By 1990, the small-scale wind turbine innovation subsystem in Denmark had developed so well, that there was no longer any need for the state to own shares in a wind turbine production company and there was no need to extend the
Wind Power Programme did not exist anymore. From this time on, all wind energy activity in Denmark took place within the small-scale wind turbine innovation subsystem. This subsystem will be described in the following sections.

4.5.6 Conclusion

Let us consider the learning processes within the large-scale wind turbine subsystem in this period. Learning by searching remained important in the developing and upscaling of the wind turbines. Learning by doing and learning by using became more and more important, since more turbines were being built and operated. All large Danish utilities were involved in the large-scale wind turbine innovation subsystem in this period. Learning by interacting with the utilities still went well, although the utilities became less enthusiastic about wind energy as a result of the large number of operating problems and the high costs incurred through these problems. Danish Wind Technology was the manufacturer of the turbines of 1 MW and smaller. This company was integrated well into the subsystem and learning by interacting went smoothly. The 2 MW Tjæreborg turbine was built by a number of companies who had no interest in the further development of wind turbines; they were therefore less well integrated into the subsystem.

Although a great deal was learnt in this subsystem between 1975 and 1990, the turbines remained very expensive and operating problems continued. The Danish state, which did not have a history of setting up companies and owning large shares in them, sold its shares in Danish Wind Technology around 1990. By that time, the companies within the small-scale wind turbine subsystem had demonstrated their ability to build wind turbines that were cheaper and more reliable than the wind turbines built within the large-scale wind turbine subsystem.
Part B: The small-scale wind turbine innovation subsystem

4.6 1975 - 1980

In Denmark, as in the Netherlands, a small-scale wind turbine innovation subsystem developed as from the 1970s, which was relatively independent of the wind energy R&D programmes 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 Juul’s wind turbine and started developing wind turbines based on this example. They 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).

4.6.1 Riisager

The first small entrepreneur who started to manufacture wind turbines was a carpenter called Riisager. He copied Juul’s design and built a 22 kW wind turbine using materials that were at hand, like wood (for the blades) and lorry gears. Like Juul’s turbine, Riissager’s turbine was stall regulated and had three broad rotor blades that were supported with rods. Although Riisager applied for R&D support, he did not receive any (Karnøe, 1991). He scaled up his turbine to 30 kW in 1976, and sold about 50 turbines between 1975 and 1978 (Karnøe, 1991).

4.6.2 The Tvind turbine

Another important project in this period was the Tvind turbine. This turbine was constructed and built between 1975 and 1978. Influenced by the debate on economic growth, income distribution and environmental pollution, teachers and students at the Tvind school decided to build the world’s largest wind turbine. This turbine had a generating capacity of 2 MW and a 54 meter down-wind rotor. It did not have an asynchronous generator, as did the Riisager turbines, and therefore the frequency of the electricity produced was not of high enough quality to be fed into the electricity grid. Measurements demonstrated that it was a good wind turbine, although there were problems with regard to the structural dynamics; the problems were probably caused by the down-wind position of the rotor (Karnøe, 1991).

The Tvind turbine was built by left-wing oriented people on a voluntary basis. These people had different educational backgrounds. The design, blade profile and
calculations were performed with the help of engineers. For example, the blade profile was developed by an engineer who had also developed blade profiles for the F.L. Smidth turbines in the Second World War. The fact that the Tvind turbine worked, was psychologically very important for the grassroots movement. Furthermore, experience was obtained in designing and manufacturing fibre glass rotor blades (Karnøe, 1991).

Many other small Danish builders experimented with wind turbine designs, mainly based on previous designs. For example, some engineering was added to Riisager’s wind turbines. They were provided with an active yaw system to overcome the turbine’s slow response to changes in wind direction and with fibre glass blades, made with a small version of the Tvind mould. Furthermore, in this period a method was developed to produce electricity that was of high enough quality to be fed into the electricity grid (Karnøe, 1991).

4.6.3 The role of the wind turbine users

Up till 1979, the wind turbines were sold to idealistic buyers. They did not buy the turbines because they expected to save money, but because they supported the green movement (Jørgensen and Karnøe, 1995). Because they were so much in favour of the development of renewable energy technologies, they were very active in trying to help the manufacturers to improve the wind turbines. Furthermore, they were concerned about the safety and reliability of the turbines. The early turbines did not perform satisfactorily: often gearboxes were damaged, generators burned out and blades were lost (Van Est, 1999).

Therefore, in 1978 the turbine owners set up the Danish Windmill Owners Association, which initially consisted of about 40 people. The association offered suggestions to manufacturers about how they could improve their turbines with respect to safety and reliability. Furthermore, the association set up a monthly magazine, called 'Naturlig Energi', in which the performance of different types of turbines was disclosed. Because they were organised, the users created a strong selection environment for the first Danish turbine builders. They strengthened and stabilised the demand for wind turbines (Karnøe and Garud, 2001; Heymann, 1998).

Another very important achievement of the Danish Windmill Owners Association was the fact that they negotiated collectively with the utilities. In Denmark, the utilities were obliged to accept the electricity produced by independent small electricity production units. The Danish Windmill Owners Association negotiated about the buy-back tariff that the utilities would pay the small electricity producers. Because turbine
owners were organised, they were more powerful in the negotiations than the individual wind turbine owners in the Netherlands (Karnøe and Garud, 2001).

As from 1975, the grassroots movement organised so-called Wind Meetings, which provided a forum for knowledge-sharing between wind turbine producers and users. As a result of these meetings, which were held four to eight times a year, a large collective knowledge base was created. Those present at the meeting felt they were part of a community, a factor which promoted the development of trust and knowledge sharing. They all had the same goal: to produce a significant number of reliable well-functioning wind turbines to compete with the large centrally owned power stations (Jørgensen and Karnøe, 1995).

4.6.4 The first small wind turbine companies

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 Juul’s, Riisager’s 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 Wind Meetings. Their 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.

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).

The manufacturers could apply to the Danish Board of Technology, an agency of the Ministry of Industry, for R&D subsidies of between 5,000 and 10,000 USD. Project proposals were evaluated by the newly created Renewable Energy Committee. This
committee, which consisted of prominent people like a professor at the Danish Technical University, established links with political parties and ministries. The committee played an important role in winning legitimacy for wind energy, also for small wind turbines (Karnøe and Garud, 2001).

4.6.5 The Risø Test and Research Centre

As a part of the Danish Wind Power Programme, set up to support the technological development and adoption of wind power (see part A of this chapter), in 1978 a three-year grant of 5.5 million DKK was given to create a Test and Research Centre. This Centre was located at the site of the Risø research centre, which had been established in the 1950s to do research into nuclear power. The Test and Research Centre had a very low status within the Risø research centre and was located in a small wooden shed in a remote part of the site (Van Est, 1999)²⁹.

By 1979, the first wind turbine had been erected at Risø (Karnøe, 1991). The Test and Research Centre consisted of both theoretical thinkers and hands-on engineers, most of whom had some previous experience with wind turbines. One of them had designed the blades of the Twind turbine. They were not in favour of nuclear power stations and they wanted to develop a good alternative, namely wind turbines. Since existing knowledge on wind turbines was very limited, the members of the Test and Research Centre had much to learn. The Test and Research Centre was completely separate from the research performed on the Nibe turbines, by the Danish Technical University³⁰ (Karnøe, 1991).

Because the Test and Research Centre had only received financing for three 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 Test and Research Centre, it could in the future get its financing through orders from the manufacturers. Therefore, the goal of the members of the Test and Research Centre was not to develop the technically best wind turbine, but to develop a wind turbine industry. The challenge they faced was to develop the kind of knowledge that would be of interest to the turbine manufacturers (Karnøe, 1991).

²⁹ This was also true for the wind energy group at the Dutch research institute ECN.

³⁰ The Test and Research Centre was only involved in the design of the blades of the Nibe turbines. The rest of the design and the measurements were performed by the Danish Technical University (see part A of this chapter).
Chapter 4

4.6.6 Financial support for wind turbine buyers

At the beginning, it was hard for the members of the Test and Research Centre to win the trust of the turbine manufacturers. Many companies did not want to share their products and design rules with the Test and Research Centre. However, things changed in 1979. The second energy crisis, which occurred in 1979, and growing unemployment made the Danish government take a new measure to encourage the development and adoption of wind power. They decided to start supporting the demand for wind turbines. As from 1979, turbine buyers could receive a 30% investment subsidy. Three conditions had to be met to receive this subsidy (Van Est, 1997). First of all, only private wind turbine buyers would be eligible for an investment subsidy. Secondly, the owner(s) of the wind turbines had to live within three kilometres of the wind turbine. Thirdly, the turbine they bought had to be approved by the Test and Research Centre. In this way, the government could keep control over the development of small wind turbines. No money would be wasted on unreliable wind turbines. Furthermore, turbine buyers would not be allowed to erect wind turbines everywhere in the country.

This measure was very important for the turbine manufacturers, since it increased the market for wind turbines at a very early stage. The measure was also very important for the Test and Research Centre, since it forced the turbine manufacturers to co-operate with the Centre (Karnøe and Garud, 2001).

4.6.7 The approval criteria

The approval criteria were not very rigorous. The main reason for this was, that such criteria were simply not available in 1979 (Karnøe, 1991). There had been no time to develop them and the knowledge on which criteria could be based was lacking. Furthermore, it was decided that in such an early phase of technological development rigorous criteria would not be beneficial for the manufacturers. The approval criteria were (Karnøe, 1991):

- the wind turbine had to have both an aerodynamic and a mechanical brake system, just as Juul’s turbine had
- the loads on the tower and foundation had to be calculated and documented and the static loads on the blades had to be measured.

Since the Test and Research Centre felt it lacked sufficient knowledge to develop the criteria on its own, it developed them in co-operation with the turbine manufacturers and the Windmill Owners Association. The criteria were based on the measurements made on the Gedser turbine. Because of the uncertainties involved, the criteria were rather conservative, and encouraged the building of heavy wind turbines. Although it
was not realised at the time, the heaviness of the wind turbines reduced the dynamic loads, making them less vulnerable. However, the Test and Research Centre was flexible, constantly incorporating suggestions that were put forward during formal and informal interactions with turbine manufacturers and owners (e.g. during the Wind Meetings). Furthermore, an old Riisager turbine was erected on the Risø site and measured by the Test and Research Centre. These measurements provided important new knowledge about turbine loads and structural dynamics (Karnøe, 1991). The good performance of the turbine’s stall regulations convinced the members of the Centre that the stall regulation was the best method of regulating a wind turbine.

Often, the turbine drawings and calculations the turbine manufacturers handed in were insufficient. Therefore, members of the Test and Research Centre often visited the companies. Then, they could see the designs and talk to the manufacturers. These informal interactions were very important for the development of trust between the manufacturers and the members of the Test and Research Centre and for the exchange of knowledge (Karnøe, 1991).

4.6.8 The turbine market

In the period 1976-1979, about 170 small wind turbines were erected, 120 of them in 1979. The progress was clearly influenced by the investment subsidy. The real pioneers like Riisager lacked the experience and capital to operate on a larger scale and therefore could not benefit from the growing market. The small agricultural machine companies like Vestas and Bonus were able to produce on a larger scale, using the know-how of the pioneers and the patents they bought from them (Heymann, 1998). They produced wind turbines by assembling standard components (Jørgensen and Karnøe, 1995). For their designs they preferred available and well-known technical solutions. When faced with technical problems, they increased the structural stability by making the turbines stiffer. New technical solutions were only introduced after satisfactory test operation (Heymann, 1998). Most wind turbines were sold to co-operatives composed of a group of farmers. These were the same kind of customers the turbine companies used to deal with. Furthermore, building small series of turbines involved the same kind of design and manufacturing work as they were used to.

Local ownership, imposed by the subsidy rules, often advanced local production, since buyers preferred to purchase turbines from a manufacturer they knew and trusted (Van Est, 1997). In this way, local user-producer networks were built up. The fact that every manufacturer had its own local customers decreased the competition between the manufacturers. This made it easier for them to disclose information to the Test and Research Centre and during the Wind Meeting, at which other manufacturers
were present. The manufacturers communicated informally, on the basis of a barter economy about solutions for different problems (Karnøe, 1995). Furthermore, the importance of learning by doing lowered the risk of providing information to other manufacturers. They would not be able to incorporate the information satisfactorily into their own turbines unless they had gained adequate experience beforehand (Van Est, 1997).

Although local ownership was meant to control the market for wind turbines, it was beneficial for the turbine manufacturers. Furthermore, local ownership increased public support for wind energy. People who were aware of the disadvantages of wind turbines also saw the advantages because wind turbines offered local employment. Most of the people living near the wind turbines were part-owners of the turbines.

On average, the turbines produced between 1975 and 1980 had a power capacity of 10-30 kW and a rotor diameter of 4-10 metres. Many design concepts were used: HAT turbines with two, three or four blades or VAT turbines. However, the most used model was the three-bladed HAT turbine based on the Juul/Riisager design. Around 1979-1980 it became evident that this design functioned best. Therefore, this design became the dominant design in Denmark (Karnøe, 1991). The development of a dominant design was not imposed by the Test and Research Centre, but the Centre did contribute to this development by deriving most of its knowledge from the Gedser and Riisager turbines and also by deriving the approval criteria from these turbines (Dannemand Andersen, 1993).

### 4.6.9 The small-scale wind turbine subsystem in 1975-1980

In this period, the Danish small-scale wind turbine subsystem was built up. This subsystem was very strong, right from the beginning. Many small manufacturers were present in the subsystem, most of them with the same background: they had experience of producing agricultural machines.

Up till 1979, the turbine buyers were mainly grassroots enthusiasts who bought wind turbines because they wanted to stimulate local self-sufficiency by introducing small-scale decentralised energy production. After 1979, when the investment subsidies for wind turbine buyers were introduced, other buyers entered the subsystem; these were mainly farmers and co-operatives. Policy-makers were present in the subsystem as from 1979, when they introduced the investment subsidies. They were not very active within the subsystem, because they saw large-scale wind energy as the most promising form of renewable energy that could make a significant contribution to Denmark's energy supply in the future.
The Test and Research Centre at Risø played a central role in the small-scale innovation subsystem since its establishment in 1979. The members of the Centre did their best to become actively involved in the technology development of the small wind turbine builders. Because they had not been given a large amount of funding, the survival of the Centre was dependent on the survival of the small wind turbine manufacturers. Figure 4.4 depicts the small-scale wind turbine innovation subsystem in the period 1975-1980.

![Diagram](image)

Figure 4.4: The small-scale wind turbine innovation subsystem in the period 1975-1980.

### 4.6.10 Conclusion

What can be said about the learning processes within the small-scale wind turbine subsystem in this period? Learning by interacting was definitely the most important learning process in this period. Turbine builders, buyers and researchers formed a tight network in which a large amount of information was exchanged. Turbine builders learned from turbine users about the quality and the failures of their turbines. Experiences were exchanged during informal contacts. During more formalised contacts, the Wind Meetings, experiences were exchanged between turbine builders, users and researchers. The turbine users increased their influence on the technology development process by setting up a magazine, Naturlig Energi, in which they published details of the performance of the various turbines. In this way, new buyers could be informed and the turbine buyers could together stand up to the manufacturers and insist that they improved their turbines with the help of input from the users.
Local ownership, imposed by the subsidy rules, favoured learning by interacting between turbine users and builders, since most turbine users lived near the turbine builders.

After its establishment in 1979, the Test and Research Centre was a very important actor within the subsystem. It built up a trusting relationship with the manufacturers and began to build up a knowledge base for the subsystem. During informal contacts at the Test and Research Centre, and during the Wind Meetings, the members of the Centre co-operated in solving practical problems encountered by the manufacturers.

The approval criteria, set up in 1979, forced the manufacturers to co-operate with the Centre and exchange knowledge with it. The approval criteria also guided the technology development process, by the insistence on the presence of two independent braking systems in the turbine.

Learning by searching was not prominent in this period in the small-scale wind turbine subsystem. The manufacturers produced designs by imitating earlier wind turbines, like the famous Gedser turbines and the Riisager turbines. Since these turbines had proved reliable, imitating them was seen as a good way to design turbines in accordance with the design philosophy in the subsystem: to make turbines that worked reliably and safely. In the subsystem there was absolutely no drive to build elegant and extremely cost-effective wind turbines.

When, in time, more and more turbines were built, learning by doing and learning by using became more and more important. Users learned how their turbines operated, and what failures could occur. Manufacturers learned how to build turbines and how to solve practical problems in their own workshop or in the field, in co-operation with users and researchers.

4.7 1981 - 1985

4.7.1 Energiplan 1981

In 1981, the adverse effects of the second oil crisis put renewable energy back on the Danish political agenda. Directly after the second oil crisis, in 1979, a separate department to deal with energy-related matters, the Ministry of Energy, had been set up. Before 1979, wind energy-related matters had been handled by the Ministry of Housing (Karnøe, 1998). The newly established Ministry was given the task of preparing a national energy plan. This plan, called Energiplan 1981, was presented in 1981. Grassroots supporters had an influence on the contents of this plan, because they were asked to comment on the preliminary versions (Van Est, 1999). The
Energiplan 1981 contained a number of measures and proposals from the Alternative Energy plan that was put forward by grassroots supporters in 1976. First of all, two long-term energy scenarios were presented, one with and one without nuclear energy. Secondly, the need for permanent energy saving was stressed. Thirdly, the maximum development of decentralised co-generation plants and a stronger accent on renewable energy options were put forward as important goals. With respect to wind energy, the government aimed at the installation of 60,000 small wind turbines that would be able to supply 8.5% of the energy demand in 2000 (Van Est, 1999). The use of large wind turbines was regarded as an alternative to the small wind turbine development.

This clearly indicates that the development of small wind turbines was regarded as a very serious option, whereas in 1976 only large wind turbines were considered to be worth developing and financing (see section 4.3.1). In 1981, small wind turbines were put forward as the most promising option. R&D funding was placed second to a policy of developing a wind turbine industry by way of market stimulation. In this way, wind energy policy came to be part of both energy and industrial policy. However, market stimulation slowed down in 1981 and the investment subsidy was reduced from 30% to 20% (Karnøe, 1991).

4.7.2 The role of the Test and Research Centre

In spite of the reduction in investment subsidies, optimism persisted. At the end of 1981, 21 manufacturers had received type approvals for one or more wind turbines. The Test and Research Centre at Risø played a large role in this optimism, both by functioning as a binding agent within the innovation subsystem and by working hard to increase the legitimacy of wind turbines as electricity production units. For example, the Centre compiled a wind atlas for Denmark, in which the economic value of wind energy was stressed (Hvidtfelt Nielsen, 2001).

The Test and Research Centre played a very important role in assembling and upgrading a joint knowledge base for the innovation subsystem. The knowledge consisted mainly of industrial knowledge about practical solutions to problems. Furthermore, the Test and Research Centre conducted experiments that had a practical, problem-solving focus. As from the mid-1980s, systematic research was performed and reliable, empirically based models were developed. The knowledge was transferred both in a formal way, via reports, technical regulations and norms, and in an informal way during interactions between actors during formal and informal contacts. The way in which the Centre handled the knowledge acquired by the companies increased their trust in the Centre (Dannemand Andersen, 1993).
4.7.3 Technology development

The actors in the innovation subsystem worked together in this period, trying to increase the market for wind turbines by increasing the product quality and the cost-effectiveness of wind turbines. They succeeded in reducing investment uncertainties by developing good procedures for approval and financing. The most important technical development activity within the companies was the scaling up of the turbines from a 30 kW capacity with a 10 metre rotor (averagely) in 1981 to a 55 kW capacity with a 20 metre rotor (averagely) in 1985 (Karnøe, 1991). This upscaling involved incremental innovations, since the design of the turbines was not changed. As a result of these incremental innovations and the gradual elimination of design weaknesses, the cost effectiveness of the turbines rose by up to 50% (Karnøe, 1991). The figure of 55 kW was dictated by the standard generators that were available. As explained in the previous section, the turbine manufacturers did not use specially designed components for their turbines, but made use of standard components that were readily available. Only one manufacturer, Vestas, began on its own to develop and produce wind turbine components like blades and control systems. Vestas considered it important to gather in-house knowledge about these components and to become independent of the production capacity and delivery times of suppliers (Karnøe, 1991).

4.7.4 The Danish home market

Several hundreds of wind turbines were installed in Denmark between 1980 and 1982 (Van Est, 1999), almost all of them being three-bladed stall regulated upwind turbines. Because of the large numbers the manufacturers gained considerable experience of how to produce wind turbines in the most efficient way. Furthermore, since the turbines were produced in series, costs could be reduced. Learning by using and learning by interacting with users gave the manufacturers good insight into the failures in their designs. Turbine development was characterised by the implementation of ad-hoc solutions and trial-and-error learning based on rules of thumb and the intuition of the manufacturer (Karnoe, 1991).

The buyers of the turbines continued to be grassroots advocates and co-operative groups of farmers. Their choice of wind turbine to buy was strongly influenced by the information about the electricity production and failures of the various wind turbines given in the magazine Naturlig Energi. Since utilities could not profit from the investment subsidy, they showed no interest in buying small wind turbines in this period (Van Est, 1999; Karnøe, 1991).
4.7.5 Wind turbine exports

At the end of 1981, optimism within the small-scale wind turbine subsystem decreased. Two fierce storms swept over Denmark and destroyed 2% of the wind turbines. This event, and the destruction of a 55 kW Windmatic turbine the debris of which kept a main road blocked for hours, caused a large amount of bad publicity for wind energy (Van Est, 1999). The bad publicity and the reduction in oil prices at the beginning of the 1980s resulted in a decline in the demand for wind turbines in Denmark. The home market almost halved in 1982 (Van Est, 1999). The wind turbine manufacturers started to look for alternatives. The Technology Council of the Ministry of Industry granted the manufacturers a subsidy to examine the American market in 1982.

The examination was performed by a consultant, who concluded that the American authorities, and particularly the Californian authorities, provided substantial subsidies for wind turbine buyers. Federal and state tax credits jointly amounted to an investment subsidy of 40-45%, which meant that even turbines that hardly produced any electricity were profitable (Gipe, 1995). Furthermore, by way of the Public Utility Regulatory Policies Act, utilities were compelled to buy electricity from private electricity producers at fair prices. These measures made the Californian market very attractive for wind turbine manufacturers. Thirdly, according to the consultant, many competing turbine producers were active on the Californian market, but none of them had a clear technological lead over the Danish manufacturers (Karnøe and Garud, 2001).

Exports to California started immediately. In the years before, Californian turbine owners had had bad experiences with the unreliability and low electricity output of the American-made wind turbines (Gipe, 1995). Therefore, they were willing to try European-made turbines. The Danish turbines looked the most promising; the manufacturers could demonstrate that their turbines had relatively good performance characteristics and favourable reports had appeared in the magazine Naturlig Energi published by the Danish Windmill Owners Association.

By the end of 1982 about 40 Danish wind turbines had been sold to customers in California (Karnøe, 1991). The number increased to about 2,000 per annum in 1985 (Karnøe and Garud, 2001). The export of wind turbines provided the Danish manufacturers with large growth opportunities. The number of people employed by the Danish turbine manufacturers grew from about 300 to about 2,500 between 1982 and 1985 (Karnøe and Garud, 2001). During this period, the Danish market share in California increased from 0% to 65%, and the cumulative installed turbine capacity expanded from 71 MW to 1,250 MW. The cumulative installed wind turbine capacity...
of 1,250 MW was more than 10 times the cumulative installed capacity in Denmark at the time. The Danish turbines, mainly 55 kW and 65 kW turbines, performed far better than those of their competitors, who were 15 American and eight European companies (Jørgensen and Karnøe, 1995). Furthermore, the strong dollar favoured Danish exports (Van Est, 1999).

There were both advantages and disadvantages in exporting to California. Firstly, the fast growth of the Danish turbine companies posed organisational challenges. Many companies had to introduce more formal product development teams, which meant that product development was no longer integrated with the shop floors producing the turbines and handling the operational problems. However, the product development teams were not isolated from the shop floors. There were still frequent interactions, and the product developers were still able to learn from manufacturing and operating problems (Karnøe and Garud, 2001).

Secondly, before granting funds or insurances the Danish insurance firms and certification companies insisted on explicit criteria and explicit presentation of the knowledge used in the design of turbines. This made the introduction of formal product development teams even more important and enhanced the role of the Test and Research Centre, which was required to approve the turbines. Furthermore, it resulted in the entrance of a new actor into the small-scale wind turbine innovation system: the engineer agency Tripod. This agency, consisting of engineers who had worked in the Nibe turbines project at the Danish Technical University, developed measurement methods and calculation programmes that could handle the problems connected with aerodynamics and structural vibrations in wind turbines. This formalised knowledge was exactly what the insurance firms and certification companies required. Therefore, although the manufacturers were at first sceptical about providing Tripod with design information, Tripod soon became an important actor in the subsystem (Karnøe, 1991).

Thirdly, because the markets were no longer local, the Danish companies had to set up formal procedures for the servicing and repairing of the turbines and for the establishing of product guarantees. These procedures were new for the turbine companies and they were developed by an expensive process of trial-and-error (Karnøe and Garud, 2001).

### 4.7.6 A speed-up in technology development

During the first few first years of this period, the Danes exported mainly well-developed 55-kW and 65-kW turbines, but the situation changed as from 1983. Although the Danes won the competition with the American and the other European
manufacturers, they started competing with each other on equal terms from a technical perspective (Van Est, 1999). A technological rat race began, in which manufacturers were forced to develop larger and more cost-effective wind turbines as rapidly as possible. New Danish manufacturers entered the Californian market, hoping to get a share of the profits. The strategy of these new manufacturers was to try and leapfrog over the older manufacturers by introducing new and larger turbines on the basis of the best existing technology. The existence of a publicly available, simple design, and the availability of free advice from the Test and Research Centre made it possible for them to do this (Van Est, 1999). However, because of their lack of experience built up by learning by doing and learning by interacting with turbine users they found manufacturing good wind turbines more difficult than they had expected.

At the same time, a second reason arose for the rapid development of larger and more cost-effective wind turbines. Up till 1983, thousands of small wind turbines had been erected in the windy Californian passes. If thousands more were to be installed there would be a shortage good sites. Therefore, Californian wind park owners wanted to save space by erecting wind turbines with larger generating capacities. Secondly, the prospect of the expiry of the energy tax credits in 1986 created the need for more cost-effective wind turbines. Since the costs for installation, maintenance and operation were more or less independent of turbine capacity, larger turbines offered the benefits of economies of scale (Van Est, 1999).

The Danish manufacturers were forced to scale up their wind turbines first to 75 kW with a 17 metre rotor and then to 100-130 kW with rotor diameters of 19-20 metres in a relatively short period. As a result, the companies started to export new, relatively unproved wind turbine designs. The strong price and performance competition made it impossible to sell the older turbine types at their old price, which lowered the profit margins on the older turbine types. Manufacturers furthermore shifted rapidly from batch to serial production in order to meet the growing demand. The cost reduction resulting from the serial production was not offset by the price reductions carried through in the struggle against competitors. As a result, by 1985, at the height of the California export boom, a quarter of the total Danish turnover involved a loss, and seven of the twelve Danish manufacturers active on the American market had negative trading results (Van Est, 1999).

4.7.7 Technical problems

Trading results became even more negative because many technical problems arose, particularly with the newly developed turbines. Because the newly developed turbines had not been tested sufficiently, the technical problems had not been noticed by the manufacturers. Selling turbines on the international market removed the important
factor of geographical proximity. The manufacturers could not build up a relationship with their customers and learn from their mistakes by learning by doing and learning by interacting with users, as they had done in Denmark. The fact that the Californian wind park owners serviced their own wind turbines reduced the feedback still further. Furthermore, the Danish manufacturers had not considered the fact that the Californian wind regime was completely different from that in Denmark. They had assumed that their turbines would function just as well in California as in Denmark, but this was not the case. The harsh Californian wind regime put extra demands on the turbines (Van Est, 1999).

As a result of the above-mentioned factors, the turbines from almost all Danish manufacturers had severe technical problems, particularly relating to gears, overproduction in the generators, oil cooling systems and blades (Karnøe, 1991). The Danish products, especially the larger turbine types, were of poorer quality and therefore the Californian customers lost their trust in the Danish turbines. It also proved very hard for the Danish manufacturers to exercise good project management, product service and maintenance since they were exporting so many wind turbines to California. The Californian market, which had been so promising at the beginning of this period, created severe problems for the Danish manufacturers at the end of this period. Around 1985, when the problems arose, many insurance companies lost their faith in wind energy and withdrew from the subsystem. Many manufacturers also disappeared from the subsystem (Van Est, 1999).

4.7.8 Growth in the Danish home market as from 1984

However, the Californian market had a positive effect on the Danish home market. Following the example of the Californian wind parks, in 1984 in Denmark investment subsidies of 40% became available for large-scale, privately-owned wind parks. In addition, a new governmental subsidy was introduced for electricity produced by renewable energy sources (Van Est, 1999). For every kWh of electricity produced, the owner of the renewable energy source was to receive about 25 øre. Thirdly, in 1984 a 10-year agreement was reached between the utilities, the Windmill Owners Association and the turbine manufacturers (Van Est, 1999). According to this agreement the utilities had to:
- buy all the electricity that independent owners of renewable energy sources fed into the electricity grid at the rate of 85% of the consumer price
- pay 35% of the costs of connecting the energy sources to the electricity grid, on condition that the government would maintain the investment subsidy programme

As a result of these measures, the cost-effectiveness of wind turbines increased enormously in Denmark. Investing in wind turbines became interesting for institutions
Wind energy in Denmark

and local municipalities. Projects were quickly established by project developers. Cumulative installed wind turbine capacity in Denmark rose from 8 MW in 1984 to about 20 MW in 1985 and about 30 MW in 1986 (Karnøe, 1991) (see figure 4.5). About 25% of this capacity was installed in wind parks (Karnøe and Garud, 2001). However, this fast growth and the prospect of further fast growth in the wind turbine capacity in the country was not very promising in the utilities' opinion. The government was also frightened by the large number of orders from project developers. Therefore, the utilities secretly started negotiations with the government about new regulations (Karnøe, 1991).

In December 1985, these negotiations resulted in a new restriction. New siting criteria were formulated: all investors had to live within a radius of 10 kilometres of their turbine(s) and the turbine(s) had to be erected in the municipality where the owners lived. Furthermore, the extent to which individuals could invest relative to their use of electricity was restricted: the amount of wind power generated must not exceed the owner's electricity consumption by more than 35%. This intervention ended a short period during which projects were rapidly established in the whole country by large investors. These new investors were damaging for the public image of wind energy. To the public, local attachment and local benefits were very important (Van Est, 1997). One third of the annual turbine production was cancelled, which led to problems within the industry.

4.7.9 The first 100-MW agreement

By way of compensation for the imposition of the new restrictions on private wind turbine owners, the government forced the utilities to sign a 100-MW agreement. This
agreement forced the utilities to erect 100 MW of wind turbine generating capacity within the next five years (Van Est, 1999). In this way, the utilities could keep control over the production of electricity by wind turbines. ELSAM was responsible for 55 MW, ELKRAFT for 45 MW (Gipe, 1995). The utilities agreed to develop wind energy projects in a way that would optimise the conditions for a broad industrial and technological development, including the development of new prototypes. For the Danish wind turbine manufacturers, the agreement offered good and stable prospects with regard to the home market. The timing was excellent; orders in Denmark had been cancelled, there were problems in California and the Californian tax credits were to expire quite soon.

By way of the 100-MW agreement, the small turbine manufacturers would be incorporated into the network that the Danish government considered suitable for the development of wind energy: the network of the large-scale wind turbine innovation subsystem. Since in this subsystem no large companies showed any interest in producing wind turbines, the only way in which wind turbines could be produced for utilities was to include the small wind turbine manufacturers in this subsystem.

4.7.10 The small-scale wind turbine innovation subsystem in 1981-1985

In this period, the small-scale wind turbine innovation subsystem remained complete and tight. Up till the first 100-MW agreement in 1985, all Danish wind turbine buyers were private persons or co-operatives. They co-operated with the manufacturers to improve the wind turbines. The Test and Research Centre remained a very important actor in the subsystem. It served as the knowledge base of the subsystem and took an active part in the development of the technology. The policy-makers started to play a more active role in the subsystem in this period. In 1984, they started to promote the erection of wind turbines in turbine parks by introducing a large investment subsidy and high buy-back tariffs for these turbines. Furthermore, they involved the utilities in the subsystem by signing the first 100-MW agreement with them in 1985. By way of this agreement, the utilities were forced to take part in the small-scale wind turbine subsystem.

The export of wind turbines to California brought about changes in the Danish small-scale innovation subsystem, especially in 1984-1985 when large numbers of turbines were exported. First of all, the turbine manufacturing companies grew fast. They were forced to make organisational changes, e.g. to introduce special product development teams. Secondly, the manufacturers started to co-operate with actors outside Denmark, like Californian project developers and turbine service and repair companies. Thirdly, the role of the insurance firms and certification companies within the Danish small-scale innovation subsystem became larger. Because of the large
number of turbines produced and the high risks involved, they demanded explicit criteria and representation of knowledge used in design. This led to the entry of the engineer agency Tripod into the subsystem, which developed ways to represent the knowledge in a formalised way. Around 1985, when the problems in California arose, many insurance companies lost their faith in wind energy and withdrew from the subsystem. Many manufacturers also disappeared from the subsystem. Figure 4.6 depicts the small-scale wind turbine innovation subsystem in the period 1981-1985.

![Figure 4.6: The small-scale wind turbine innovation subsystem in the period 1981-1985.](image)

### 4.7.11 Conclusion

Now let us look at the learning processes within the small-scale wind turbine subsystem in this period. Within the Danish market, learning by interacting remained the most important form of learning. Until 1985, almost all turbine buyers were still local private persons and co-operatives. They exchanged a lot of information with the turbine manufacturers about the problems they were having with their turbines. The Test and Research Centre still played an active role in the exchange and build-up of knowledge. The employees helped with finding practical solutions to operating and manufacturing problems. They also performed some practical, problem-focused research. Furthermore, on the basis of the knowledge gathered by interaction with manufacturers, measurements on turbines and practical research, they started building simple, empirically based models that turbine manufacturers could use to design their
turbines. The engineering agency Tripod also started to build models and devise calculation programmes.

This more formalised knowledge was what the manufacturers needed, especially for the export of turbines to California. Certification and insurance companies were demanding formalised forms of knowledge. Furthermore, the demand for fast upscaling of wind turbines in California resulted in the design and manufacture of larger and larger wind turbines. Learning by way of trial-and-error was far more expensive with these turbines; this explains why calculation methods and models were needed as input for design. Learning by using and learning by doing were especially important on the Californian market, since thousands of wind turbines were sold. Californian product developers learned that, although the operation statistics of the turbines were very good in Denmark, the Danish turbines were not always adjusted to the far harsher Californian weather conditions. Furthermore, they learned that it was risky to buy turbines that were prototypes or not fully proven commercially. Because the Danish manufacturers made use of Californian repair and service companies, they were far less able to learn from their mistakes than in Denmark. Learning by interacting between the Danish manufacturers and the Californian buyers went far less smoothly than with the Danish buyers.

Danish manufacturers learned how to manufacture their turbines in series, and how to do this in the most efficient way. They also learned how to design turbines not just on the basis of trial-and-error, but also on the basis of more formal calculation methods and how to record their knowledge in a more formalised way. Furthermore, they learned managerial skills from their Californian activities, such as how to organise information exchange between separate product development teams and shop floors, how to guarantee product performance and insurance and certify a uniform turbine quality. This knowledge could serve as a good input for future activities, provided the companies were able to stay in business after the problems they had encountered on the Californian market in the mid-1980s.

4.8 1986 - 1992

4.8.1 Problems for the Danish turbine manufacturers

In 1986, the Californian wind turbine subsidies expired and the dollar exchange rate fell. Furthermore, because many newly developed and not fully tested turbines had been sold to California in the previous years, many technical problems arose, especially with the blades and the gears (Karnøe, 1991). This resulted in an unexpected need for repairs. In California the technical problems made people lose

In Denmark too, banks, institutional investors, media and the turbine users reduced their trust in wind turbines. Many institutional investors stopped investing in wind turbines and insurers were unwilling to issue policies for wind developments. Simultaneously, as from 1985 the Danish investment subsidies were reduced continuously, dropping to 10% in 1989 and to 0% in 1991 (Gipe, 1995). It had been reasoned in 1985 that by the year 1991 wind turbines would have become cost-effective and competitive energy production units and therefore subsidies would not be needed anymore. Only an indirect investment subsidy would remain the general energy tax put on energy produced by wind turbines was refunded to the turbine owner by the government (Jørgensen and Karnøe, 1995). The subsidy per kWh on renewable energy sources would also remain (Van Est, 1999). However, the decrease in investment subsidy made the demand for wind turbines decrease. The combination of these factors resulted in a collapse of wind turbine sales and to the bankruptcy of many Danish manufacturers in 1985 and 1986 (Karnøe, 1991).

### 4.8.2 A new start

However, many firms were able to make a new start. Many employees of firms that were unable to start afresh were hired by firms that continued to build turbines. In this way, knowledge and competence remained present in the innovation subsystem (Karnøe and Garud, 2001).

A great deal of new knowledge was developed during the export period, especially managerial knowledge. The companies had learnt to reduce risks by (Van Est, 1999):
- not focusing on only one export country, thus avoiding the danger of possible demand reductions as a result of policy changes
- hedging against exchange rate risks
- having more than one supplier for each turbine component or produce their components themselves, in order to ensure a stable supply of components

From a technical point of view, they had learnt to:
- develop wind turbines in a more controlled way, especially by performing more tests
- certify a uniform turbine quality
- guarantee project performance and insurance

The fact that many firms were able to make a new start was a result of large efforts to revive the reputation of wind energy, especially on the part of the Windmill Owners

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31 As mentioned in Chapter 3, this also happened in the Netherlands in this and the following period.
Association. This Association still had a large number of members and was therefore able to lobby the government urging them to take more structural action to restore trust in wind energy. This lobbying, combined with the appearance of large, reliable, financially strong Japanese turbine manufacturers, like Mitsubishi, on the international turbine market, convinced the government that it should take action. The Ministry of Energy set up a committee to investigate possible ways of relieving the financial burden on Danish investors; the Ministry was anxious to secure and support the technological development of Danish turbines and safeguard their competitive position on the international market. The Wind Turbine Guarantee Company was set up and given a state guarantee of 750 million DKK, to guarantee the long-term financing of large export projects (Van Est, 1999). This opened up new export opportunities for the Danish manufacturers.

4.8.3 A new approval system

One of the conditions that the manufacturers would have to meet in order to qualify for the guarantees was that their turbines would have to be approved according to a new approval system (Hvidtfelt Nielsen, 2001). As mentioned before, the existing approval system was not very strict. It was described in a 50-page document and consisted of a design review and an examination of the basis of the calculations. A new, more thorough approval system was needed to set levels for design, manufacturing, transportation, installation and servicing of the turbines, especially since the technical problems with the turbines had increased the costs of insurance. Therefore, insurance companies began to demand that well-known classification companies like Germanischer Lloyd and Det Norske Veritas should be responsible for approving turbine projects.

The Danish government and manufacturers wanted to offer a Danish alternative to these companies by developing a new Danish approval system. They argued that by raising the quality of Danish wind turbines to international industrial standards and by lowering certification costs the Danish position on the export market would be strengthened again. A new approval system was developed by a newly established working group under the Energy Agency, in co-operation with the Test and Research Centre, the manufacturers, the insurance and certification companies and a number of other organisations. In the spring of 1991, the Danish Energy Agency issued an order concerning type approval and certification of wind turbines. According to this order, every wind turbine erected in Denmark after May 11th 1991 had to be type approved by the Test and Research Centre or by another institution authorised by the Danish Energy Agency. The technical basis of the new approval system covered more than 300 pages (Dannemand Andersen, 1993). The guarantee company was also established in 1991 (Van Est, 1999).
The primary aim of the new approval system was to bring into line the wind turbine manufacturers, the approval authorities (the Energy Agency and the Test and Research Centre) and the classification companies. To make the system more flexible, there were three different categories of approval: A, B and C approvals (Hvidtfelt Nielsen, 2001). The A approvals were the 'real' type approvals used by the larger manufacturers, the B approvals were the 'reduced' approvals used by the smaller manufacturers, and the C approvals were a kind of exemption used for temporary approvals of prototypes and test models. All approval categories consisted of design, product and installation approvals. In the design approval, the safety, the structural strength, and the electrical system of the turbine design were assessed. This was done by verifying the documentation of the manufacturer. To obtain the design approval, taken over from the previous approval system, the design had to incorporate two independent braking systems. While the design approval checked the turbine model, the product approval checked the quality of individual wind turbines and their main components. Product approval was concerned with the verification of the quality management system of the manufacturer, including the control of the competencies of the production labour, and production and quality control. The installation approval was based on all damage and repairs (Hvidtfelt Nielsen, 2001).

4.8.4 Fast technology development once again

The reduced subsidies in California and Denmark forced the manufacturers to make their wind turbines even more cost effective. As in the previous periods, they used two strategies to do this: scaling up and optimising existing designs. Between 1986 and 1988, the wind turbines were scaled up from about 75 kW to 150-250 kW. After 1988, these turbines were optimised, and the development of even larger turbines with generating capacities of 300-500 kW began (Karnøe, 1991).

Also as a result of the many technical problems that arose in the turbines in California, product development was more thorough than before. The experience gained in the hectic export period was thoroughly evaluated. Technology development was performed in special R&D departments. The relationship of the manufacturers with the Test and Research Centre also changed: they asked the Centre for a more sophisticated form of knowledge to supplement their own knowledge base (Dannemand Andersen, 1993). Instead of scaling up and optimising previous designs that were based on the old Gedser turbine, turbine designers engaged in new technological developments for the first time. For example, integrated gear-axis-yaw systems were designed. Furthermore, attention was paid to the elegance of the design, as a result of the siting problems that were beginning to arise (Karnøe, 1991).
A big problem at the beginning of this period was the scarcity of turbine blades. The manufacturers followed three strategies to overcome this problem (Karnøe, 1991):
- to manufacture their own blades, which is what Vestas did (as described above)
- to import blades from a foreign blade manufacturer, which is what Nordtank did
- to order blades from the newly established Danish blade manufacturer LM

LM developed new 11-metre and 12-metre blades for turbines with a capacity of 150-180 kW and 180-250 kW respectively (Karnøe, 1991). They used a newly developed blade profile, which had very good aerodynamic characteristics. The blades were designed for stall-regulated turbines, the traditional Danish regulation system.

Because all Danish manufacturers except two used the same blades manufactured by LM, their turbines remained very similar from a technical point of view: they continued to be stall regulated three-bladed upwind turbines (Karnøe, 1991).

4.8.5 Turbine demand from utilities

The main reason why the remaining firms were able to stay in business was the 100-MW agreement with the utilities. This agreement had been signed in 1985. Until 1988 the utilities were involved in developing organisational competencies and in identifying good sites for the erection of wind turbines. Local resistance made it difficult to find sites for the turbines. The prospect of a large home market enabled the remaining manufacturers to stay in business. Market stimulation policies in other European countries like Germany, Great Britain and the Netherlands, which started at the end of the 1980s, were likely to create a promising new export market and offer even better opportunities for the Danish manufacturers (Karnøe and Garud, 2001).

The lack of demand for turbines from 1986 until 1988 caused by the Danish utilities was an advantage for the manufacturers. It gave them more time to improve their wind turbine designs and to develop new concepts.

The utilities wanted larger turbine models, because they were thought to be more cost-effective and because they produced more electricity. This was the main reason for the fast development of 300-500 kW turbines in this period. The turbines bought by the utilities functioned well, although many of them had been developed quite recently. This improved the utilities’ opinion of wind turbines. It opened the way for learning by interacting between manufacturers and utilities. The utilities contributed their expertise in electrical-technical subjects and the financing and insurance of larger power production units to this learning process (Karnøe, 1991).

4.8.6 Good prospects for the turbine manufacturers

The year 1988 was a turning point for the Danish manufacturers. The utilities placed large orders and the technological developments had resulted in well-functioning,
cost-effective wind turbines that were able to compete with coal. Furthermore, exports increased, particularly because of a new export guarantee offered by the state. As a result of the technology development in the previous years, the Danish turbines had regained their relatively good name compared to turbines from other countries. Turbines were exported to other European countries, especially Germany and Spain, but also to California, India and China (Karnøe, 1991).

The new European markets were very different from the utility-dominated, large-scale projects in California. The European markets, called ‘extended home markets’, were characterised by widely dispersed wind turbines and small wind parks with tens of turbines averagely, as opposed to the 40-400 turbines in Californian wind parks. The European markets strongly resembled the Danish market (Gipe, 1995). This, and the fact that the European markets were nearer to Denmark in a geographical sense, made it easier for the Danish manufacturers to deliver to these markets than to the Californian market. Furthermore, the Danes applied what they had learned from their Californian experience and established subsidiary companies in many European countries, like Vestas Netherlands.

Environmental problems and the Chernobyl disaster in 1986 enhanced the legitimacy of wind energy in this period. In April 1990, the energy plan Energi 2000 was published. The plan emphasised the need for renewable energy. The overall objective of the plan was stabilisation of global CO₂-emissions by the year 2000 at the latest, and a 20% reduction by 2005. This objective was taken over from the 1988 UN conference on ‘The Changing Atmosphere’, which was one of the many follow-ups to the Brundtland report.

In Energi 2000, the following goal was formulated with regard to wind energy: 1,500 MW of wind turbine capacity was to be installed before 2005. This goal was to be met by way of agreements with the utilities. In 1990, the second 100-MW agreement was signed between the government and the utilities. The utilities were required by policymakers to make a sincere and long-term contribution to the establishment of a significant wind turbine capacity in Denmark, not just as turbine users, but as co-developers. Their continued participation in the wind turbine innovation system was essential. Their help was needed in order to further technology development and establish a further 100 MW of wind turbines before January 1st 1994 (Van Est, 1999).

However, the policy of reducing the investment subsidies for private and co-operatively organised wind turbine buyers was not changed. It was still argued that subsidies were no longer needed, since turbines had become cost-effective. Therefore, the demand from Danish private buyers and co-operatives, who traditionally had been the most important turbine owners, decreased in this period. In 1991, the investment
subsidies were abolished from one day to the next. A large number of orders were cancelled (Karnøe, 1991; Van Est, 1999).

The prospect of a continuing demand for turbines from the utilities offset the manufacturers’ problems caused by the decline in demand from private investors. The continuation of the utility market offered them the possibility of recovering the costs of the large investments they had made in terms of money, expertise, and time during the previous years when they had developed a range of utility-grade wind turbines. Figure 4.7 shows the development of cumulative installed wind turbine capacity in Denmark in the period 1986-1991. Table 4.8 depicts the newly installed capacity in the years 1987-1991, together with the percentage of this capacity owned by the utilities.

Figure 4.7: The development of cumulative installed wind turbine capacity in 1986-1991 (source: IEA, 1993).

Table 4.8: The newly installed capacity, per year, and the percentage of this capacity that is owned by the utilities32 (sources: Nielsen, 1993; Anonymous, 1993; Møller and Harrison, 1994).

<table>
<thead>
<tr>
<th>Year</th>
<th>Newly installed capacity (MW)</th>
<th>Percentage owned by utilities (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>40</td>
<td>13</td>
</tr>
<tr>
<td>1988</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>1989</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>1990</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>1991</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

32 See section 3.8.9 for the same table on the Dutch situation.
4.8.7 Siting problems

By this time, siting problems had worsened in Denmark. In the previous period, local inhabitants were often in favour of wind energy because they could reap the benefits, either because they were part-owners of the turbines or because the nearby turbine manufacturers provided job opportunities. In the case of large turbine parks owned by utilities, local benefits were absent. To overcome the siting problems, at the utilities’ request a special wind turbine siting committee was appointed by the government in 1991. This committee was responsible for finding sites for the second 100 MW utility programme and for recommending general siting rules. It estimated that in Denmark 1,000 to 2,800 MW of wind turbine capacity could be installed, taking into account local objections and the preservation of scenic areas. Because of the siting committee, most Danish counties included wind energy in their regional plans (Gipe, 1995).

The siting problems posed a new technological challenge to the turbine manufacturers: how to reduce the noise produced by the turbines. Furthermore, the large size of the new turbines caused new technical problems. Stall regulation, the traditional Danish form of power regulation, created problems when larger blades were used. Because the velocity of the blade tip is far greater than the velocity of the blade root in the case of large blades, it is very difficult to design blades that start to stall at the same moment at every point of the blade. Furthermore, foreign turbines showed that pitch regulation was more cost-effective. Therefore, many Danish companies started to experiment with pitch regulation. Vestas developed blades that were completely pitch regulated, and Danwin developed a combination of both regulations: stall regulation at ‘normal’ wind speeds and pitch regulation at very low or very high wind speeds (Karnøe, 1991). Vestas was very satisfied with pitch regulation, because this form of regulation enabled them to turn the blades into vane position when the wind was not blowing hard enough; this reduced the vibrations and loads and therefore increased the turbine’s life span (Karnøe, 1991). All these new technological developments made the Danish turbines more and more sophisticated.

Most Danish companies offered a range of turbines in this period: mainly two to five different generating capacities between 100 and 500 kW. Furthermore, some companies offered turbines with different rotor diameters for different wind regimes: relatively large rotors for inland sites and relatively small rotor for coast sites (Karnøe, 1991). In this way, buyers could obtain the most cost-effective turbine for a specific site. This clearly reflects the scarcity of good sites and therefore the need to adjust turbines as well as possible to the sites available. Here we have yet another example of the large influence that the Danish turbine buyers exerted on technology development.
4.8.8 Offshore wind energy

Another way to solve the siting problems was to erect wind turbines at sea. The Ministry of Energy set up a Committee for Offshore Wind Farms as early as November 1987, just after the first siting problems had arisen. This committee was to ensure the best possible start for wind energy offshore. In 1989, a suitable site for the first offshore wind park was located. The site was north of Lolland, near the town Vindeby. In the summer of 1989, the utility ELKRAFT declared that it was willing to construct the Vindeby offshore wind park as part of the first 100-MW agreement in order to gain experience in the field of offshore wind turbine installations. This wind park would be the first offshore wind park in the world. ELKRAFT decided that the turbine chosen for this wind park would be a commercially available wind turbine of proven standard. A call for tenders went out for a very corrosion-resistant wind turbine that was specially equipped for easy and cheap maintenance work offshore. In June 1990, Bonus was selected to build turbines for the wind park. Bonus would adapt its largest available wind turbine, a 450-kW turbine with a rotor diameter of 35 metres, to the tough weather conditions at sea (Van Est, 1999).

In mid-1991, the wind park was commissioned. It consisted of 11 stall-controlled wind turbines in two rows, with a combined generating capacity of 5 MW. The park was situated at a distance of 1.2 to 2.4 kilometres from the coast. The water depth at the site varied between two and six metres. The costs of the project, including a two-year measurement programme, were 80 million DKK (IEA, 1992).

4.8.9 The small-scale wind turbine innovation subsystem in 1986-1991

At the start of this period, many manufacturers disappeared from the subsystem because they went bankrupt. However, most of the knowledge and the employees remained in the subsystem, because they were taken over by other manufacturers. A number of manufacturers were able to start up again.

The number of foreign turbine buyers decreased, because the Californian subsidies had expired. The number of Danish private and co-operative buyers slowly decreased too, because of the step-by-step reduction in the Danish investment subsidies. Although an indirect investment subsidy and a relatively high buy-back rate were still available, many private and co-operative buyers decided not to buy a wind turbine because of the risk and/or the price. However, a new actor emerged in the subsystem: the Danish utilities. They became wind turbine buyers as a result of the 100-MW agreement they signed in 1985. After two years of hesitation, the utilities started to call for tenders for wind turbine parks. They played a more passive role in the
technology development than the private and co-operative buyers, but they did steer technology development by demanding new, larger wind turbines.

The insurance companies, many of which had lost their faith in wind energy in the mid-1980s, remained present in the subsystem and enabled the manufacturers to keep insuring their turbines and to stay in business. However, they demanded a change in the approval system for wind turbines; this changed the role of the Test and Research Centre within the subsystem. This Centre now started to play the role of a more formal approval agency. Tripod also remained active in the subsystem by producing more formalised knowledge.

The policy-makers played a more active role in the subsystem in this period. They signed the second 100-MW agreement with the utilities in 1990, requesting a sincere and long-term contribution from the utilities to the development of wind energy. Furthermore, they established the Wind Turbine Guarantee Company, in order to secure and safeguard further Danish wind turbine exports, and they started the development of the new approval system. Figure 4.8 depicts the small-scale wind turbine innovation subsystem in the period 1986-1991.

![Figure 4.8: The small-scale wind turbine innovation subsystem in the period 1986-1991.](image-url)
4.8.10 Conclusion

Let us now turn to the learning processes within the small-scale wind turbine innovation subsystem in this period. Learning by searching began to occur in a more formalised way in the subsystem. For example, on the basis of R&D Vestas developed a pitch control system. Whereas the stall control system had been imitated from previous designs, like the Gedser turbine, the pitch control system was completely new for the Danish manufacturers. Furthermore, after the Californian problems the Danish manufacturers started to use more formal R&D, based not only on previous experience but also on the newly developed more formal design calculations and models from the Test and Research Centre and Tripod. In the further upscaling of the turbines, the use of formal knowledge instead of trial-and-error methods became more and more important.

Learning by interacting remained important, but it became more formalised than in the previous periods. After the introduction of the new approval system, the Test and Research Centre started to function as a more formal approval authority, demanding formalised knowledge for the approval procedure. The role of learning by interacting with private and co-operative users decreased, because demand from this user group decreased. The turbines they bought were mainly smaller models, but many of the learning processes in this period were focused on the further development of the larger turbine models.

Learning by interacting with utilities became important in this period. The utilities were anxious for new, larger turbine models and steered the development efforts of the wind turbine manufacturers. The manufacturers, who had proved by 1998 that their turbines with operating capacities of around 300 kW functioned well and were cost-effective, used the design of these successful turbines for the development of larger models. Problems with the larger models were reported by the utilities and led to further adjustments, new design models and more calculations. The siting problems reported by utilities and local authorities triggered technology development: manufacturers started to improve the elegance and decrease the noise of their turbines.

4.9 1992 - 2000

4.9.1 Continuing stimulation measures from the government

In the 1990s, domestic demand for wind turbines was relatively low, especially as a result of the siting problems. The manufacturers actively sought foreign markets in order to increase their export of turbines. In 1995, turbines were sold to a large
number of countries, including Germany, Great Britain, Sweden, the Netherlands, the USA and China. In that year, the average Danish export share was 85% (Karnøe and Jørgensen, 1996).

The Danish government was of the opinion that domestic wind turbine sales still needed to be supported, by way of industrial policy and by way of energy policy. It was important to keep stimulating the demand for wind turbines. In 1992, the Wind Turbine Law was enacted. It stated that utilities had to pay all the expenses for reinforcement of the grid in connection with the erection of wind turbines, but the expenses of connecting the turbine to the public grid were to be paid by the turbine owners (Van Est, 1999). Furthermore, all utilities had to keep buying electricity generated by independent electricity producers at a rate a 85% of the electricity price.

In 1994, the government relaxed the conditions under which profits from investments in wind energy were tax-free. Before 1994, all the participants in a wind project had to live near the turbines. From 1994 on, only half the participants had to live near the turbines. Furthermore, the maximum share of a participant in a wind project was raised from 9 MWh to 20 MWh a year (Van Est, 1997). Thirdly, turbine owners who replaced an older model with a new one could get a reimbursement of 15% of the value of the old turbine. In this way, the total generating capacity of wind turbines in Denmark could be increased without the need to solve siting problems. The government still forced municipalities to find locations for wind turbines, but the siting problems remained. In 1993, the Siting Committee had sent out a circular in which it required the municipalities to indicate sites where wind turbines could be placed. However, a weak point was that the government had added the clause that municipalities did not have to take action if no space could be found. Therefore, the siting problems were not solved by this circular (Van Est, 1997). In the same year, a majority in the Danish parliament voted for a payback rate of 60 øre per kWh and for a more streamlined programme to regulate the connection of wind turbines to the electricity grid (Van Est, 1997).

In 1996, again new rules came into force. The maximum share of a participant in a wind project was further enlarged from 20 MWh to 30 MWh. Furthermore, the residence criterion was relaxed: from then on, a person who worked in a firm or owned a house or real-estate in a municipality had a right to take part in a wind project in that municipality, even if he lived elsewhere (Van Est, 1997).

In the same year, the Executive order was issued concerning the grid connection of wind turbines (Van Est, 1997). According to this order, utilities were obliged to provide grid connection facilities at any site which municipal planners had set aside for the erection of at least 1.5 MW of wind turbine capacity. If the planned turbine
capacity was lower than 1.5 MW, utilities were obliged to provide access to the local 11-20 kV grid, but the turbine owner was responsible for paying for the extension of the grid needed to reach the site. However, if the cabling could be used for other purposes during the normal extension of grid facilities, the utility had to pay for the entire grid extension. If the grid had to be reinforced, this also had to be paid by the utility, unless the utility could prove that the reinforcement in the area would be very uneconomic. In spite of all these measures, turbine demand from private persons and co-operatives did not return to its previous level (Van Est, 1997).

4.9.2 Turbine demand from the utilities

In this period, turbine demand from the utilities grew, as a result of the second 100-MW agreement, although not as much as expected. In 1992, only about 14 MW was installed, and in 1993 only 5 MW. By the end of 1993, the total wind turbine capacity owned by the utilities had grown to 110 MW, instead of the 200 MW they had agreed upon (IEA, 1994). The major cause was the siting problem. The utilities did not feel responsible, since they had entered the second 100-MW agreement under the condition that the government would ensure that sites were available (Van Est, 1999). However, since demand from private investors declined further, the utilities’ share of wind turbine capacity in the country grew considerably in the 1990s. Whereas in 1987 the utilities owned less than 5% of the total turbine capacity, the percentage increased to 30% in 1990 and about 34% in 1996 (Heymann, 1998).

In this period, the role of the utilities within the small-scale wind turbine innovation system became very different. Whereas in the previous periods, the utilities had played a somewhat passive role, their role became more active in the 1990s. Turbine demand from utilities became larger than demand from private persons and co-operations. Negotiations between energy agencies and utilities continued in order to determine the utilities’ future role in the development of wind energy. Joint private and utility ownership of wind turbines became possible. In addition, the utility trade association formed its own subsidiary to deploy its wind energy competencies as an exporter of wind energy and a wind park operator (Karnøe and Garud, 2001).

Furthermore, the utilities changed their strategy and began purchasing the cheapest large proven commercial wind turbines available on the market (Van Est, 1999). In the previous period, they had often bought the largest available wind turbines, but these were often prototypes or not sufficiently proven commercial turbines. By erecting the largest wind turbines they saw an opportunity to fulfil the agreement in the fastest way. However, they knew from experience that buying prototypes might mean high operating costs, because the turbines had not been sufficiently tested. Buying proven commercial wind turbines proved to be cheaper and less risky. Figure
4.9 shows the development of the cumulative installed wind turbine capacity in Denmark in the period 1992-2000.

![Cumulative installed capacity 1992-2000](image)


### 4.9.3 A changing role for the Test and Research Centre

In this period, the relationship between the Test and Research Centre and the turbine manufacturers had become very different from the relationship in the early 1980s. This was partly the result of a slow change over the years, and partly the outcome of the introduction of the new approval system. The main changes in this relationship were the following (Dannemand Andersen, 1993):

- The interaction had slowly become professionalised and formalised, both with respect to research and to approval regulations.
- Before the introduction of the new approval system, research and regulation were closely connected. After the new approval system had been introduced, these two functions became far more separated.
- Before the introduction of the new approval system, approval was based mainly upon assessments. The assessment procedure was slowly changed into a more formal approval base and more formal procedures.
- Before, most research was based upon experience-based competence building, which resulted in large improvements in the cost-effectivity of the wind turbines. In this period, it was far harder and more expensive to carry through this kind of improvement. This was not possible without more science-based research and formal mathematical models. An example of this more science-based research by the Test and Research Centre was the research into a small two-bladed turbine. This research was started because two-bladed turbines were in use all over the
world and the Danes did not have any experience with them, because since the
1970s they had built only three-bladed turbines. The turbine that was investigated
was very sophisticated: it was very flexible, had a downwind rotor and free
yawing (IEA, 1995).33

- Before, informal interactions played the largest role in the exchange of
information between the Test and Research Centre and the manufacturers. In this
period, the licensing and insurance authorities asked for a more formal method of
knowledge transfer, via channels that could be documented.

### 4.9.4 Offshore wind energy

The Vindeby wind park functioned very well. Electricity production was about 60% higher than on comparable land sites (IEA, 1995). The Test and Research Centre performed a measurement programme. As a part of this programme, wind conditions and turbulence at the offshore location were mapped (IEA, 1995).

In 1995, the second offshore wind park was built, in the Kattegat Sea, three kilometres off the Danish coast. It was called the Tunø Knob wind park and was built by the utility ELSAM. It consisted of 10 Vestas 500 kW pitch controlled wind turbines (IEA, 1995). Like the Bonus turbines at the Vindeby wind park, these Vestas turbines were well-proven and commercially available. They were modified for the marine environment, in that each turbine was equipped with an electrical crane so that major parts such as generators could be replaced without the need for a floating crane. Furthermore, the gearboxes were modified to allow a 10% higher rotational speed than on the onshore version of the turbine. This would produce more noise, but that would not be a problem at sea. The total costs were 87 million DKK (IEA, 1995). The wind park performed extremely well, and production results were substantially higher than expected. In the late 1990s, the Danish utilities announced major plans for the installation of up to 4,000 MW of wind turbines offshore as from the year 2000 (Windpower, 2001).

### 4.9.5 Technology development

Besides developing offshore turbines, the Danish manufacturers continued their slow scaling up of onshore turbine models. By 1994, 600 kW turbines were commercially available. In 1994, Bonus installed a newly developed 750 kW turbine with a 50 metre rotor diameter at Tjæreborg. This turbine was the first Bonus turbine equipped with pitch control (IEA, 1995). The reason for this change in power control philosophy was that stall control had proven to be far more difficult when a turbine

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33 So far, neither this design principle nor ideas from it have been taken over by any Danish manufacturer.
had very large blades. Also, pitch control yielded higher power production. In 1995, the Bonus 750 kW turbine suffered from overspeeding, which caused serious damage to the rotor (IEA, 1997). The reason for this problem was the newly developed pitch control system. Failures in the pitch bearings prevented the blades from moving to the stop position. The design was improved and scaled up to 1 MW (IEA, 1997; Danish manufacturers, a.n.).

After they had signed the second 100-MW agreement, the utilities asked for tenders for 1 MW turbines (IEA, 1993). Many manufacturers therefore started scaling up their turbines to megawatt-size. As from the mid-1990s, the first megawatt wind turbines were built. In 1995, the prototype of the NEG Micon 1.5 MW turbine was commissioned. It had a 60 metre rotor and two 750 kW generators operating in parallel, which meant that the turbine could also operate at a power capacity of 750 kW, using only one generator. It was upgraded to a 64 metre rotor (IEA, 1996). In 1996, Vestas commissioned a 1.5 MW turbine. It had a 63 metre rotor and a 1.5 MW generator (IEA, 1997). The second version had a 68 diametre rotor and a dual 1.65 MW / 300 kW generator (Danish manufacturers, a.n.).

In 1997, developments focused on refining the existing 500-600 kW turbines and improving the MW-turbines (IEA, 1998). Refining the existing turbines included improving them and slowly scaling them up, thereby creating a range of turbines with different power capacities and rotor diameters, suitable for sites with different wind regimes. The manufacturers used the platforms of their 500 kW turbines as a starting point. Since the platforms on which the main axis, the generator and the rotor are assembled take a long time to construct and are expensive to design, the manufacturers’ design philosophy was based on making variations on the same platform (Van Kuik, 1999). Making use of its 500 kW platform, NEG Micon developed a 750 kW turbine with a 44 metre rotor diameter and a 600 kW turbine with an 48 metre rotor diameter for sites with low wind speeds (IEA, 1998). Vestas upgraded its 600 kW turbine to 660 kW with a 46 metre rotor and its 1.5 MW turbine to 1.65 MW. Wind World announced the development of a 2.5 MW turbine, jointly financed by the European Union (IEA, 1998).

Although most of the turbines sold were still the well-functioning and well-proven turbines in the capacity range of 600-750 kW, the market for megawatt-turbines took off in 1998. Megawatt-sized machines were considered to be ideal for offshore applications and for areas where space for siting was scarce (Windpower, 2001). Bonus commissioned a 2 MW turbine in 1998. It had a 72 metre rotor diameter and had active stall power control, which meant that the blades could be pitched into the stall position. In 1999, NEG-Micon commissioned a 2 MW turbine, with a 72 metre rotor diameter. Its predecessors, up until the NEG-Micon 1.5 MW turbine, all had stall
control, in accordance with the traditional Danish control philosophy. The 2 MW turbine had active stall power control, like the Bonus 2 MW turbine. In the year 2000, Nordex commissioned the prototype of its 2.5 MW turbine. It had a rotor diameter of 80 metres. The turbine had pitch control (Windpower, 2001).

Clearly, the Danish manufacturers had to change their philosophy in this period. The trial-and-error approach did not work any longer when MW-size wind turbines were being built. Therefore, sophisticated turbine design models and programmes, developed by the Test and Research Centre and other research organisations, were used for the new turbines. Furthermore, the traditional Danish stall regulation was no longer considered as the best solution. As mentioned above, large blades presented problems; it was difficult to design them in such a way that every part of the blade started to stall at the same moment. Furthermore, pitch-controlled turbines from foreign manufacturers were found to yield higher energy production. Therefore, many Danish turbine manufacturers started using pitch systems in which the blades are rotated into vane position, or they used an active stall system in which the blades are rotated into stall position. The turbine manufacturers who did not proceed to pitch regulation started introducing incremental innovations into the stall regulation. For example, they borrowed the principle of vortex generators from the aircraft industry (Boersma, 2000). These vortex generators are small strips, attached to the blades, that can postpone the moment when the blades start to stall, thereby increasing the energy production (Windpower, 2001).

4.9.6 The small-scale wind turbine innovation system in 1992-2000

The increasing siting problems, severely inhibiting turbine sales in this period, forced the policy-makers to play an even more active role in the subsystem. The residence criterion was relaxed twice and utilities were forced to improve grid facilities. These measures were aimed at increasing turbine demand from private and co-operative customers. However, their demand did not grow much in this period. Demand from the utilities and therefore their role in the subsystem did grow in this period. Although the utilities worked more slowly than expected, they erected wind turbine parks with relatively large turbines, thereby increasing the total turbine capacity in the country at a fast pace. They avoided the siting problems by starting to erect wind turbine parks at sea.

The role of the Test and Research Centre within the subsystem changed further in this period; it had started by being a co-operating 'partner' in technology development, exchanging knowledge with the manufacturers mainly during informal interactions, but it had now become a more formal research and approval authority. Furthermore, the Centre started doing science-based research, e.g. into a model of a flexible turbine
with a passive yaw system. Figure 4.10 shows the small-scale wind turbine innovation subsystem in the period 1992-2000.

![Diagram of wind turbine innovation subsystem]

**Figure 4.10**: The small-scale wind turbine innovation subsystem in the period 1992-2000.

### 4.9.7 Conclusion

What can be said about the learning processes in this period? Learning by searching became more important, since formal R&D was required for the design of the large MW-turbines, mainly because trial-and-error learning had become far too risky and expensive, but also because many manufacturers introduced new features in their turbines in this period. An example of a new feature was the pitch control system, which was used by more and more turbine manufacturers, in order to improve power control and to increase energy output. For the development of their pitch control system, the manufacturers could not rely on experience from the past, but had to perform R&D. Furthermore, the formalised results of this R&D were required as input for the new approval procedure. The Test and Research Centre also started learning by searching in this period, in that it did research into a theory-based design of a flexible wind turbine.

Learning by interacting between turbine manufacturers on the one hand and turbine users and the Test and Research Centre on the other hand remained important, but was not as important as in the previous periods. The interactions were more formal and
knowledge from the Test and Research Centre was transferred to the manufacturers in a more formalised way, e.g. via scientific reports or design models. Operational experience obtained with the megawatt and offshore turbines was transferred from the utilities, who owned the turbine parks, to the manufacturers. This experience was used as input for further turbine refinement and upscaling.