Chapter 2

Electrical Power from the Wind - The First Attempts

Large-scale utilisation of electricity started with the construction of the first power plants. The world's first power plants were built in New York with a power output of about 500 kW (in 1882) and in Berlin (1884) [1]. Three-phase current was introduced as early as 1891. Power plant technology evolved rapidly and produced ever-increasing power outputs. By the beginning of the twentieth century, almost all large cities in the industrialised countries were supplied with electricity.

Electrification of the rural areas took place at a considerably slower pace. The necessary preconditions were only created by the interconnection of various types of power plants and the setting up of extensive transmission networks. Whereas in Europe and particularly in Germany, this development reached almost the remotest village by the twenties, the opening up of the rural areas in the large territorial states required enormous efforts. In the USA, the large regions of the West were supplied with electricity as late as 1932 in the so-called "Rural Electrification Programme".

The first attempts to generate electric current with the help of wind power were being made in that period of time when the large cities were already being supplied with electricity, but complete coverage of users in rural areas was not yet feasible. The spread of traditional windmills in Europe and of wind turbines in America was still nearly at its peak. It was probably inventive do-it-yourself enthusiasts in America who were the first to try to drive electric "dynamos" with their wind turbines which were actually designed for pumping water. However, the first systematic development aimed at utilising wind power for the generation of electricity took place in Denmark.

2.1 Poul La Cour - A Pioneer in Denmark

Like no other, the name Poul La Cour marks the turning-point from historical windmill building to the modern technology of power generating wind turbines (Fig. 2.17). His is the merit of perfecting traditional windmill technology on the basis of the scientific principles worked out by him, and he was a pioneer of electricity generation by means of wind power - all this in the nineteenth century [2].

Poul La Cour was a professor at an adult education centre in Askov. Encouraged by the Danish government which was looking for ways of supplying also Denmark's rural areas with electricity, La Cour built an experimental wind turbine driving a "dynamo" in 1891 (Fig. 2.1). The remarkable fact is that he also at once tackled the problem of energy storage. He used the direct current generated by his wind turbine for electrolysis and stored the hydrogen gas thus produced. From 1885 to 1902, gas lamps using this method illuminated the school grounds in Askov.

As far as the wind wheel was concerned, La Cour's electricity-generating wind turbine strongly followed the model of the traditional windmills. Although he was well aware of the advantages of aerodynamically shaped windmill sails, he used a rotor with four shutter sails. He knew that this technology could be managed much better in the country.

In the subsequent years La Cour expanded his activities in Askov to establish a well-equipped test station for wind turbines. He was possibly the first to carry out tests in a wind tunnel, which he had built himself, and he set up a second, larger test station in 1897. In his book "Porsogsmellen", published in Copenhagen in 1900, he reported on this work [3]. In 1903 La Cour founded the Association of Danish Wind Power Engineers (DVES) which, among other things, offered training courses for "wind electricians".

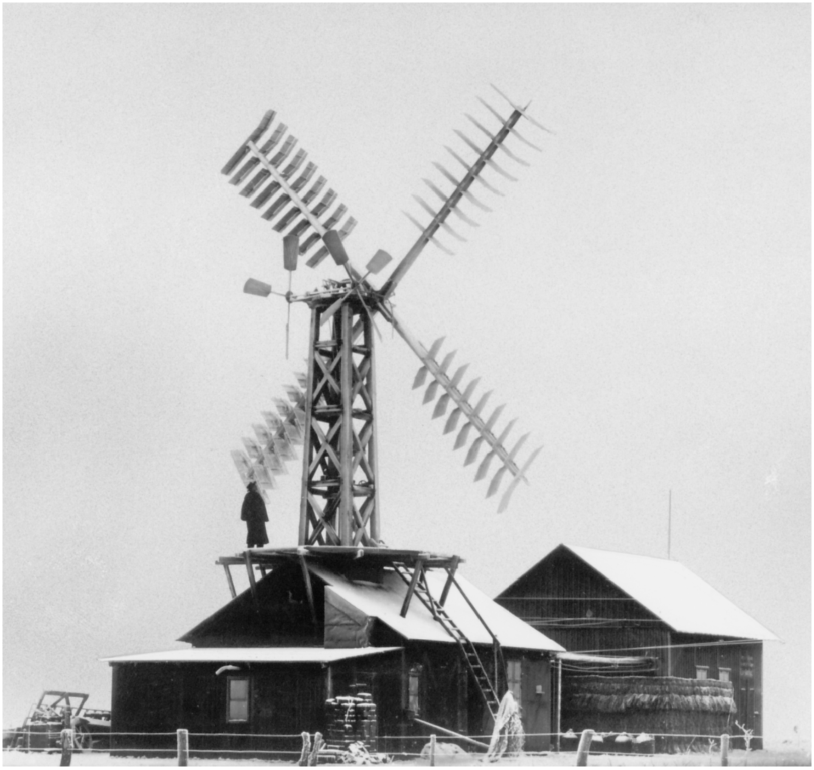


Fig. 2.1. Poul La Cour's first electricity producing wind turbine in 1891 in Askov, Denmark [1]

The extent of La Cour's success became apparent when the Lykkegard company began with the industrial utilisation of his developments. By 1908, it had already built 72 electricity-generating wind turbines, modelled after the test station at Askov, which supplied power to rural settlements. This development was accelerated by the dramatic rise in fuel prices during World War I, so that by 1918, about 120 wind turbines were in operation [4].

One of the main technical reasons for this success of wind power utilisation for the generation of electricity was the fact that many rural areas of Denmark were supplied with direct current even after World War II. Operating a wind turbine in parallel with diesel- or gas-engine-type power stations generating direct current was technically easier than with alternating current.

The La-Cour-Lykkegard turbines were built in various sizes with power outputs ranging from 10 - 35 kW. The rotor, with a diameter of up to 20 m, had four shutter sails, making it possible to remain below a certain rotational-speed limit. Yawing was carried out by two fantail type side wheels. The electrical generator was installed at the base of the latticed steel tower and was driven by the rotor via a long shaft and intermediary gearbox. Electricity was fed into the small isolated consumer grids via a buffer battery (Fig. 2.2).

These grids were fed by diesel- or gas-engine generators and supplied larger farms or small settlement areas. The overall efficiency of the wind turbines was indicated to be about 22 %. At a good site, the annual energy yield amounted to about 50 000 kWh.

The operational experience gained with these wind turbines was analysed in depth later on behalf of the "Reichsarbeitsgemeinschaft Windenergie" (Working Group Wind Power of the German Reich) [4]. It turned out that their reliability was normally extremely high. There are reports of wind turbines of this type, which were operated between 1924 and 1943, where the bearings and gears had to be replaced for the first time after 20 years of operation.

In Denmark, interest in the generation of electricity by means of wind power waned after World War I. Diesel fuel was relatively inexpensive during this period. However, the situation changed again with the outbreak of World War II. Fuel prices soared and immediately the interest in using wind power for the generation of electricity was reawakened. Lykkegard wind turbines which had been closed down were taken into service again and several new ones were built.

In addition to the La Cour concept, which was somewhat outdated by now, a new manufacturer entered the market with more modern designs. The F.L. Smidth company, a manufacturer of machines for the production of cement whose entire export market had collapsed due to the events of the war, turned to building wind turbines [5]. Using the name of "Aeromotor" for their design, Smidth started by developing a wind turbine with a rotor diameter of 17.5 m and a power output of about 50 kW at a wind speed of approx. 11 m/s. The aerodynamic design of the rotor with two profiled rotor blades made of laminated wood was in keeping with the state-of-the-art achieved in the meantime. The two-bladed rotor was designed for a tip-speed ratio of about 9. The rotor blades had no twist and could not be pitched. Speed was limited by an aerodynamic brake. Twelve wind turbines of this type were built, some with a lattice steel tower (Fig. 2.3), the majority with concrete towers (Fig.2.4).

Fig. 2.2. La-Cour-Lykkegard wind turbine in Denmark. (rotor diameter 18 m, approx. 30 kW power output at 12 m/s wind speed) [4]

Problems with the dynamic characteristics of the two-bladed rotor caused the company to develop a second, larger type with three rotor blades (Fig. 2.5). With a rotor diameter of 24 m, it yielded a power output of about 70 kW at a wind speed of about 10 m/s. Seven wind turbines of this type were built, all of them with concrete towers.

Except for one, all Smidth Aeromotors were equipped with DC generators. Many of the features of their aerodynamic and mechanical design are typical of the "Danish line" to the present day. It can be rightly stated that in the first half of the 20th century, electricity generation from wind power was already more than an experiment in Denmark. Even if, measured against the total electricity generation, the proportion of "wind electricity" will have been a matter of only a few percent, in some areas at least electricity from wind power was a first solution for supplying electric energy.

Fig. 2.3. Smidth "Aeromotor" (rotor diameter 17 m, rated power approx. 50 kW), 1941 [5]

Fig. 2.4. Smidth "Aeromotor" with concrete tower (rotor diameter 17 m, rated power approx. 50 kW), 1942 [5]

Fig. 2.5. Smidth "Aeromotor" with three-bladed rotor (rotor diameter 24 m, rated power approx. 70 kW), 1942 [5]

2.2 Large Wind Power Plants - Ambitious Projects in Germany

In Germany, the first attempts of using wind power for the generation of electricity go back to before World War I. Some companies, Köster and Hercules among others, manufactured American wind turbines under license. Until the thirties, a total of 3600 wind turbines were built in Germany by about ten manufacturers. Most of these were used for pumping water, their intended purpose, but some of them were modified for the generation of electricity.

After World War I, Major Kurt Bilau tried to develop electricity-generating wind turbines based on more advanced technical concepts. Bilau recognised that the American low-speed rotor did not have the appropriate characteristics. His "Ventimotor", with a four-bladed rotor and higher tip-speed ratio, was one of his first attempts. Bilau described his results in two books and thus contributed not inconsiderably to the idea of also utilising wind power for generating electricity in Germany [6]. However, physics was not one of his strong points. In his second book, which was published in 1942, he still tried to prove that his Ventimotor, with its "streamlined" airfoils, could achieve a higher power coefficient than the maximum value of 0.593, which had been calculated by Betz in the meantime [7].

In Germany, however, the decisive impulse came from the theoretical camp. Against a background of aircraft aerodynamics, the physicist Albert Betz, director of the Aerodynamische Versuchsanstalt (Aerodynamic Research Institute) in Göttingen, approached the problem of the wind rotor's physics and aerodynamics from a strictly scientific point of view (Fig. 2.17). In an article published in the "Zeitschrift für das gesamte Turbinenwesen" (Journal of Turbine Science) in 1920, he proved that the maximum physically possible utilisation of the wind by a disk-shaped, turbine-like wind energy converter is restricted to 59.3 % of the power contained in the air current [8]. In his book "Windenergie und ihre Ausnutzung durch Windmühlen", which was published in 1925, he summarised the results of his research and formulated a theoretical basis for the aerodynamic shaping of wind rotor blades [9]. The theory has been was completed by H. Glauert shortly after Betz's publication and has kept its validity to the present day [10]. This theoretical basis now permitted modern high-speed wind rotors to be calculated reliably. In addition to the principles of aerodynamics, advanced lightweight design principles in aircraft engineering were also developed in the twenties which was also an important prerequisite for implementing large rotors.

One of the first to work with these new scientific findings was the steel construction engineer Hermann Honnef who developed concepts for absolutely gigantic wind power plants (Fig. 2.6). Colossal lattice towers were to have carried up to five wind rotors, each with a diameter of 160 m and a power output of 20 000 kW. These wind rotors were to consist of two concentric contra-rotating wheels. In order to provide the necessary rigidity, the very slender rotor blades were configured as "double spokes" in the inner area. The two contra-rotating rotors each bore a metal ring with a diameter of 121 m. These two contra-rotating rings formed a so-called "ring generator", with one ring acting as the pole ring and the other as armature ring. In cases of extreme wind speeds, the upper part of the lattice tower, which carried the rotors, was intended to tilt into an inclined position and eventually to a horizontal position.

In retrospect, it must be noted that Honnef's plans were indeed based on mathematical and engineering principles [11]. Their realisation would, however, have most certainly caused considerably more problems than Honnef imagined in 1932. It is, therefore, less the technical concept which is fascinating about Honnef's plans but the idea in itself. Honnef wanted to utilise wind energy on a large-scale technical basis. It was no longer the idea of supplying remote farms with electricity which inspired him, he wanted to build large "wind power plants" which were to generate electricity in combination with conventional power plants at an economical price. In this respect, Honnef was a pioneer of the large wind turbines.

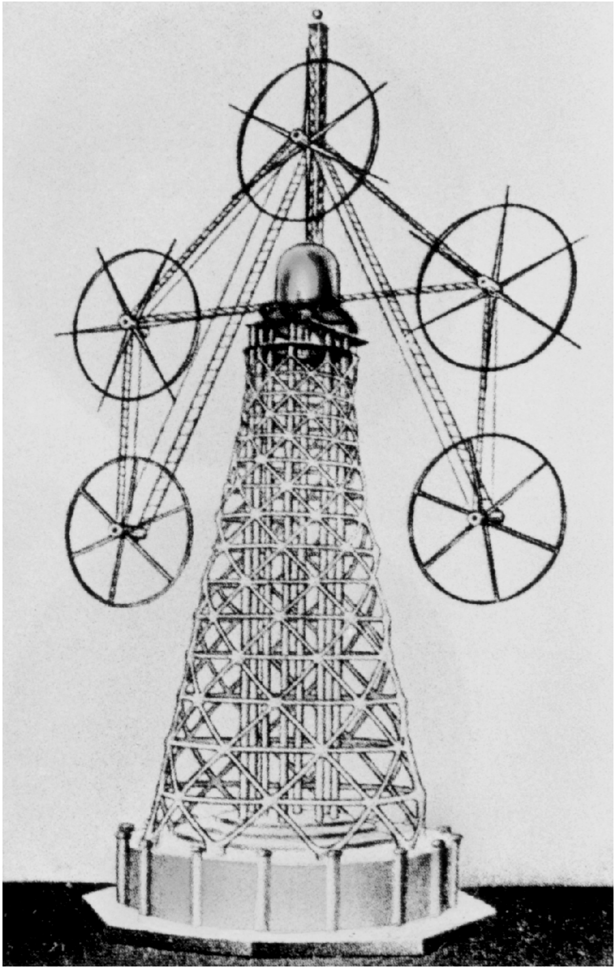


Fig. 2.6. Vision of a large wind power plant by Hermann Honnef: 5 rotors, each with 160 m diameter and 20 000 kW power output; tower height 250 m, 1932

In the years from 1930 to 1940, Germany saw much theoretical and design activity in the field of wind power technology. The motivation behind this was in part certainly the striving by the German Reich for self-sufficiency in the supply of fuel and power. In 1939, the "Reichsarbeitsgemeinschaft Windkraft", RAW, was formed, where renowned scientists, technicians and industrial firms worked together. The RAW supported numerous projects and published their results in so-called "memoranda".

Among the projects on which the work of the RAW was concentrated, one deserves special mention. In 1937, the engineer Franz Kleinhenz published plans of a large wind turbine project [12]. Unlike Honnef, Kleinhenz knew how to win the co-operation of renowned scientists and industrial firms. His plans took shape in co-operation with the Maschinenfabrik Augsburg-Nürnberg (MAN). His concept was improved and refined in many details in a number of stages from 1938 to 1942 (Fig. 2.7). Even today, the technical data of the MAN-Kleinhenz project convey an impression of advanced technology:

- 130 m rotor diameter,
- three or four rotor blades,
- 10 000 kW rated power,
- tip-speed ratio of 5,
- rotor positioned upwind,
- 250 m hub height,
- directly driven generator with a diameter of 28.5 m or several generators via a mechanical transmission,
- tower as guyed tubular steel tower, upper part yawing with the rotors.

By 1942 the project was ready for implementation, but the war prevented its actual construction.

Fig. 2.7. Project MAN-Kleinhenz (rotor diameter 130 m, rated power 10 000 kW), 1942

While Germany was busy mainly with theories and great plans in the thirties, some pioneers set to work in another country. In 1931 a large wind turbine was built in the

USSR in Balaklava, not far from Yalta on the Crimean peninsula (Fig. 2.8). The wind turbine with the name WIME D-30 had a three-bladed rotor with 30 m diameter and a generator rated power of 100 kW. The rotor speed was regulated with the aid of control flaps. Yawing was carried out by moving the entire wind turbine on a circular rail track [13].

This wind turbine was operated from 1931 to 1942 and was said to have operated comparatively reliably. The electricity it generated was fed into a small grid, which was supplied by a 20 MW steam power station. A second, similar wind turbine with the name of ZWEI D-30 was installed a few years later on the coast of the Arctic Ocean. It had a conventional tower and a yawing system with two fantails.

The apparently good results of these experimental turbines encouraged the builders to design a 5000-kW wind turbine with a rotor diameter of 100 m. Similar to the MAN - Kleinhenz project, however, these plans, too, fell victim to the war.

Fig. 2.8. Russian wind turbine WIME D-30 in Balaklava on the Crimea (rotor diameter 30 m, rated power approx. 100 kW), 1931

2.3 1250 kW from the Wind - The First Large Wind Turbine in the US

A decade before the beginning of the rural electrification programme, first efforts were made in the US to develop advanced electricity-generating wind turbines. As the declared aim was to supply power to those private consumers who were not yet connected to the public utility grid, development was concentrated on small wind turbines with rated powers of a few kilowatts. These small wind turbines, which became known as "wind chargers", were used for recharging batteries and thus provided a modest power supply for rural settlements and remote weekend houses.

The brothers Marcellus and Joseph Jacobs deserve special mention here. In 1922, they started to develop a small wind turbine [14]. After initial tests with two-bladed aircraft propellers, they developed a three-bladed rotor with a diameter of 4 m, which directly drove a low-speed DC generator (Fig. 2.9). This Jacobs "wind charger" proved to be a vanguard design and a sensational sales success. From 1920 to 1960, tens of thousands of these wind turbines were produced in various versions from 1.8 to 3 kW rated power. They won wide acclaim for their reliability and low maintenance requirements. One of these wind turbines was taken along by the American Admiral Byrd in 1932 on his expedition to the Antarctic and operated without maintenance for more than 22 years until 1955.

Fig. 2.9. Jacobs "wind charger" (rotor diameter about 4 m, rated power 1.8 to 3 kW), 1932

As the electricity supply of the rural areas no longer presented a general problem, plans were made in the USA to deploy large wind turbines within the public utility grid, interconnected to conventional power plants. The American engineer Palmer Cosslett Putnam (Fig. 2.17) must be given the credit of being the first to implement these plans. In 1940, he approached the S. Morgan Smith Company, a water turbine manufacturer in York (Pennsylvania), with his concept and some ideas of the technical design of a large electricity-generating wind turbine. Morgan Smith entered into a contract with the Central Vermont Public Service Company concerning the erection of a wind turbine based on Putnam's plans.

Palmer C. Putnam won over renowned scientists and technicians of the Massachusetts Institute of Technology (MIT) to cooperate in this project. Among others, Theodore von Karman was responsible for the aerodynamic design of the rotor. In October 1941, the turbine was installed on Grandpa's Knob, a hill in the state of Vermont. It was the world's first really large wind turbine as proven by the technical data (Fig. 2.10):

- 53.3 m rotor diameter,
- 1 250 kW rated power,
- 35.6 m tower height.

The two-bladed rotor with stainless-steel rotor blades was positioned downwind from the lattice tower. The rotor blades were connected to the rotor shaft via flapping hinges in order to reduce the dynamic loads caused by wind gusts. The speed and power output of the wind turbine were controlled by an hydraulic blade-pitching mechanism. Electricity was generated by a synchronous generator with 1250 kW rated power.

The Smith-Putnam wind turbine operated for about 4 years and fed electricity into the utility grid of the Central Vermont Public Service Company for about one thousand operating hours until March 26, 1945, when a rotor-blade fracture interrupted its operation.

This structural weakness at the blade root had in fact been detected by technicians at an early stage, but, due to a lack of funding, no preventive repair was carried out. The later repair was also not carried out for the same reason and the turbine was disassembled.

In the course of the project, Putnam undertook detailed investigations with regard to a later series production of his wind turbine and he compiled these in 1947 in his still highly readable book "Power from the Wind" [15]. Due to his earlier experience, he first tackled the question of the economically optimal size of a wind turbine and drew the following conclusions:

- rotor diameter 175 - 225 feet (53.3 - 68.5 m),
- tower height 150 - 175 feet (45.7 - 53-3 m),
- generator power 1 500 – 2 500 kW.

These results, achieved by Putnam in 1942, are remarkable when compared with currently prevailing opinions, even the size of the latest wind turbines is increasing more and more.

Fig. 2.10. Smith-Putnam wind turbine, in Vermont, USA. (rotor diameter 53.3 m, rated power 1250 kW), 1941 [15]

Putnam proposed to the S. Morgan Smith Company a pre-production model with a rotor diameter of 200 feet (60.69 m) producing a power output of 1500 kW. The technical concept largely corresponded to that of the experimental turbine, but the design had been improved in many details, above all from the point of view of reducing the manufacturing costs. Based on a series of 6 to 10 wind turbines, economic calculations yielded specific investment costs of 190 Dollars/kW (1945). The utility company, in contrast, calculated with economically affordable specific costs of 125 Dollars/kW, based on the then electricity-generation costs of 0.6 Cents/kWh and, as a result, no further wind turbines were manufactured. In 1945, therefore, the Smith-Putnam wind turbine was off the mark by a factor of 1.5 with respect to economic efficiency.

2.4 Wind Turbines in the Fifties - Before the "Energy Crisis"

After World War II, the prices of the primary fuels coal and oil dropped again and a period of extremely cheap oil imports began. The availability of fuels for the generation of electricity was no problem at all. The subject of environmental protection had not yet been thought of and if so, not in connection with the production of electricity. Nevertheless, attempts at generating electrical power by means of wind turbines continued in the fifties in some places, after the shortages of the first post-war years had been mostly overcome.

In England, the John Brown Company erected an experimental wind turbine on the Orkney Islands in 1950 for the North of Scotland Hydroelectric Board (Fig. 2.11). However, the three-bladed wind turbine with a rotor diameter of 15 m and a rated power of 100 kW was not a success and its interconnected operation with the diesel power station on the Orkney Islands lasted only a few months. The main technical reason for the failure was probably the complex rotor design, with blades connected to the shaft via flapping hinges and drag hinges.

At about the same time the Enfield Cable Company also built a 100-kW wind turbine in England, based on the plans of the French engineer Andreau (Fig. 2.12). The Andreau-Enfield wind turbine is based on a technical concept which has maintained its uniqueness to this day [16]. Instead of the usual mechanical gearbox for connecting the rotor directly to the generator, Andreau thought up a pneumatic power transmission system. Air, which was sucked in at the base of the hollow tower, flowed through the tower and hollow rotor blades, and being submitted to centrifugal forces, left the rotor blades at the blade tips. This caused a fast-moving air stream in the tower, which drove the generator via an air turbine in the tower.

However, although this method avoided the problematic fixed-speed connection of the rotor to the generator, it was not convincing in its overall efficiency which, at about 20 %, was uneconomically low when measured against the construction costs. The wind turbine was first set up in St. Albans (Hertfordshire) in 1951, but was dismantled again due to the unfavourable site. In 1957, it was set up again for a short period of time in Grand Vent (Algeria), but obviously no detailed testing was carried out. At that time the public interest in wind energy utilization disappeared and the promoters could not rise more funds for their experiments.

Fig. 2.11. Wind turbine of the John Brown Company on the Orkneys. (rotor diameter 15 m, rated power 100 kW), 1950 [16]

Apart from the French engineer Andreau, who implemented his ideas in England, a number of other engineers in France worked on designing larger wind turbines [16]. In 1958 Romani built a large experimental wind turbine in Nogent le Roi near Paris with the support of the public utility company "Électricité de France" (EdF) (Fig. 2.13). The Best-Romani wind turbine had a rotor diameter of 30.1 m and operated with a synchronous generator with 800 kW rated power. It was tested until 1963 and dismantled after some blade damage had occurred.

In parallel with this project, Louis Vadot developed two wind turbines which were set up in Saint-Remy, France, on the coast of the English Channel. Vadot started out with a smaller wind turbine with a rotor diameter of 21.1 m and a rated power of 132 kW (Fig. 2.14). A larger wind turbine with a rotor diameter of 35 m and an installed generator power of 1000 kW followed which was based on the same technical concept. Both wind turbines had induction generators. Operational experience with these two wind turbines is said to have been comparatively good [16]. However, both wind turbines were dismantled in 1964 and 1966, respectively, as the EdF was no longer interested in the utilisation of wind power.

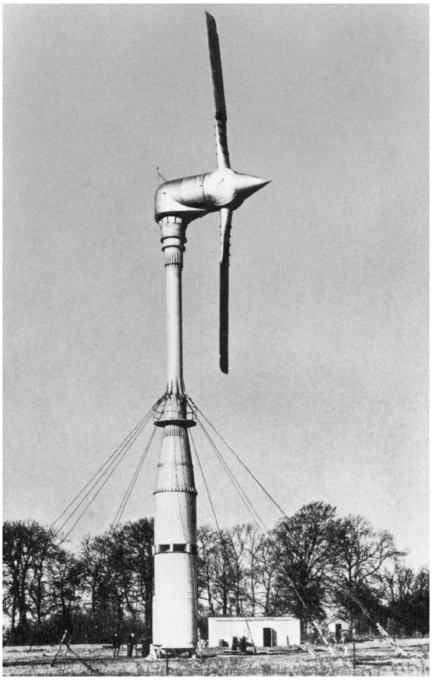


Fig. 2.12. Andreau-Enfield wind turbine in St. Albans (Hertfordshire) (rotor diameter 24 m, rated power 100 kW), 1956

Fig. 2.13. Wind turbine by Best-Romani, France (rotor diameter 30 m, rated power 800 kW), 1958 [16]

Fig. 2.14. Neypric-Vadot wind turbines in Saint-Remy: Small wind turbine (rotor diameter 21 m, rated power 800 kW); large wind turbine (rotor diameter 35 m, rated power 1000 kW), 1962-1964 [16]

Naturally, the Danes were also represented with experimental wind turbines in the fifties. Basing his concept on the technical model of the Aeromotors, J. Juul built a 200-kW wind turbine with a rotor diameter of 24 m in Gedser in 1957 (Fig. 2.15) [17].

Fig. 2.15. Danish Gedser wind turbine (rotor diameter 24 m, rated power 200 kW), 1957

The Gedser wind turbine operated from 1957 to 1966, but then shared the fate of all other wind turbines of this period and was decommissioned. Remarkably, or possibly prudently, it was not disassembled. It was thus the only historical wind turbine which survived to see the renaissance of wind power technology after 1975. Following an agreement between America's NASA and the Danish authorities, the Gedser wind turbine was recommissioned in 1977 and served as an experimental turbine for several years. The results obtained here, together with the technical documentation from the Hütter W-34 wind turbine, formed the starting point for NASA's research work in the field of wind power technology from 1975 onward.

In the Federal Republic of Germany, the “Studiengesellschaft Windkraft e.V.” (Society for the Study of Wind Power) was founded in 1949. Ulrich Hütter (Fig. 2.17), who had already distinguished himself with his papers on the theory of wind turbines in 1942, had a leading role in this. On behalf of the Allgaier Werkzeugbau GmbH in Uhingen, Germany, Hütter initially designed a small wind turbine with a 10-m rotor diameter and 8 to 10 kW rated power [18]. About 90 units of this wind turbine were built and proved to be quite satisfactory. In 1958, Hütter then started to develop a larger wind turbine, the W-34, which was to have a rotor diameter of 34 m and a rated power of 100 kW. In 1958, the wind turbine was erected in Stötten (now Schnittlingen, near Stuttgart) in the Swabian Alb in Germany (Fig. 2.16). The technical concept of Hütter's W-34 has been influencing wind turbine design in numerous features right to the present day. It was particularly the designers of the large experimental wind turbines which marked the first phase of modern-day wind-energy technology after 1975, who followed Hütter's ideas, some of them borrowing directly from the technical example of the W - 34, in particular the large German experimental turbine Growian was designed after the example of the W-34 (see Fig. 2.25).

Hütter made the rotor blades of the aerodynamically refined, two-bladed high-speed rotor of an advanced glass-fibre composite material, a method which was later generally used, especially in glider construction. The rotor blades were joined to the rotor shaft via a teetering hub, which permitted teetering movements of the rotor to compensate for asymmetrical aerodynamic loads. The rotor's teetering movements were damped aerodynamically by mechanically coupling the teetering angle to the blade-pitch angle. With this "teetering hub", Hütter had found a more efficient way than Putnam who had introduced the more complex, individual flapping hinges for the rotor blades and was forced to counter the full force of the flapping movement by means of hydraulic dampers (Chapt. 6.6.2).

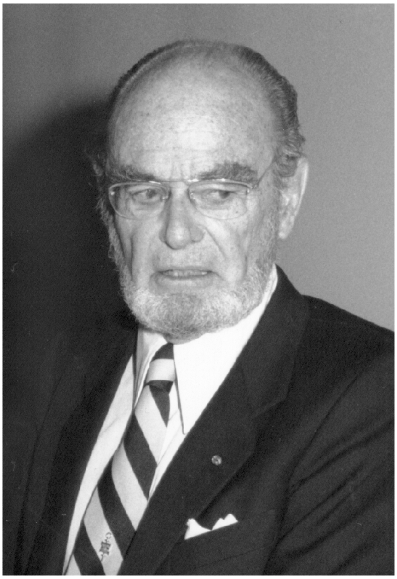
In relation to its rotor diameter, the W-34 had only a relatively low-rated generator power of 100 kW compared with most other wind turbines of this period. Hütter aimed at utilising the relatively low average wind speeds in the interior of the country. Moreover, he gave high priority to a lightweight construction of the wind turbine, ideas which considerably influenced the design of the later German wind turbines after 1980.

The W-34 was operated in the Swabian Alb in Germany from 1958 to 1968. However, compared to the ten -year period, the number of operating hours was not very high. Also, the funds available for the project were so scarce that only rudimentary systematic measuring and testing could be carried out [19]. In 1968, the wind turbine had to be dismantled as the lease for the land had expired.

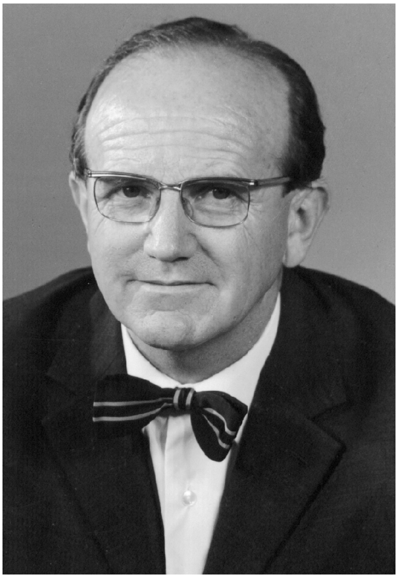
Fig. 2.16. W-34 wind turbine by U. Hütter in Stötten in the Swabian Alb, Germany (rotor diameter 34 m, rated power 100 kW), 1958-1968

Poul La-Cour, Denmark 1846–1908

Albert Betz, Germany, 1885-1968



Palmer Cosslett Putnam, USA, 1910-1986



Ulrich Hütter, Germany, 1910-1989

Fig. 2.17. Pioneers of wind-power technology

If one tries to draw a conclusion from the experience gained with the first large wind turbines of these years, essentially two reasons for their lack of success will emerge: all of the wind turbines described bore the hallmarks of improvisation to a greater or lesser extent. In practical operation, numerous problems and faults had to be dealt with not all of which originated on the technical side alone but which were also due to poor organisation. All in all, this situation led to relatively modest energy yield values despite the fact that some of the wind turbines were in existence for many years.

The real reason for the discontinuation of these developments, however, is to be found in the overall energy situation of these years. Due to the extremely low prices of primary fuels, electricity from the wind had no chance economically. This technology had no way of lifting itself out of its position as outsider under the given circumstances, a position which seemed rather bizarre to most contemporaries in any case. Accordingly, the operators were not highly motivated to invest new funds in order to overcome technical difficulties.

2.5 After the Energy Crisis - A New Start toward Modern Wind Power

Occasionally, when the subject of energy is being discussed, one can still see television pictures of empty roads and freeways on the so-called "car-free" days in 1973. What had actually happened was that the price of crude oil had risen to a multiple of its original price within a few months and the Western industrialised countries were suddenly made aware of their dependence on this economically vitally important primary energy source. Suddenly, everyone spoke of an "energy crisis".

In retrospect we know that the actual problem was not the availability of the oil but its increased costs and, above all, the awareness of how dependent we were on the oil exporting countries, the political stability of which could not be assessed to any degree of certainty. The primary aim was, therefore, to reduce our dependence on oil as a primary energy source. In 1973, the problem of environmental pollution due to the excessive combustion of oil scarcely figured yet in public discussions. The terms 'energy crisis' and 'environmental protection' were not yet quoted in one breath as they are today and it took another ten years for this theme to be accorded any importance.

The "oil price shock" of 1973 initially triggered a fierce public debate about how the dependence of the Western economies on oil imports could be reduced. In addition to energy saving measures, the popularity of which is still limited despite all protestations to the contrary, the politicians turned their attention to the search for other energy sources. In particular, the utilisation of renewable energy sources - i.e. of solar energy in its various forms - was discussed in countless studies and working groups and increasingly the aspect of environmental protection in the years to come.

In the United States of America, where they are even more dependent on crude oil than the European countries, NASA, the National Aeronautics and Space Administration, was given the task of developing approaches to a solution to this problem. After the Lunar Programme had been wound down, NASA was interested in new fields of activity and was considered to be extremely competent technologically after its success with the Moon landing. At the same time, large industrial companies, primarily in the aerospace industry co-operating with NASA, were engaged to study the subject.

In 1973, the *U.S. Federal Wind Energy Programme* was adopted. Its political management was handed to the *Department of Energy (DOE)* and a budget of approx. $ 200 million was authorised. In the following years, numerous theoretical and experimental studies were conducted, the results of which are still of significance and, in addition, several large experimental wind power plants were built and intensively tested [20]. Apart from the state funded projects, there were also some noticeable private initiatives in which it was attempted to develop modern wind power plants without much public funding. Neighbouring Canada, too, became involved in the development of wind energy technology for generating power. Similarly to the USA, the initiative came from governmental research institutions [21].

It was not long after that that the beginnings of the development of modern wind energy technology appeared in Europe where, in particular, Denmark, Sweden and the Federal Republic of Germany took the lead.

In Denmark, a commission of experts declared in 1974 "that it should be possible to generate 10 % of the Danish power requirement from wind energy without creating particular problems in the public power grid". The initial research work was concentrated on recommissioning the 200-kW plant near Gedser, built in 1957 by J. Juul. The turbine, which had been decommissioned in 1967, was overhauled in collaboration with NASA, and an extensive test programme was carried out. This led directly to the erection of two large experimental turbines in the vicinity of Aalborg [22]. At the same time, as well as the development of large turbines, the private use of small turbines was being promoted. Pieking up where developments had stopped in the forties, it was now possible to produce and sell the first commercially usable small 55-kW turbines in relatively large numbers. To start with, the buyers of these turbines received considerable subsidies but these were reduced over the years. By 1990, more than 2500 turbines, with outputs from 55 to about 300 kW, had been installed. This was a total of approximately 200 MW and formed the foundation stone for the Danish wind turbine industry.

In the neighbouring country of Sweden, the *National Swedish Board for Energy Source Development (NE)* was founded in 1975. In a ten-year programme, about 280 million Swedish crowns were made available for the development of wind energy. In addition to theoretical and experimental research work, two large experimental turbines with a rated power of two and three Megawatt, respectively, were built [23].

In the Federal Republic of Germany, the state subsidised work on the development of wind energy goes back to the year 1974. The starting point was a programme study which needs to be mentioned in some detail at this point since it had a decisive influence on the first phase of wind energy technology in Germany. The then *Bundesministerium für Forschung und Technologie* (BMFT - Federal Ministry for Research and Technology), headed by H. Matthöfer, commissioned a study with the title "Energy Sources for Tomorrow?" from the *Kernforschungsanlage Jülich GmbH (KfA)* (Nuclear Research Organisation-note the ironical question mark).

In Part III of the study, the possibilities and limits of the "Use of Wind Energy" are dealt with [24]. Both the *Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt* (now DLR German Aerospace Research Institute) and the *Forschungsinstitut für Windenergie (FWE)* (Research Institute for Wind Energy) established by

Prof. U. Hütter played a leading role in the study, as did a number of large industrial companies. The central view of the study was that the experimental turbine W-34 constructed by U. Hütter in the fifties (s. Chapt. 2.4) provided the appropriate technology for modern wind turbines and that this technical concept could be adopted without major technical problems for a rotor size of up to 110 m in diameter and a rated power of 3 Megawatts.

In a first estimate of cost and economic viability, two sizes were examined in greater detail: a variant with a rotor diameter of 80 m and 1 MW power, and a larger variant with 113 m diameter and 3 MW output. The low ratio of power to rotor diameter in present-day terms is due to the fact that Hütter favoured a lightweight construction (he was an aircraft designer) and that he intended to use the wind turbines also inland under weaker wind conditions. The larger variant with 3 MW output was accorded a somewhat better economic viability, which is why the more extensive sample calculations for the power generation costs of a 100- and 300-MW wind park were carried out with this variant. The authors formulated the resume of the study as follows:

"Although, from a technical point of view, a 3-MW turbine with a hub height of 72 *m and a rotor diameter of* 113 *m could be built immediately, it appears to be appropriate, to maintain continuity, to proceed with a smaller step in researching the problems of vibration and control of a large turbine. For this reason, an 1-MW turbine with a tower height of about 52 m and a rotor diameter of* 80 *m should be constructed in the short term. The size of the turbine is already adequate for interconnection with the grid since the power output reaches a significant level"* [24].

This warning was ignored by the politicians who had commissioned this study and who wanted to present the public with a quick and spectacular result. They called for the 3-MW project to be built, thus giving birth to the "Growian" (Große Windkraft-Anlage - large wind turbine) project which was to gain much notoriety in subsequent years. It is also part of this story that, although the 'engineers' expressed doubts, they did not mount any determined resistance against the demands of the 'politicians' to immediately construct a project of this magnitude. The author of this book, too, must confess to having adopted this attitude, having come into contact with the subject of wind energy for the first time in 1978 when working on the so-called "Construction Documentation for Growian" commission from MAN (Maschinenfabrik Augsburg Nürnberg AG).

The older reader will still remember the headlines associated with the name "Growian" in the German press. All the technical problems - of which there were more than enough naturally - were quoted as proof that the generation of power from wind energy was a fantasy of backward-looking green ideologists. Some presumed that the Growian project had been built intentionally in order to discredit the use of wind energy right from the start and suspected a conspiracy between the utilities and "big industry".

In the ensuing years, however, the success of wind energy utilisation was not hampered by the technical problems and the associated headlines about Growian. The successful small turbines from Danish and later also from German production became more and more numerous until the so-called *Einspeisegesetz für Strom aus regenerativen Energien* (Law relating to supplying power from regenerative energy sources) brought the breakthrough in Germany.

2.6 The Large Experimental Turbines of the Eighties

In the eighties, the state-subsidised and state-initiated programmes for developing the wind energy technology were primarily orientated towards the construction of large experimental turbines. Apart from political motives, the opinion prevailing initially that the large utilities should be the potential buyers of these turbines was a decisive argument for concentrating on the development of wind turbines in the Megawatt power range, a development which came much too early from today's point of view. The large experimental turbines were built almost exclusively by large and well-known industrial companies since only these were able to develop and build projects of this magnitude from a standing start, as it were. The names read like a "Who's Who?" guide through industry: Boeing, General Electric and Westinghouse in the US, MAN, MBB, Dornier, Voith in Germany or Kvaerner in Sweden.

The development began in the United States. From 1975 to 1987, a series of large experimental turbines designated MOD-0 to MOD-5 were erected and tested (Figs. 2.18 to 2.22) and a number of duplicates were built of some of these, e.g. of MOD-0 and MOD-5.The programme started with the 100-kW Mod-0 design, which was built by several manufacturers at different sites, followed by one unit of the MOD-1 and three units of the MOD-5, having a rated power of 2.5 Megawatt. The last design was the MOD-5 on the island of Hawaii.

Fig. 2.18. MOD-0, (rotor diameter 38 m, 200 kW), in Clayton, New Mexico, NASA (USA), 1975

Fig. 2.19. MOD-1, (rotor diameter 60 m, 2000 kW), in Blowing Rock, North Carolina, GENERAL ELECTRIC (USA), 1979

Fig. 2.20. MOD-2, (rotor diameter 91 m, 2500 kW), BOEING (USA), 1980

Fig. 2.21. MOD-5, (rotor diameter 97 m, 3200 kW), BOEING (USA), 1987

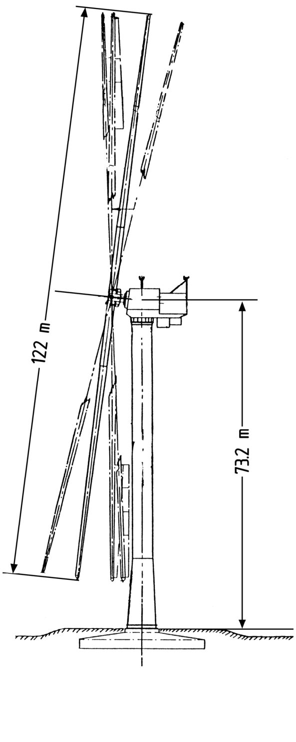


Fig. 2.22. Project MOD-5A (rotor diameter 122 m, rated power 7300 kW), GENERAL ELECTRIC (USA), 1983

The final and largest project, the MOD-5A designed by General Electric, no longer reached completion. The turbine was intended to have a rotor diameter of 122 m and a rated power of 7 300 kW (Fig. 2.22). A so-called “aileron-controlled” two-bladed rotor was provided as a special feature (see also Chapt. 5, Fig. 5.57). The project was cancelled in 1993 in favour of the MOD-5B since this design was largely based on the preceding MOD-2 turbines and could be implemented more rapidly and inexpensively with the subsidies by the DOE which were still available. After the MOD-5B had been tried out in the Hawaiian Islands, the state subsidised development for the large experimental turbines came to a halt in the United States.

In Denmark, a start was made by a private initiative. In 1975, the "Tvind Turbine" was erected by a syndicate at an adult education school in Ulfborg (Fig. 2.23). The turbine was built with much enthusiasm and idealism but constructed rather amateurishly in some respects. After that, the Danish utilities built the experimental systems Nibe A and Nibe B (Fig. 2.24).

In Germany, the Growian project formed the focus of the programme (Figs. 2.25 and 2.26). In addition, however, innovative designs such as the Voith WEC-520 (Fig. 2.27) or several units of the single-bladed design "Monopteros" (Fig. 2.28) were constructed. Some years later - as a second beginning as it were - the Aeolus II turbine followed in co-operation with Sweden (Fig. 2.29) and the WKA-60 on the island of Heligoland (Fig. 2.30).

In the Swedish programme, the first experimental turbine bearing the designation WTS-75 (later Aeolus I), with a rated power of 2 MW and a rotor diameter of 75 m, was erected in 1982 on the island of Gotland (Fig. 2.31). A few months later, this was followed by another large turbine with 3 MW output and a rotor diameter of 78 m (Fig. 2.32). It was installed in the South of Sweden in Marglarp, not far from Malmö. The technical design of the two experimental systems was deliberately selected to be different. The turbine on Gotland represented the so-called "stiff line" with a hingeless rigid rotor hub and a rigid prestressed concrete tower. The WTS-3 in Marglarp embodied lighter-weight and more flexible principles of construction. The two-bladed rotor was provided with a teetered hub and the tower was a steel shell tower in a "soft" design from the point of view of vibration characteristics.

The two Swedish prototypes were developed in co-operation with a US company (WTS-3) and a German company (WTS-75), respectively. In the United States, the sister model to the WTS-3, the WTS-4, was built by Hamilton-Standard, and in Sweden and in Germany, the WTS-75 was developed - a few years later - and became the Aeolus II (see Fig. 2.29).

In these years, the governmental research institutions in Canada initiated a development programme focused on a particular technology. Managed by the *National Research Council (NRC),* the programme was concentrated on the development of vertical axis wind turbines (VAWTS) of the Darrieus type of construction. Some small-scale experimental turbines were tried out in remote regions in conjunction with diesel generators. The programme reached its peak in the construction of the largest ever Darrieus rotor in 1985. The "Éole" project had an equatorial diameter of 64 m, a height of 100 m and a generator power of 4 MW (Fig. 2.33). However, the experiences gained in the relatively short operating time were not very encouraging and the turbine was dismantled and only a few test results were published. Not long after that, the Canadian development programme was terminated since it was clear by now that the VAWT type of construction did not offer an alternative which was economically equivalent to the horizontal-axis turbines.

Fig. 2.23. Tvind turbine near Ulfborg, (rotor diameter 52 m, 2000 kW), (Denmark), 1978 (photo Oelker)

Fig. 2.24. Nibe A and Nibe B, (rotor diameter 40 m, 630 kW), ELSAM (Denmark), 1979

Fig. 2.25. Growian on the Kaiser-Wilhelm-Koog, (rotor diameter 100 m, 3000 kW), MAN (Germany), 1982

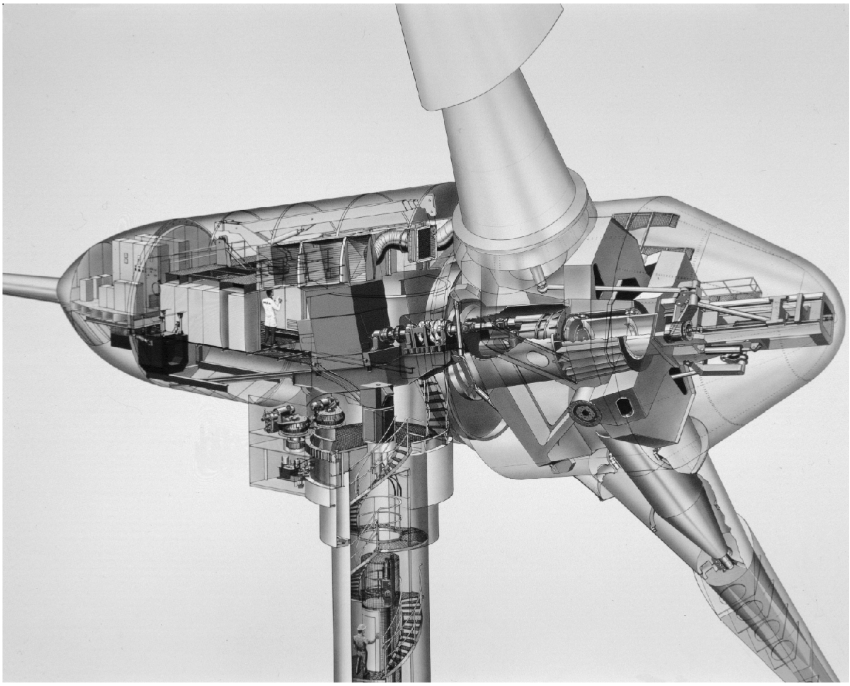


Fig. 2.26. Nacelle and teetered hub of Growian

Fig. 2.27. WEC-520 (rotor diameter 52 m, 270 kW), VOITH (Germany), 1982

Fig. 2.28. Monopteros (rotor diameter 48 m, 600 kW), MBB (Germany), 1985

Fig. 2.29. Aeolus II in Wilhelmshaven, Germany, (rotor diameter 80 m, 3000 kW), three Monopteros in the background, 1990

Fig. 2.30. WKA-60 on Heligoland, Germany, (rotor diameter 60 m, 1200 kW), 1993

Fig. 2.31. WTS-75 (Aeolus I), (rotor diameter 75 m, 2000 kW), Kvaerner (Sweden), 1983

Fig. 2.32. WTS-3 (rotor diameter 78 m, 3000 kW), Swedyard (Sweden), 1982

Fig. 2.33. Darrieus turbine Éole (4 MW rated power), HYDRO-QUEBEC (Canada), 1987

Some other countries also built government - funded experimental wind turbine systems in these years. On the island of Sardinia, the Gamma-60 was built (Fig. 2.34).

In the United Kingdom, the 3-MW LS-l by Windenergy Group and the HWP-55 turbine by the Scottish Howden Company can be mentioned (Figs. 2.35 and 2.36) and in Holland, the NEWECS-45 was tested (Fig. 2.37).

A further generation of European experimental turbines, taken into operation towards the end of the eighties, was less ambitious with regard to dimensions, and was of smaller scale throughout. In contrast to the first units which were produced in national programmes, these systems were developed and tested in a co-ordinated EU programme. They were promoted by the EU Commission in two large research and demonstration programmes *Joule* and *Thermie* [25].

The development programmes WEGA I and WEGA II were set up with the express aim of bringing the large wind turbines in the megawatt range closer to being used commercially. In the WEGA I programme, the experiences gained from the existing test installations in the EU were evaluated by an international group of experts and the basic conditions for the development of new systems were formulated (Figs. 2.38 and 2.39). The theoretical background was formed by a fundamental study in which the relationships between plant size, production costs and economic viability had previously been analysed [26]. Initially, the European wind turbine manufacturers were slow to begin developing commercial systems of this size. The risk was thought to be very high, the "Growian experience" still being fresh in most memories. But in the end, the EU initiative was adopted so that the systems sponsored in the WEGA programme formed in some cases the direct starting basis for the first commercial systems of the megawatt class (Fig. 2.40).

Fig. 2.34. Gamma 60 (rotor diameter 60 m, 1500 kW), AERITALIA (Italy), 1987

Fig. 2.35. LS-1 (rotor diameter 60 m, 3000 kW), WEG (United Kingdom), 1988

Numerous governmental and private organisations were involved in the research programmes, the development tasks and the evaluation of the test results. A special role was-played by the *International Energy Agency (IEA)* which organized an international exchange of tests results in a working group created especially for this purpose.

The large first-generation prototypes were intensively tested in the first years of their existence and were then operated for another ten years, interrupted by relatively long periods of rest. If one wants to measure their success from the number of operating hours, the "most successful" turbines reached numbers of "a few thousand" operating hours whereas the least successful ones only attained "a few hundred" hours [27]. Compared with the politically motivated expectations, this was disappointing. Looking more closely at the whole picture, however, one arrives at a quite different assessment. This first generation of large experimental turbines largely laid the technological foundations for the modern wind energy technology and, above all, provided the necessary documentation, available to a wider public.

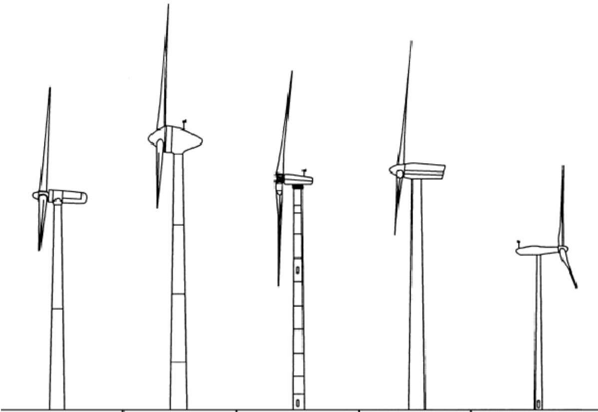
For the first time, a wide scientific technical foundation was created by governmental research establishments and industry and the electrical utilities, on the basis of which the personal and factual preconditions could be established to bring wind energy technology to its present day level. This assessment in no way ignores the personal contributions of many individual "pioneers" who, with much commitment, have already designed and successfully constructed wind turbine systems long before this but the creation of an enduring and successful wind energy technology required a diversified foundation based on scientific and technical principles. This development crystallised around the large experimental turbines of the nineteen-eighties which, in serving this task, have consumed themselves, which can also be said of numerous other examples in technology.

Fig. 2.36. HWP-55, (rotor diameter 55 m, 1000 kW), HOWDEN (United Kingdom), 1989

Fig. 2.37. NEWECS-45, (rotor diameter 45 m, 1000 kW), STORK (Holland), 1985

Fig. 2.38. Tjaereborg experimental turbine (rotor diameter 61 m, 2000 kW), ELSAM (Denmark), 1989

Fig. 2.39. Spanish AWEC-60 in the test field in Cabo Villano/North-Western Spain (rotor diameter 60 m, 1500 kW rated power), Union Fenosa, 1989



1000 kW	1500 kW	1000 kW	1500 kW	600 kW
54 m	66 m	53 m	63 m	41 m
1996	1996	1996	1996	1996
Denmark	Germany	Sweden	Denmark	United Kingdom
Bonus 1 MW	Enercon E-66	Nordic 1MW	Vestas V63	WEG MS4

Fig. 2.40. Development of large wind turbine systems as part of the European WEGA II programme promoted by the European Union.

2.7 First Successes with the Small Wind Turbines in Denmark

After the energy crisis in 1973, there was only one country in which there was a certain tradition of successfully operating small wind turbines for power generation and this was Denmark (s. Chapt. 2.1). The basic technical concept had been developed in the nineteen forties and had found relatively wide application, although this was still modest by today's standards.

Some small- and medium-sized firms in Denmark, which were active in manufacturing agricultural machinery (for example Vestas) or in some other fields of constructing simple machines and equipment, took their chance and began to build small wind turbines after the traditional model of three-bladed rotors and grid-connected induction generators and to sell these initially to private owners or agricultural holdings.

Compared with today's commercial units, the first wind turbines gaining any numerical importance in this field of application were still comparatively small with an output of 50 to 60 kW and a rotor diameter of 15 to 16 m (Fig. 2.41). In 1986, the contribution made in this way to Danish power generation was still less than one percent, but rose steeply in the following years. In Denmark, the wind turbines were not only operated by individual users of electric power. Many turbines or small groups of turbines were built and operated as "community installations" by consumer associations. This made it easier to organise their financing and operation and the legal regulations in Denmark presented no obstacles to this way of supplying oneself with electrical energy.

Fig. 2.41. Remote installation of a small wind turbine at a private electricity user's holding in Denmark, 1985 (photo Rüth)

Until 1985, the operators in Denmark received about 30 % of the purchase value of the units as a direct subsidy from the government. Moreover, no tax was levied on the supply of energy by the wind turbines. Given this prerequisite, the utilities were able to pay a relatively favourable price for the kilowatt-hour fed into the grid (about 40 0re, or about 0.07 $US/kWh, in 1994). The governmental subsidy was greatly reduced after 1986 and was eliminated completely not much later. Nevertheless, the installation of wind turbines, which in the meantime were offered at better prices, never came to a complete standstill.

In addition to these economic background conditions, a number of other factors must also be mentioned which encouraged the successful use of wind turbines in Denmark. For example, the practice of issuing building permits was already based on generally recognised assessment criteria at a very early point in time. The technical maturity and safety of the units have been attested with a test certificate by the Wind Turbine Test Station in Risø since the early nineteen-eighties. The meteorological and geographic preconditions for the successful use of wind turbines have also been researched and published in the *Danish Wind Atlas.* And, not least, the pattern of rural Danish settlements with its many single farms generally favoured the decentralised installation of wind turbines.

2.8 The Wind Farms in the United States

In parallel with the federal support for the development of large-scale wind power plants, the State of California, in a different type of initiative, supported subsidies for the utilisation of regenerative energy sources by indirect measures. In 1976, the Senate decided to provide for a direct tax credit of 10 % of the investment costs for solar energy utilisation. This tax credit could only be claimed by private investors. The Federal Government followed suit two years later. In their *National Energy Act* passed in 1978, further concessions were granted for the tax to be paid to the Federal Government and, over the years, supplementary tax laws were added including one relating to the accelerated depreciation of investments of this type. By the end of 1985, the tax advantages for the investors had accumulated into a maximum of 50 % of the investment costs and, in some cases, even more, taking into account the possibilities of accelerated depreciation.

The revenue from power sales had the same degree of importance as the fiscal measures. Under the *Public Utilities Regulatory Policy Act* (PURPA), the public utilities were obliged to accept the power generated from regenerative energy sources in their grids and to pay for it in accordance with the principle of "maximum avoided costs". This means that they had to use as a basis for their calculations the highest costs saved at the conventional power stations. In 1984/'85, the two largest utilities in California, the Pacific Gas and Electric Company (PG&E) and the Southern California Edison Company (SCE), paid an average of 10 cents, in some cases up to 12 cents, in some cases up to 12 cent, for the power fed into their grids depending on the time of day and the season. In 1986, they still paid 0.07 - 0.09 $US/kWh on average.

There is one more comment which should be made regarding the energy industry in general. The construction of conventional power stations had decreased dramatically since the beginning of the seventies, partly because the building of new power stations was hampered severely by the environmental conditions imposed by now. Many projects for nuclear power stations came to nothing because of the enormous increase in the capital costs involved. In this situation, the utilities were willing to purchase power without having to risk any investments of their own and this willingness, ultimately, proved to be of benefit to the wind farms financed by private investments.

Against this economic background, the first wind farms were built between 1979 and 1980. So-called "developers" or "wind farmers" concluded delivery contracts with the utilities mentioned above, purchased or leased suitable stretches of land and encouraged private investors - especially those taxed highly - to buy wind turbines which were then erected and operated on their land.

At the beginning, the technical basis for the wind farms consisted of relatively small wind turbine units with a power of up to about 100 kW which were developed by US companies and constructed quickly by mass production techniques. Unlike Denmark, however, these manufacturers had no basic fund of proven technical designs and experience that they could tap into. Their systems, whilst quite innovative technically in some cases, turned out to be generally not very reliable so that there was an increasing demand for more thoroughly proven designs. In the meantime, the Danish manufacturers had been able to accumulate a considerable amount of experience in their home market and used the opportunity to expand their production by exporting to the United States.

After a tardy beginning, the development took off dramatically around 1981. New wind farms sprang up almost daily, many of which disappeared as quickly as they had come into being. Some regions of California were virtually in the grip of a gold rush mentality which also extended to business practices.

The Californian wind farms were essentially concentrated in three regions: the area of the Altamont Pass, east of San Francisco; the Tehachapi Mountains, not far from Bakersfield; and the area of the San Gorgonio Pass, near Palm Springs, about four hours' driving east of Los Angeles (Fig. 2.42). There are an additional number of relatively small regions where wind farms are installed but these are not very significant numerically.

Some explanations are needed with regard to the local meteorological conditions since these are somewhat unique. The Californian wind farms are located on the heights of the coastal foothills bounding the Central Valley to the west and to the east. In the interior east of the Sierra Nevada range, there are the desert regions of the Great Basin, for example the Mojave Desert and Death Valley. During the hot season, which lasts almost all year in California, the air over the desert regions heats up considerably and the rising masses of air produce a low-pressure region into which the cooler air from the Pacific flows via the coastal foothills. At exposed heights mean annual wind velocities of up to 9 m/s are reached. In the mountainous terrain, however, the wind conditions are extremely dependent on the location.

This meteorological mechanism is also responsible for the diurnal variation of the wind velocity. The heating up of the desert reaches its peak only around noon which means that the wind over the mountains does not rise up before noon either, and it then blows quite consistently in the afternoon and evening until about midnight. This diurnal variation creates a special advantage for the wind farms. The peak of the power production coincides well with the noon and evenings peaks in demand and the payments for the power generated, calculated in accordance with the "rnaximum avoided costs" formula, are also highest at these times.

The number of installed wind turbines rose rapidly until 1995. By the end of 1985, about 40 % of all wind turbines in California had come from Denmark. The Danish wind turbine industry, with an annual production of more than 3000 units in 1985, had been built up mainly for the Californian wind farms. At the beginning of 1987, about 15 000 units with a total power output of approximately 1,400 MW had been installed in the wind farms of California (Figs. 2.43 to 2.46).

In the years between 1986 and 1987, the economic situation of the Californian wind farms changed considerably. On the one hand, the high tax credits for the investors expired at the end of 1985 and, on the other hand, the power generation costs, which are closely linked to the oil price in California, dropped. For these the utilities offered

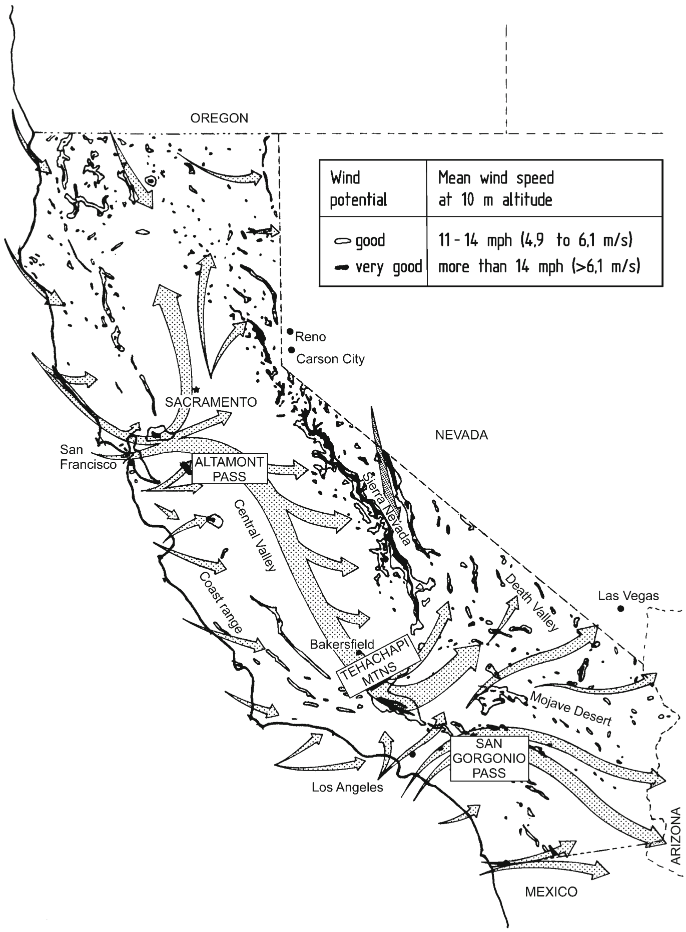


Fig. 2.42. The most important areas of installation and the wind conditions of the wind farms in California

Fig. 2.43. Wind turbines from US Windpower at the Altamont Pass, 1985

Fig. 2.44. Wind farm with Danish Micon turbines at the San Gorgonio Pass, 1986

Fig. 2.45. Wind farm with MAN-Aeroman turbines on the Tehachapi Mountains, 1986

Fig. 2.46. Flowind wind farm with vertical axis Darrieus turbines on the Tehachapi Mountains, 1986

much lower supply tariffs for new contracts and the wind farmers thus came under pressure from two sides.

Nevertheless, the pessimists did not win the day. Wind farms continued to be built, albeit at a somewhat slower rate. It was especially the undertakings which were reasonably well off and had long-term supply contracts with the utilities which survived the loss of the tax credits. The manufacturers of the wind turbines also played a role in the survival of the wind farms. Producing new and larger units, which were offered at much lower specific costs than the first series, they created the prerequisites for power generation costs which approach economic viability even without tax advantages for the investors so that those wind farms which were well organised survived.

In the late nineties, however, after more than fifteen years, many wind farms in California had left an impression which was rather depressing. Due to the further deterioration in the economic background conditions at the beginning of the nineteen-nineties, all development had come to a virtual standstill. No new wind farms were being built and those still in existence were hopelessly outdated.

It was not until after the year 2000 that the utilisation of wind energy was rediscovered in the US. Rising oil prices and an increasing shortfall of available power due to the construction of new power stations having been neglected reawakened a general interest in wind power. In Europe, in the meantime, developments had progressed far and much larger and more reliable wind turbine systems were available. In addition, taxation stimuli for investments in renewable energies were promised again, after almost 10 years of restrictive fiscal policies. The number of new wind turbines rose again slowly initially, and then quickly, and was no longer restricted only to California as in the eighties. In 2007, almost 5000 MW of wind power was newly installed. Considering this rate of growth, the US are well on the way to become a leading country of wind power utilisation again.

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