# 1

# The History of Wind Energy

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## 1.1 Introduction

Wind has been used as a source of energy for more than 1500 years. In times when other sources of energy were unknown or scarce, wind energy represented a successful means for industrial and economic development. Wind energy became a marginal source once cheaper, easier to exploit and easily obtainable sources of energy became available. From the point of view of the contribution of wind energy to economic development, one can divide the history of wind energy into four overlapping time periods (see Figure 1.1). Except in the first period, the emphasis here is the generation of power by wind:

- **600–1890: Classical period**. Classic windmills for mechanical drives; more than 100,000 windmills in northwestern Europe. The period ended after the discovery of the steam engine and because of the ready availability of wood and coal.
- **1890–1930: Development of electricity-generating wind turbines**. The development of electricity as a source of energy available to everyone leads to the use of windmills as an additional possibility for generating electricity. Basic developments in the field of aerodynamics. The period ended due to cheaper fossil oil.
- **1930–1960: First phase of innovation**. The necessity of electrifying rural areas and the shortage of energy during the Second World War stimulated new developments. Advances in the field of aerodynamics. The period ended because of cheaper gas and fossil oil.
- **From 1973: Second innovation phase and mass production**. The energy crisis and environmental problems in combination with technological advances ensure a commercial breakthrough.

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Edited by Alois Schaffarczyk. Translated by Gunther Roth.


**Figure 1.1** Historical development of the use of wind as a source of energy. The first and last periods have had the greatest effects on society

During the classical period, the ‘wind devices’ (windmills) converted the kinetic energy of the wind into mechanical energy. After direct current and alternating current generators were invented and came to be used for public power supply, windmills were used for electrical power generation. This development began effectively in the late nineteenth century and, after the energy crisis in 1973, became a great economic success.

In order to differentiate clearly between the different plants, they are called windmills or wind turbines in this book.

## 1.2 The First Windmills: 600–1890

Water mills were very probably the precursors of windmills. Water mills, again, were developed from devices that were operated by people or animals. The devices that are known to us from historical sources possessed a vertical main shaft to which cross bars were attached in order to drive the main shaft. The cross bars were operated by farm animals such as horses, donkeys or cows. It seems only logical that the vertical windmills developed from these devices. However, there are few historical sources to provide proof of this. More sources can be found on the ‘Nordic’ or ‘Greek’ water mills that evolved from the animal-operated devices (see Figure 1.2). These types of water mills had their origin about 1000 BC in the hills of the Eastern Mediterranean area, and were also used in Sweden and Norway [1].

The first windmills with vertical main shafts were found in Persia and China (See Figures 1.4). In the middle of the seventh century AD, the building of windmills was a highly prized trade in Persia [3]. In China, vertical windmills were introduced by traders. The first European to report on the windmills in China was Jan Nieuhoff, who travelled there in 1656 with one of the Netherlands ambassadors. Figure 1.3 shows an illustration by Jan Nieuhoff [4]. Similar windmills were in use in China until quite recently (see Figure 1.4).

Other types of devices were treadmills that were operated by the bodily strength of people or animals. Spades were arranged radially to the main shaft. The horizontal water mill developed from the treadmill by the replacement of people or animals by flowing water. A further development in the first century AD was the so-called Vitruvian water mills, which were introduced by the Roman Vitruvius. This water mill can be seen as the prototype for the undershot water mill that can be found throughout Europe in rivers and streams with low water-level differences. Also, it is assumed that the Vitruvian wheel is the forerunner of the horizontal windmill [1].

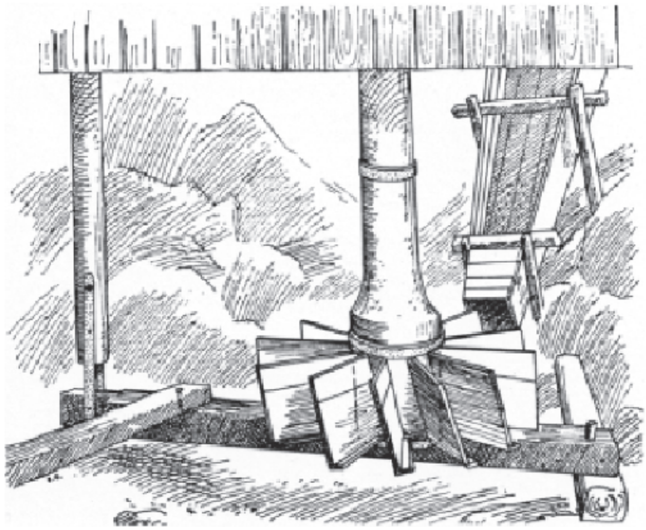


**Figure 1.2** Water wheel with vertical axis of rotation near Göteborg, Sweden. From Ernst, *The Mills of Tjorn* (1965) published by Mardiska Museet, Stockholm [2]. Reproduced with permission of Mardiska Museet, Stockholm

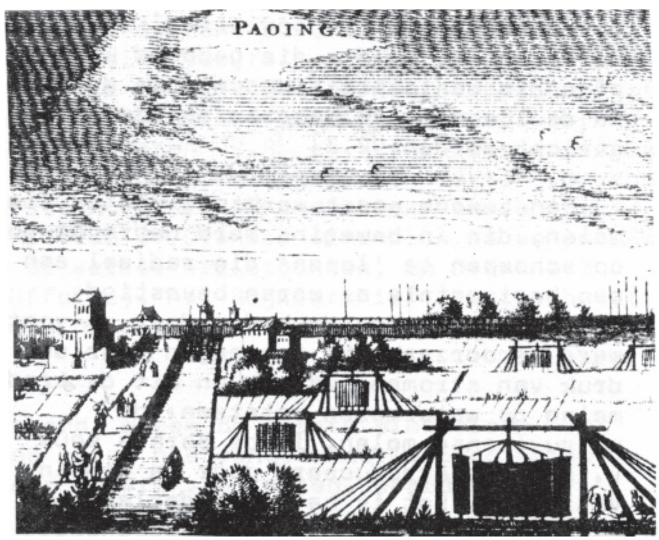



**Figure 1.3** Drawing of Chinese windmills in Paoying (Chiangsu) by Jan Nieuhoff, 1656 [4]. Reproduced with permission of Cambridge University Press

The first horizontal windmills were found during the crusades in the Near East and later in northwest Europe. These windmills possessed a fixed rotor construction that could not be rotated in the wind (yawing). The rotor blades of these windmills were similar to those that can be seen today, for instance, on the Greek Island of Rhodes. By about 1100 AD there were reports of fixed post mills that were positioned on the city walls of Paris. It is unclear whether


**Figure 1.4** Left: Chinese wind wheels at Taku that pump brine solutions for the extraction of salt (Hopei [3]). Reproduced with permission of E & F N Spons; right: schematic depiction of the function of a Chinese windmill. Solid lines represent blades and dash-dotted lines represent sails [5].

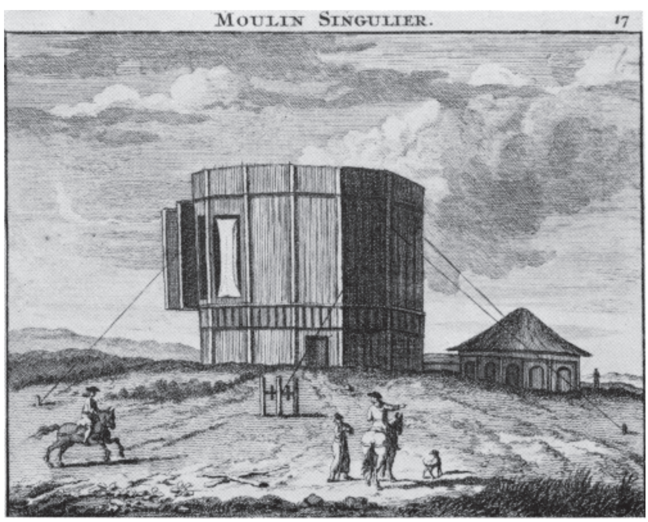



**Figure 1.5** A vertical axle windmill from the year 1718 [2]. Reproduced with permission of Hugh Evelyn

the windmills that were widely distributed came from the Near East to Europe or were reinvented in Western Europe. Some authors even doubt the existence of horizontal windmills in the Near East during the Crusades [3,6]. Others, again, speak only of vertical windmills at that time [4,7].

The assumption that the windmills of Western Europe were invented independently of those of the Near East is supported by documents that have been found in the archives of the Netherlands Province of Drenthe. In these documents that originate from the year 1040, at the time of the Crusades, there is mention of two windmills (Deurzer Diep and Uffelte). During the Renaissance some vertical windmills were also built in Europe (see Figure 1.5). Especially well known was the windmill built by Captain Hooper in Margate, England [2].

### 1.2.1 Technical Development of the First Horizontal Windmills

The first windmills possessed no yaw mechanisms and the blades consisted of a frame of longitudinal and lateral bars through which sailcloth was tied (see Figure 1.6, left). The power output was controlled in that the sail was wholly or partly furled up by hand (see Figure 1.6, right).

For reasons of statics, the main shaft had an angle of inclination (dimension of the milling building, the axle load on the axial sliding bearing, the possibility of erecting a load-bearing building or a conical tower for stabilisation).

The development of the classical windmill in Western Europe will be described before investigating the global development of windmills into wind turbines with which electrical power is generated today.

Although the wind comes mainly from a particular direction in the windy regions of Europe, the wind direction varies so strongly that a yaw mechanism makes sense in order not to lose too much energy with side flows of the wind. This requirement led to the first post windmills (see Figure 1.7), which could be yawed into the wind. These windmills were used for milling corn. By means of a strong beam attached to the mill building, the whole house, which stood on a fixed substructure, could be turned until the rotor was vertical to the wind.

Often the support beams of the substructure were covered with wooden planking so that a storeroom was created. The millstone and the gear wheels were situated in the rotating mill building. One of the first depictions of this type of windmill, dating from the year 1299, comes from a convent in Oedenrode, in the Noord Brabant region in the Netherlands.

Another attempt to turn the rotor into the wind was attempted by building a windmill on a floating platform. The platform was fixed by means of a joint to a pile that was sunk into the ground of a lake in the north of Amsterdam in 1594. Probably because of the lack of stability, such a windmill was never built again, but the concept can be taken as the first attempted offshore wind turbine.

The so-called ‘Wip’ (Dutch) or ‘Koker’ (German) windmill was developed from the post windmill (see Figure 1.8). After 1400, windmills were used in the flatter regions of the Netherlands not only for grinding corn, but also for pumping seas and marshlands dry. The pump arrangement, usually a bucket wheel, was attached to a fixed position of the mill building. Only the transfer elements of the windmill were positioned inside, which made the rotating part of the windmill markedly smaller. By the start of the sixteenth century, there was a requirement for more pumping capacity and so the ‘Wip’ windmill was replaced by a mill with a rotating cover. Only the bevel gear drive was situated inside the cover, with the result that this part weighed relatively little. As the demand for power output increased, windmills were built whose only rotating part was the cover. The drive machinery was able to be positioned in the mill building and no longer needed to be placed in the movable part (e.g. as with the post windmill) or in the open (as with the ‘Koker’ windmills. The sketches in Figure 1.9 show the development of the main features of the classical windmill.

With the increasing number of windmills, the pressure to use them more efficiently increased. Improvements resulting from this motivation were integrated into the mills. One improvement was the automatic yawing of the windmill rotor into the wind with the aid of a windrose: a rotor whose shaft was attached vertically to the main shaft of the windmill. In England in 1745, Edmund Lee fastened a windrose to a windmill. The windrose was a wooden

**Figure 1.6** Left: a post windmill of the early fourteenth century (British Museum) [2]. Reproduced with permission of Hugh Evelyn; right: ‘power control’ of a classical windmill [8]

**Figure 1.7** Post windmill, Baexem, Netherlands [8]

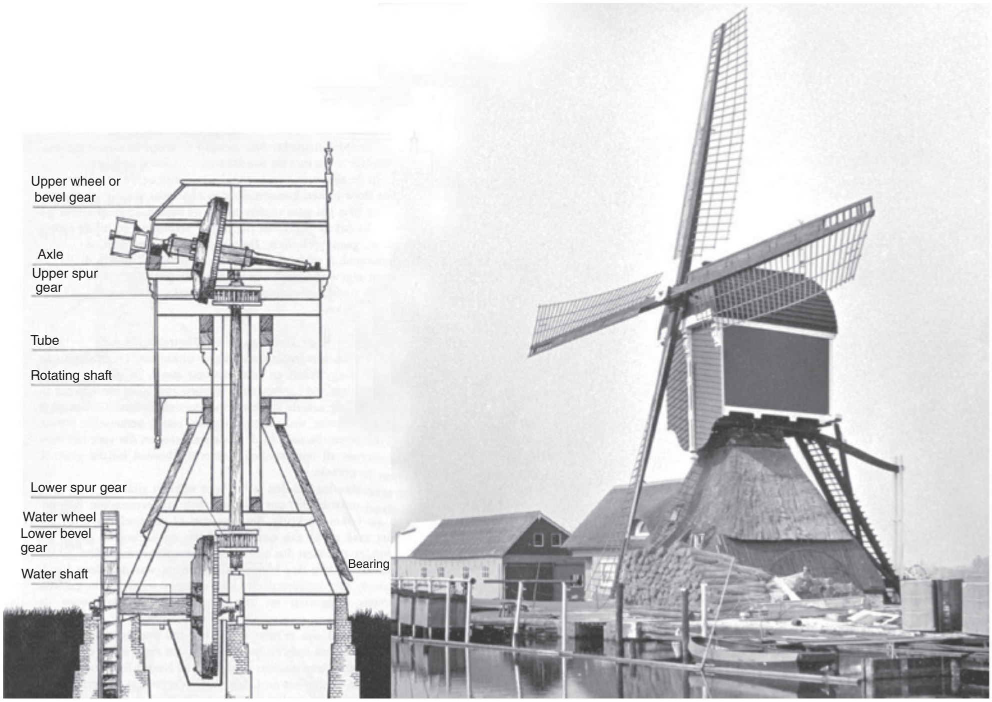



**Figure 1.8** 'Koker' windmill from South Holland. Photo (right) from [8]

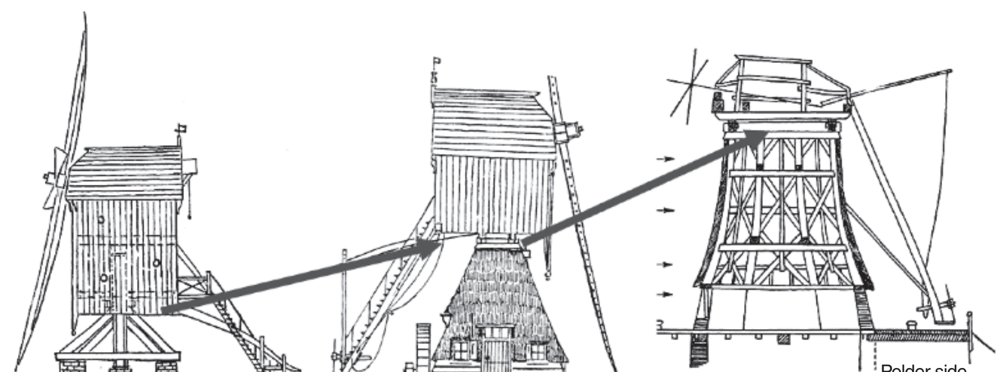



**Figure 1.9** The development of the classical 'Holland mill'

construction that was mounted to the rotating part of the windmill in order to turn the rotor into the direction of the wind. John Smeaton, also English, invented a windrose that was attached to the rotating cover of the windmill.

This innovation was so successful because it was used on a large number of windmills, especially in England, Scandinavia, north Germany and in the eastern part of the Netherlands.

**Figure 1.10** Wind direction follower with sensor on an early Lagerwey wind turbine [8]

This concept was retained up to the era of the wind turbines of the later nineteenth century and even into the late twentieth century. At the start the transmission was fully mechanical, and later the windrose acted only as a sensor in order to send a control signal to the yaw mechanism (see Figure 1.10).

In the first phase of the classical period of the windmills, they were primarily used for milling corn and for dewatering. More and more wind was also used as source of energy for all possible industrial processes. The wind played a great role as a source of energy for industria and economic development, especially in regions where no other easily available energy carriers such as wood and coal were available. This was the case especially in 'de Zaanstreek', north of Amsterdam, and in Kent in England. Windmills were used for sawmills, for the production of paper, oil and colours, for dehusking rice and crushing, as well as for the manufacture of mustard and chocolate [6]. Besides this, they were used for the ventilation of buildings (England). The construction of windmills was especially concentrated in suitable areas. The multiplicity of windmills, as in the gallery of the windmills, for draining marshes and seas can be seen as a precursor of modern wind farms.

Further innovations in the area of performance and control of the rotor were continuously implemented. The sail that was wound through the blade bars was replaced by textile strips that were fixed to the front of the blades. The vacuum on the lee side kept the cloth in place, whereby it obtained an aerodynamic profile. Power was controlled in that the wooden frame of the blade was partly covered. In order to reduce maintenance, the wooden bars and frames were eventually replaced by iron and steel structures.

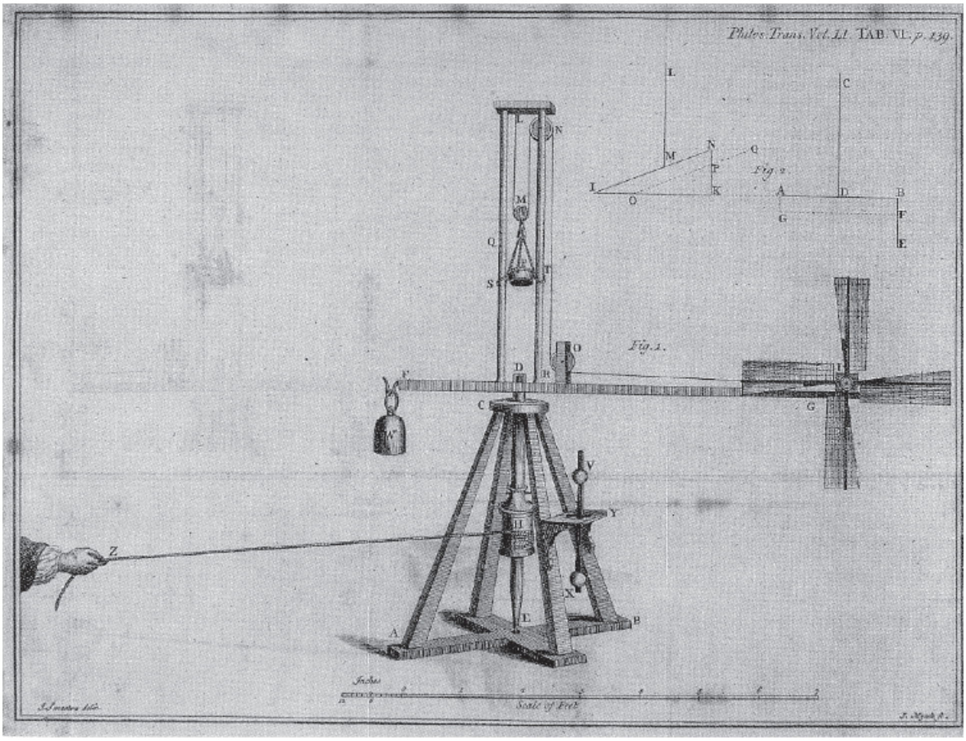



**Figure 1.11** Smeaton's test rig for determining the performance of windmill rotors

The path to a substantial increase in the aerodynamic efficiency was supported by scientific research from the middle of the eighteenth century. The most fascinating work was carried out by John Smeaton (1724–92) and can be seen as a precursor of modern research. His work was based on experiments with the apparatus that can be seen in Figure 1.11. With the pull on the sail the vertical shaft begins to rotate exactly as the arm at whose end the model of a windmill rotor is fixed. The rotor is acted upon by wind velocity flow that is equal to the blade tip speed of the arm. During the rotation, the rotor lifts a weight. By changing the rotor properties the optimum 'efficiency' (in modern terminology known as the 'performance') can be determined.

Smeaton presented the results of his experiments, *On the Design and Efficiency of Windmill Blades*, in a classic treatise that was presented to the Royal Society in 1759. The 'efficiency' was equal to the product of the weight and the number of revolutions that were carried out by the rotor in a particular period of time, whereby friction losses of the apparatus were to be equalised.

Smeaton determined the best form and 'weather' of the blades. In classical windmill technology, 'weather' designates the angle between the blade section and the rotation level. Today 'weather' is designated as the twist of the rotor blades. Later, Maclaurin investigated the local prevailing angle of attack with the aid of a distance function that describes the angle between the cross-section of the plant and the axis of the rotor. It is interesting to compare the work of Smeaton with that of current research, and for this reason the following paragraph will give the results of his experiments or ‘Maxima’ verbatim [3].

**Maxim 1**: The speed of mill blades for the same form and position is almost that of the wind. In this it is insignificant whether they are unloaded or loaded in such a manner that they produce a maximum.
**Maxim 2**: The maximum load is almost but a little less than the square of the wind speed insofar as the form and position of the blade are the same.
**Maxim 3**: The performance of the same blade with maximum power output is almost, but a little less, than the speed of the wind to the power of three.

His results from his theoretical contemplations:

**Maxim 6**: With blades with similar form and position, the number of rotations in a particular time period remains anti-proportional to the radius or length of the blade.
**Maxim 7**: The maximum loading that blades with similar form and position can take at a particular distance from the point of rotation has a value of the radius to the power of three.
**Maxim 8**: The effect of the blade with similar form and position has the value of the radius squared.

Besides the automatic wind-tracking yaw and the improved configuration of the blades, the efficiency of the windmills was improved by means of further innovations. For example, in 1772 Andrew Meikle obtained a patent for lamellae in the rotor blades in order to control the power output automatically. In 1787 Thomas Mead introduced the automatic control of these rotor blades by means of a centrifugal regulator.

With the invention of the steam machine (Watt), it was possible to generate power at will. The supply of energy could be perfectly adapted to the demand. Besides this, fuels such as coal and wood were relatively cheap. This had devastating effects on the use of windmills. During the nineteenth century, the overall number of windmills in northeastern Europe was reduced from an original 100,000 to 2000. Thanks to the active maintenance policy of the Verening de Hollandsche Molen (Dutch Mill Association), 1000 of the almost 10,000 windmills were able to be retained. These classical Holländer windmills are still capable of operation.

## 1.3 Generation of Electricity using Wind Farms: Wind Turbines 1890–1930

When the first electrical dynamos and alternating current generators were put into operation (see Box 1.1), use was made of all possible sources of power in order to drive the generators. The generators were operated by treadmills, wood- or coal-fired steam machines, water wheels, water turbines and wind rotors. In this, the wind was seen as only one of

**Box 1.1** Dynamos

The original name for the direct current generator was the ‘dynamo’. In contrast to this was the alternating current generator that generated alternating current via a slip ring or a rotor magnet. The first operational electric power station was built in New York in 1880. It consisted mainly of dynamos and operated arc lamps in a 2-mile-long circuit. There was strong competition between the proponents of direct current systems under the leadership of the American inventor Thomas Alva Edison, and the proponents of the alternating current systems under the leadership of the American industrialist George Westinghouse. Direct current had the advantage that the power could be stored in electrochemical batteries. The great advantage of the alternating current was that the voltage could easily be converted to a higher voltage level in order to reduce transmission losses and then could be converted back to a lower voltage level at the user end. Eventually the alternating current systems won the battle.

many possibilities for generating energy. In 1876, for instance, the improved direct current generator by Charles Brush was driven by a treadmill that was operated by horses.

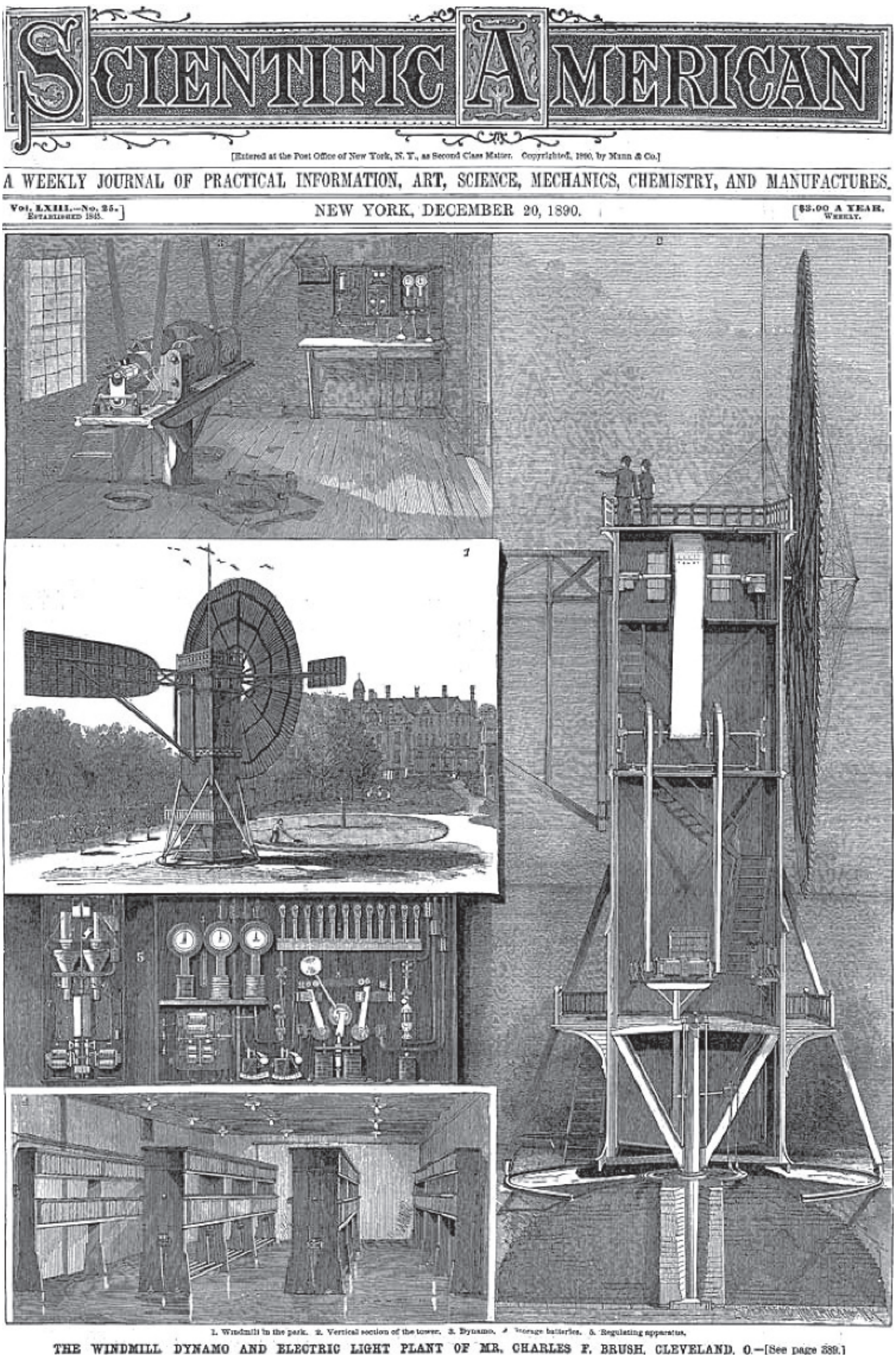
With the discovery of the dynamo it became possible to supply business users and individual households with energy by means of electricity from afar. Electricity could simply be transmitted from a central generator to the users. After the introduction of the first central electric power station, the demand for primary energy grew very quickly.

The development of the power-generating windmills (in the following called wind turbines) was not independent but overlapped with the availability of the first electric power stations and the first local power grids.

The first person to use a windmill for the generation of power was James Blyth, Professor at the Anderson College in Glasgow. His 1887, 10 m high wind turbine, whose blades were covered with sail cloth, was used to charge the batteries for lighting his holiday home.

In 1888 Charles Brush, the owner of a machine tool company, constructed a 12 kW wind turbine with a diameter of 17 m at his house in Cleveland, Ohio (US). In comparison with its rated power, the plant had a very large diameter. The rotor area was fully covered by 144 smaller rotor blades, which meant the speed of revolution was slow. This resulted in a very high transfer relationship from the rotor shaft to the generator. The power output was automatically controlled by a so-called ‘ecliptic controller’. The rotor was turned from the increasing wind out of the wind by a wind flag that was positioned vertically to the main blade wheel, whilst the main blade wheel was fixed to a slanted joint. A picture from *Scientific American* of 20 December 1890 (see Figure 1.12) shows the features of the plant.

Wind turbines were also used on board ships to generate power. The plants were erected on the deck and operated a dynamo by means of belt transmissions. The power was then used to load the batteries on board. The rotors possessed blades covered with sail cloth. Two examples of this are the *Fram*, the ship with which Fridtjof Nansen sailed to the Antarctic in 1888, and the *Chance* out of New Zealand (see Figure 1.13).



SCIENTIFIC AMERICAN

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A WEEKLY JOURNAL OF PRACTICAL INFORMATION, ART, SCIENCE, MECHANICS, CHEMISTRY, AND MANUFACTURES.

Vol. LXIII.—No. 25. Established 1845.] NEW YORK, DECEMBER 20, 1890. [$3.00 A YEAR. WEEKLY.

1. Windmill in the park. 2. Vertical section of the tower. 3. Dynamo. 4. Storage batteries. 5. Regulating apparatus.

THE WINDMILL DYNAMO AND ELECTRIC LIGHT PLANT OF MR. CHARLES F. BRUSH, CLEVELAND, O.—[See page 389.]

**Figure 1.12** Page from *Scientific American* magazine, 20 December 1890. Reproduced with permission of Scientific American/Wikimedia Commons


**Figure 1.13** Electrical generators on ships at the turn of the last century. Sailing ship *Chance*, New Zealand 1902. Reproduced with permission of National Library NZ/Wikimedia Commons

In 1891 Professor Poul la Cour constructed his first wind turbine in Askov, Denmark, in order to generate power which he used for various purposes. He connected his wind turbine, with four remote-controlled louvre blades, to two 9 kW dynamos. The power generated was used to load the batteries of the Askov Folk High School, and hydrogen was generated by the electrolysis of water with which gas lamps were operated. La Cour's developments were based on wind tunnel measurements at his school (see Figure 1.14).

The louvre blades used by Poul la Cour (see Figure 1.15) were invented and used in 1772 by Andrew Meikle in Great Britain. Meikle replaced the sail cloth with rectangular lamellae. With gusting wind, the lamellae automatically opened against the force of steel springs. This was the first possibility of automatic control and made the work of the miller much more comfortable. However, the stress of the springs still had to be set by hand. For this purpose the windmill had to be completely stopped.

Later, the lamellae were either controlled automatically or manually by means of a rod that ran through the hollow main shaft of the mill. In this way the mill could be controlled without constantly having to be stopped. The system was patented in 1807 by William Cubitt. The lamellae were controlled by means of a spider-like construction that can still be found today in classical windmills, among others in northern Germany, the UK and Scandinavia (see Figure 1.16).

Although the blades of La Cour's wind turbine possessed some innovations, the aerodynamic design was based on that of the classical windmill. It took about two decades for efficient aerodynamic profiles, developed from aviation, to be used for wind turbines.

Resulting from the experiments carried out by La Cour in Askov (see Figure 1.15), he made suggestions for their practical implementation from which, among others, the Danish manufacturers Lykkegaard and Ferritslev (Fyn) developed commercial wind turbines. By 1908, Lykkegaard had erected 72 wind turbines and by 1928 the number had risen to about

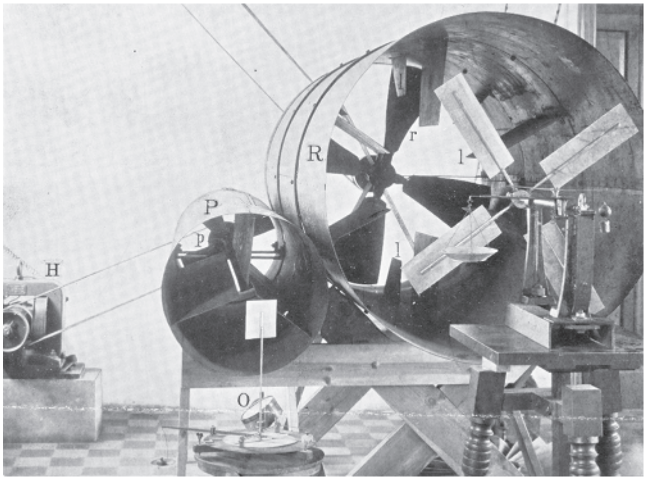



**Figure 1.14** Poul la Cour's wind tunnel. Reproduced with permission of Poul la Cour Fonden

**Figure 1.15** Poul la Cour's wind energy test rig in Askov, Denmark; right: wind turbine from the year 1891; left: larger plant from 1897 [9]. Reproduced with permission of Poul la Cour Fonden

120. The maximum diameter of the La-Cour-Lykkegaard wind turbines was 20 m. They were equipped with 10–35 kW generators. The plants generated direct current that was fed to small direct current grids and batteries. As fuel prices had increased greatly, the development of wind technology in Denmark continued during the First World War.

**Figure 1.16** Louvre blades in the mill at the Wall in the centre of Bremen [8]

Between the two world wars, attempts were made in the Netherlands to improve the efficiency of the classical windmills. At the TU in Delft, the helicopter pioneer Professor A.G. von Baumhauer and A. Havinga carried out measurements on four-blade rotors of classical windmills [10]. The stonework of the classical windmill, which was meant to support the improved rotors, would not have stood up to the axial forces as these also increased with the higher efficiencies of the rotors. In the 1950s and 1960s further experiments were carried out, all of which failed due to lack of structural integrity or for reasons of economy (Prinsenmolen; de Traanroeier, Oudeschild, Texel).

In 1920 in Germany, the leader of the Aerodynamic Experimental Institute in Gottingen, Albert Betz, published a mathematical analysis of the theoretical maximum value of the performance coefficient of a wind turbine with Zhukowsky, but after Lanchester (1915) (this is usually called the Lanchester-Betz coefficient and is 16/27 = 59.3%). It is based on the axial flow model. In addition, Betz also described wind turbines with improved aerodynamic blades [11]. Figure 1.17 shows a fast-rotating four-blade wind turbine from the Aerodynamo Company in Berlin.

The plant had brake flaps on the low-pressure sides of the blades. Immediately after the First World War it was Kurt Bilau who wanted to improve the efficiency of his four-blade Ventimotor by giving the aeroprofile of the blades a streamlined form. He even asserted that he had reached a higher efficiency than Betz stated later as the maximum value for the performance coefficients. Besides this, Bilau erected test plants in East Prussia and in southern England.

After the First World War the availability of fossil fuels rose substantially, which meant that interest in wind energy declined. In the Western industrial world, the further development of wind energy was carried out in a very low-key manner until the Second World War. However, this was not the case in the Soviet Union, because there the Stalin Regime instituted a large programme for electrification of remote areas. The little information from those times show that the Soviet engineers made use of the latest developments of aerodynamics for their concepts. An example of this is shown in Figure 1.18.

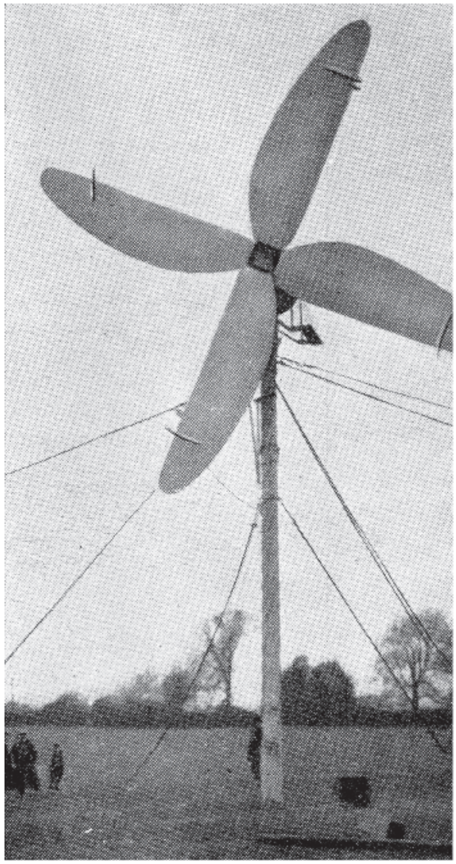


**Figure 1.17** Fast-rotating wind wheel of the Aerodynamo A.G. Berlin, Kutfürstendam. The figure shows the brake flaps used by this company on the suction side of the blades [12]. Photograph originally taken by Betz, A. and used with thanks

The rotor blades, developed by the Central Aerohydrodynamic Institute (ZAGI), can be adjusted by means of a small auxiliary blade at the rear edge of the main blade. In 1931 an experimental wind turbine was built near Sevastopol on the Crimea that was operated in parallel with a peat-fired 20 MW electric power station. The WIME D-30 plant had a rotor diameter of 30 m and a nominal output of 100 kW. It remained in operation until 1942. The wind turbine (Figure 1.19) possessed similar aerodynamic features as the smaller model in Figure 1.18.

## 1.4 The First Phase of Innovation: 1930–1960

Various countries resumed the development of wind turbines during, and immediately after, the Second World War. The reason for this was that strategic resources such as fossil fuels were becoming scarce. In this period many innovations were introduced, which probably permitted the widespread introduction of wind turbines for power generation parallel to the power grid. These innovations, primarily on the structure of the rotor, were based mainly on the innovations of the previous era.

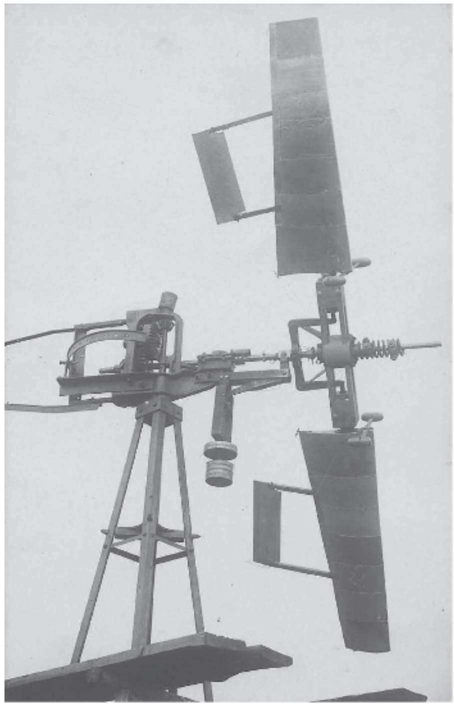


**Figure 1.18** ZAGI turbine with Sabinin's auxiliary blades. Rotor diameter 3.6 m, with complete control of the blade adjustment angle [8]

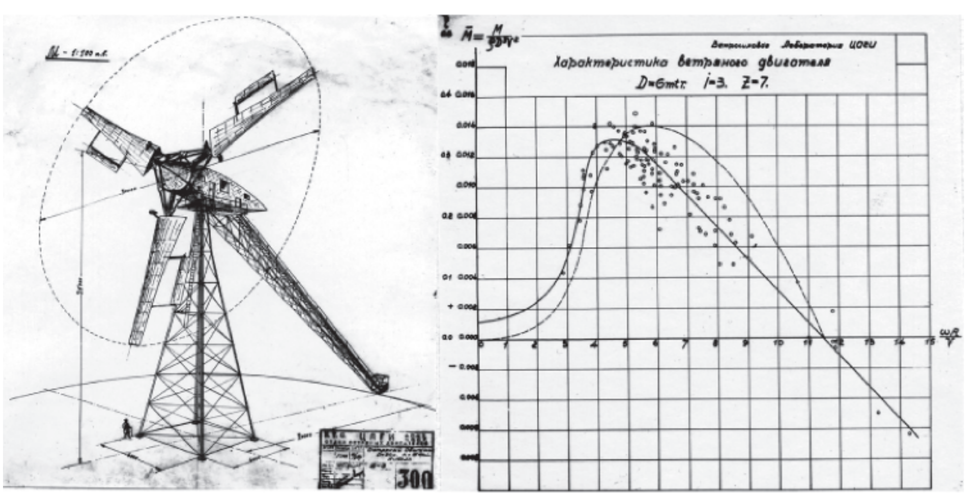


**Figure 1.19** Left: concept of the wind turbine near Sevastopol on the Crimea: in operation from 1931 to 1942, rotor diameter 30 m. Right: measured performance factors and torque coefficient as a function of the revolution speed [8]

**Figure 1.20** An out-of-service Smidth-Aeromotor in Denmark. Rotor diameter 24 m, nominal output approximately 70 kW. Photo by Paul Smulders in 1972

The most important developments occurred in Denmark, the US and Germany. During the Second World War the F.L. Smidth Company in Copenhagen developed wind turbines for generating electricity. As Denmark did not possess its own fossil fuels, wind energy was one of the few ways of generating power. The Smidth plants possessed two-blade rotors; the blades had a fixed angle of attack, were not adjustable and were stall-controlled. With these rotor blades, the performance coefficient was comparatively low but the performance curve was relatively broad. This meant that the efficiency of the overall system, when spread over a wide spectrum of wind speeds, was relatively high. The Smidth aeromotors had a rotor diameter of 17.5 m (the nominal output was 50 kW) and were erected either on steel lattices or concrete towers. After problems with the dynamic properties of the two-blade rotors, Smidth introduced a larger plant with a rotor diameter of 24 m (nominal output 70 kW). Altogether seven of these plants were built. With a single exception they were all equipped with direct current generators (see Figure 1.20). This type of plant became the blueprint for the development of modern wind energy after the first energy crisis in 1973.

It was J. Juul who used the three-blade concept of Smidth around 1957 to build a 200 kW version in Gedser with a diameter of 24 m (see Figure 1.28). The machine had an asynchronous generator and was connected directly to the grid. It had three rotor blades, was stall-controlled and possessed movable blade tips in order to prevent overturning when the load was lost. The Gedser wind turbine became the archetypal 'Danish wind turbine' of a generation of very successful wind turbines after the 1973 energy crisis.

After the publications of Betz in 1920 and 1926, Hermann Honnef, on the basis of the analytical results of Betz and others, conceived a very large structure with several rotors. This was possibly the first concept that was based completely on scientific knowledge. His concept had

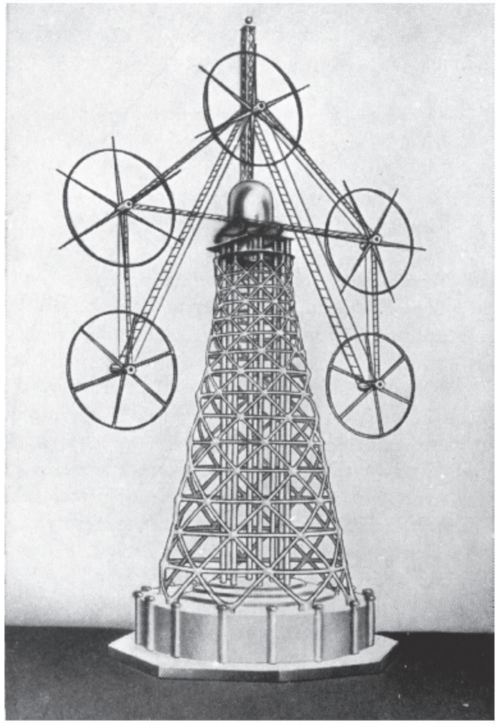


**Figure 1.21** Vision of a $5 \times 20$ MW, $5 \times 160$ m wind turbine by Hermann Honnef, 1933

five rotors, each with a diameter of 160 m, and six blades each. Each rotor was meant to drive a 20 MW generator. The rotors consisted of two counter-rotating wheels. On 80% of the rotor surface they each carried a ring (see Figure 1.21). The rings were part of a giant 'ring generator'. The concept was far in advance of what at that time was technically feasible, since it is only now (2012) that plants of similar size are being designed and built (see also Figure 1.35).

With the support of the Board of Trustees for Wind and Water Power, which was founded in 1941 in order to support inventors in the search for sources of energy, Honnef built a model of the Multirotor with two blades on a test field on the Mathiasberg, northwest of Berlin. After the war the test field was destroyed by the Soviets and the plant was melted down in the furnaces of Hennigsdorf.

With the collapse of the Third Reich, Honnef had to end his work in the field of wind energy in March 1945. Previously the search for independence in the supply of energy led in 1939 to the founding of the Reichsarbeitsgemeinschaft Windkraft (RAW: Reich Working Group for Wind Energy), in which scientists, inventors and industry collaborated. A project supported by the RAW was the three- or four-bladed wind turbine planned by Franz Kleinhenz, equipped with a rotor diameter of 130 m and a nominal output of 10 MW and was designed in cooperation with the MAN company. However, the war hindered the planned construction in 1942.

From the end of the war to the resumption of research and development for wind energy during the oil crisis in 1973 and beyond, Professor Ulrich Hütter was a leading figure in Germany, and led a test rig of the Venti-motor GmbH in Webicht, Weimar. There he obtained

**Figure 1.22** Allgaier WE 10 wind turbine

much practical experience in the design of smaller wind turbines. Hütter received his degree in December 1942 at the University of Vienna with his dissertation *Beitrag zur Schaffung von Gestaltungsgrundlagen für Windkraft-werke* [Contribution to the creation of design basics for wind turbines]. During his career he worked alternately in aviation technology and wind energy technology. The first wind turbine to be built after the end of the war was by Hütter in 1947.

In 1948 Erwin Allgaier wanted to build his wind turbine in series (three rotor blades, 8 m rotor diameter, 13 kW nominal output). Slightly larger plants (11.28 m rotor diameter, 7.2 kW nominal output) were exported to South Africa, Ethiopia and Argentina. Because of a relatively high tip speed ratio of 8, the wind turbines were very light. Also the equipped capacity per unit of covered rotor surface was very small so that the wind turbine was suitable for low wind regimes and, at the same time, delivered a relatively high equivalent full load hours (capacity factor) (see Figure 1.22).

In order to provide power in remote areas, the brothers Marcellus and Joseph Jacobs began to develop wind turbines for loading batteries in the US in the early 1920s. After experiments with two-blade plants they introduced a three-blade wind turbine with a rotor diameter of 4 m and a directly-driven direct current generator. Several thousand of these plants were sold between the early 1920s and the first years after the 1973 oil crisis (see Figure 1.23).

With the extension of the rural power grid, the supply of power to rural areas presented no great problem anymore and the development of wind energy turned towards large plants for the operation of the grid. During the Second World War, wind turbines seemed to be a potential strategic technology for the utilisation of sources of energy that could be used in times of crisis.

**Figure 1.23** Wind farm with Jacobs wind turbines, Big Island, Hawaii, 1988 [8]

**Figure 1.24** Smith-Putnam wind turbine on Grandpa's Knob near Rutland, Vermont, US [13]. Reproduced with permission of John Wiley & Sons

The first megawatt plant ever built was the Smith-Putnam wind turbine designed by Palmer C. Putnam and built by the S. Morgan Smith Company (York, Pennsylvania) that was erected on Grandpa's Knob, a 610 m high hill near Rutland, Vermont (see Figure 1.24). This plant consisted of an idler with a rotor diameter of 53.3 m. It was equipped with individually adjustable rotor blades and the nominal output of the synchronous generator was 1.25 MW.

The power output was controlled by means of hydraulically adjusted blade angles. The rotor had no blade twist and a constant blade width. The plant was in operation from 1941 to 1945, and during its 1000 hours running time fed electricity into the grid of the Central Vermont Public Service Company. After the plant lost a rotor blade on 26 March 1945, it was taken out of service as the financial means for repairing the rotor were not available. It took until the oil crisis for Putnam's experience of realising a whole series of large wind turbines to be used in the US.

Among the reasons for the development of wind energy after the Second World War were [14]:

- The rapidly rising demand for electricity, whereas most communities had no local sources of energy;
- Energy sources near the users were already depleted; and
- Poverty after the war and the political conditions led to the search for local sources of energy, instead of relying on imported fuels.

The knowledge of aerodynamics and materials that was made available by engineers occupied during the war in the military industry, and now active in civilian industry, eased the conditions for continuing with the development of wind turbines. Because of the new technologies, the possibility of building even more successful plants than that on Grandpa's Knob was opened up.

Later, in the 1950s, critical scientists and politicians recognised that coal and oil should not be burnt for the purpose of power generation but were more suited as materials. A further fact was cause for consideration: the thought of being dependent on only one source of energy (oil) that had to be imported from politically unstable regions. This consideration was the first indication of a political debate about democracy, limits of growth and utilisation, diversity and environmental loading for industrial development that began in the 1960s, and peaked with the publication of the study *The Limits to Growth* (Meadows *et al.*) of the Club of Rome [11].

From the 1950s until the onset of the first energy crisis in 1973, it was not only Denmark, the US and Germany that contributed to further development of wind energy, but also countries such as France and the UK took part. Surprisingly, the Netherlands, the country known as the Land of the Windmill, did not take part in the development for modern utilisation of wind energy, but attempted to use classical windmills for power generation.

In 1950 the John Brown Company built a three-rotor plant with a nominal output of 100 kW and a rotor diameter of 15 m that was operated in parallel with a diesel aggregate on the Scottish Orkney Islands for the North of Scotland Hydroelectric Board [3]. The rotor blades were fixed to a hub by means of blade flapping hinges. However, the complex rotor failed after some months.

At the same time the French engineer Andreau designed a two-rotor plant with a very extraordinary transmission technology. The rotor blades were hollow and had an opening at the ends. The rotor thus acted as a centrifugal pump that pulled air in through the opening at the base of the tower. The air passed through an air turbine that was positioned at the foot of the tower and drove a generator. This caused a soft transmission that was an alternative to the rigid drive trains that were based on directly-connected synchronous and induction generators. In 1951, De Havilland Propellers built a prototype plant for Enfield Cables Ltd. in St Albans (Hertfordshire) (see Figure 1.25). As it was impossible to operate the plant economically due

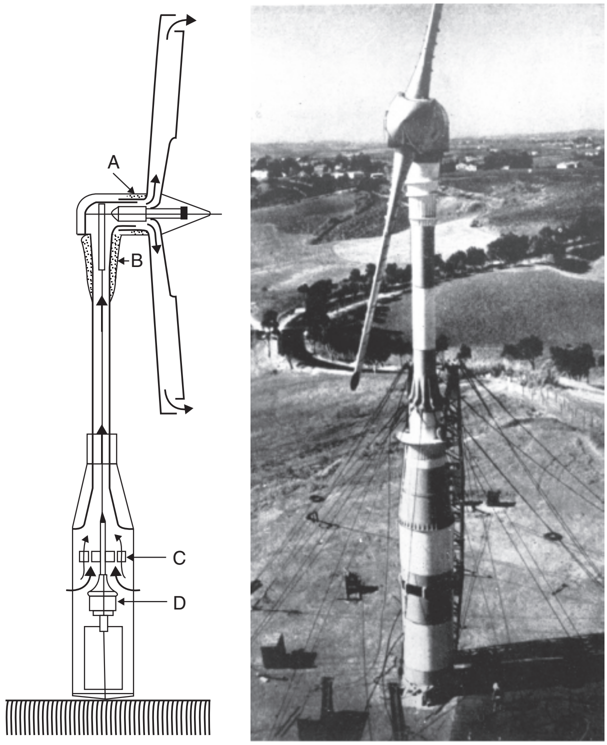



**Figure 1.25** Left: Sketch of the operation of the Andreau-Enfield wind turbine; right: Andreau-Enfield wind turbine in Algeria

to the low wind speed at the site and a low transmission efficiency of 20%, it was taken down in 1957 and re-erected in Grand Vent in Algeria, but taken out of service again after a short period of activity. Although the concept was extraordinary, it was not unique. In 1946 Ulrich Hütter had previously presented a hollow one-blade plant that was meant to act as a centrifugal pump. As a counterweight, the air turbine and the generator were fastened on the opposite side of the rotor blade (see Figure 1.26). R. Bauer designed a one-blade plant with a rotor diameter of 3 m that was operated from 1952 by the Winkelstraeter GmbH.

Besides Andreau, various other French engineers were involved in the design of wind turbines. In 1958 L. Romani built an 800 kW, three-blade pilot plant with a rotor diameter of 10.1 m for the EDF (Electricité de France) energy supplier in Nogent-le-Roi near Paris (see Figure 1.27). The so-called Best-Romani plant was equipped with a synchronous generator and was taken out of service in 1963 when a rotor blade dropped off.

At the same time Louis Vadot designed two wind turbines with similar equipment as the Best-Romani plant and erected them for the Neyrpic in Saint-Rémy-de-Landes (Manche). One of the plants had a rotor diameter of 21.1 m (132 kW), the other had a diameter of 35 m (1 MW), and both possessed induction generators. As EDF lost interest in wind power, the plants were taken out of service in 1964 and 1966.

Simultaneously with the technical development, the researching industrial associations of various countries were requested by international organisations to present their results at

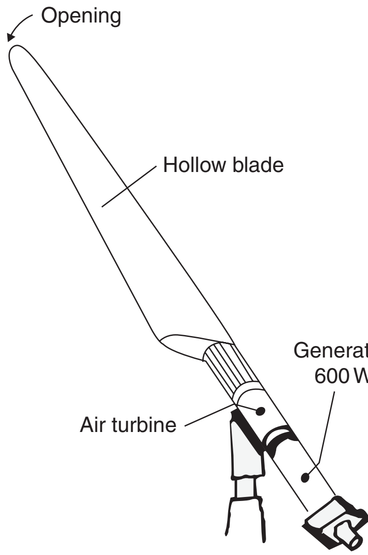



**Figure 1.26** Hütter concept of the single-blade rotor with aerodynamic force transmission. The blade length is 6 m.

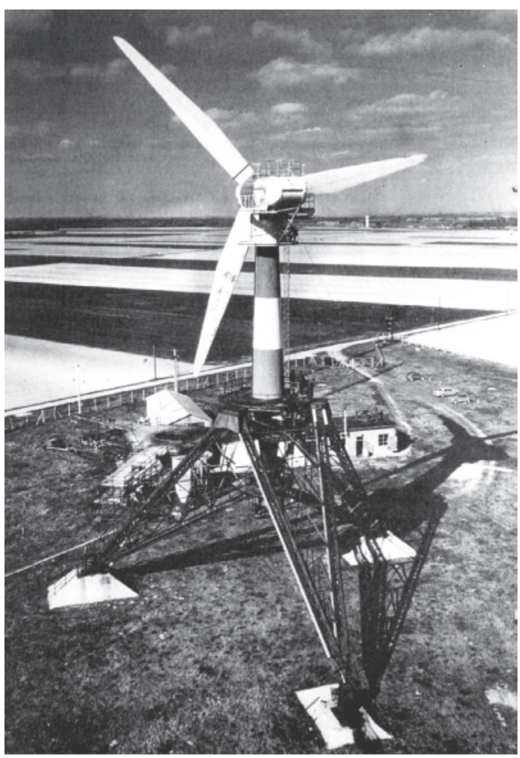


**Figure 1.27** Wind turbine by Best-Romani in Nogent-le-Roi (Eure et Loir), France

international conferences. Among these institutes was UNESCO, the Organization for European Economic Cooperation (OEEC) and the World Meteorological Organization (WMO). The proceedings of these organisations [see 15–17] provided an excellent overview on the progress of wind turbine technology from the end of the war to the start of the oil crisis.

Interestingly, the use of wind power expanded again from industrial regions to remote arid regions and developing countries. Besides the advances in theory and technology, the further potential for wind power was being increasingly discussed. These international conferences were the first modest steps towards comprehensive international grids in the field of wind power that exist today.

From today's point of view, it is surprising how many modern discoveries were made and tested in the period from 1930 to 1960. The developments were based less on analytical methods than on experiments. Not all experiments were successful and many technical errors were made. There were no financial means available for repairs or the continuation of wind power technology. Most of the pilot projects that were carried out in France, the UK, Germany, the US and Denmark were stopped and the equipment was destroyed, with the exception of the wind turbine in Gedser, Denmark. Why this plant was so successful will be explained in the next section. The development of wind power was completely stopped due to the lack of financial means. One reason was the fact that fossil fuels became particularly cheap and nuclear power more popular. This optimistic scenario came to a sudden stop with the publication of the study *The Limits to Growth* [11] and the outbreak of the oil crisis in 1973.

Table 1.1 provides a short overview of the modern concepts that were developed in this time. The overview also includes an indication of the success of the invention.

## 1.5 The Second Phase of Innovation and Mass Production: 1960 to Today

Almost all important technological developments in wind power were ended by the middle of the 1960s. Fossil fuels were freely available and very cheap, and nuclear power was seen as the solution to all future energy problems. Although in the circles of the decision-makers there was little discussion on supply security or about environmental and safety matters, society had doubts regarding the limitless growth of the economy and its influences on permanently available resources. The publication of the study *The Limits to Growth* in 1971/1972 commissioned by the Club of Rome [11], the resulting discussions, and the outbreak of the oil crisis in 1973 as the result of a further Near-East conflict, turned the supposed future problems into current and present problems.

The political reactions to the crisis led to a new energy policy that was based on the following key problems:

- The dependency on energy monopolies (oil) was to be limited by diversifying energy supply options, among others by the use of local sources of energy with a simultaneous increase in energy efficiency.
- Fossil sources of energy were to be reserved for the manufacture of materials and should not be burnt for the generation of energy faster than they could regenerate themselves.

About a decade later, environmental concerns (fossil fuels, nuclear waste) and security considerations (nuclear energy at Three Mile Island, Chernobyl) became loud in the political debate.

**Table 1.1** Innovation and development from 1930 to approximately 1960 (selection)

| No. | Description | Inventor/ developer | Country | Application today |
|---|---|---|---|---|
| | **Rotor** | | | |
| 1 | High-speed machine: three rotor blades | Smidth Aeromotor | (1942) | Yes |
| | | Jacobs (1932) | US | Yes |
| 2 | High-speed machine: two rotor blades | Smidth (1942) | Denmark | Yes |
| 3 | Stall control: three rotor blades | Smidth (Gedser) | Denmark | Yes, medium-sized turbines |
| 4 | Blade tip brakes for stall control | Juul (Gedser) | | |
| 5 | Stall control: two rotor blades | Smidth (1942) | Denmark | Yes, limited size |
| 6 | Single blade rotor | Bauer (1945) | Germany | Yes, limited |
| 7 | Complete blade angle setting, active | John Brown | UK | Yes |
| | | Neyrpic-Vadot (1962–64) | France | Yes |
| 8 | Complete blade angle setting control supported by auxiliary blade | WIME | USSR (1932) | No |
| | | ZAGI | USSR (1930) | No |
| 9 | Flettner rotor on ships | Flettner (1925) | Germany | No (with the exception of the Enercon experiments) |
| | Flettner rotor on rails [18] | Madaras (1932) | US | No |
| 10 | Counter-rotating rotor | Honnef (1940) | Germany | No |
| 11 | Introduction of GFK for rotor blade materials | Hütter | Germany | Yes |
| | **Capacity** | | | |
| 12 | >1 MW nominal power, 4 rotor blades | Draft by MAN-Kleinhenz (1942) | Germany | No |
| 13 | >1 MW nominal power, 2 rotor blades | Smith-Putnam (1.25 MW, 1945) | US | Yes |
| 14 | >1 MW nominal power, 3 rotor blades | Neypric-Vadot (1 MW, ca. 1960) | France | Yes |
| | **Pilot** | | | |
| 15 | Multirotor | Honnef (1932) | Denmark | Yes, strongly limited size in NL |
| 16 | Vertical axle rotor | Darrieus (patent 1930) | France | Yes, limited size |
| 17 | Idler | Kleinhenz (1942) | Germany | Yes, limited size |
| 18 | Concrete tower | Smidth Aeromotor | Denmark | Yes |
| 19 | Rotor works as centrifugal pump; generates flow for the air turbine drive generator; two rotor blades | Andreau Enfield | France, UK | No |
| 20 | Rotor works as centrifugal pump; generates flow for the air turbine drive generator. | Hütter | Germany | No |

Within the framework of the new energy policy, many countries turned immediately to renewable sources of energy. This included solar energy and other sources of energy such as wind power, biomass, and the generation of energy from the warmth of the ocean. Investigations were also carried out in the area of further sources such as geothermal and tidal energy. The first research programmes on a national level were introduced by 1973, and wind power played an important role in many of them. There were many similarities in the programmes: resource availability, selection of sites, technological options, requirements for research and development, potential influences on the national energy balances, (macro-)economic and social influences and implementation strategies. However, the specific approaches and projects differed substantially from country to country. Looking back, it can be said that the most successful projects were realised where time and money provided a balance between technological developments, market development (on the demand as well as on the supply side) and political support (research funds, laws, and infrastructure). However, this was not foreseeable on the middle of the 1970s. Some countries started to develop wind turbines from basics and carried out all kinds of analysis without taking the market or the infrastructure into account. Examples of this took place in the UK, the Netherlands, Germany, Sweden, the US and Canada. Without exception, they all preferred large wind turbines as a basis for long-term energy scenarios.

Because of experiences in the past, however, this was not particularly surprising. Although not all of them were successful, the experiments and analyses of Hütter, Kleinhenz, Palmer Cosslett Putnam, Juul, Vadot, Honnef, Golding and others all tended in the same direction: the introduction of wind power on a large scale would only be economically realisable when very large wind turbines with a capacity of several megawatts were used.

The construction of such large plants was seen not only as technically feasible, but also economic. This becomes clear from the minutes of the American Congress from the year 1971 that refer to a corresponding study of 1964 [19]. A research group commissioned by the government under the direction of Ali B. Cambel came to the following conclusions:

> 'Sufficient knowledge is available to build a prototype with a capacity of 5,000 to 10,000 kW which permits a realistic estimate of wind power usage. A design study and a meteorological investigation of the possible sites would have to precede the actual construction. Such a program would provide important information on the economics of wind turbines and their integration into the power grid […]. Wind energy provides a reliable source of energy also in the long term […]. It is inexhaustible and has no negative effect on the environment as it produces no damaging and undesired side products.'

Because of this, the multimegawatt wind turbines became the technical basis of all state-supported developments. The only country that did not follow this general trend of focusing on large wind turbines was Denmark. There, risky technical experiments were avoided from the start, market introduction was stimulated, and politics supported the introduction of institutional framework conditions.

Independently of the parallel state-supported programmes, pioneering companies began with the development and sales of small wind turbines for water supply, for loading batteries and for connection to the grid. Many of these companies were inspired by E.F. Schuhmacher's 'Small is Beautiful' vision of 1973. In the early 1980s about 30 companies were active in the market in Denmark and about 20 in the Netherlands. A special case is the Tvind wind turbine in Ulfborg, Denmark. Between 1975 and 1978 teachers and students of the Tvind international school centre built a 2 MW, 54 m rotor diameter wind turbine with three manually (!) pitch controlled blades. The construction of the blades and the materials used was trend setting for modern manufacturing technology.

Also non-governmental organisations (NGOs) participated with the aim of using wind power for water supply for households, for irrigating fields and for watering farm animals in developing countries. The utilisation of their own sources of energy for covering the main demands were important for further development, and required hardly any outside capital. These organisations often had connection to universities. Examples of this are the SWD/CWD in the Netherlands, the ITDG in the UK, the BRACE institute in Canada, the Folkcenter in Denmark, the IPAT in Berlin, as well as several associations in various countries as well as the US, that were networked with universities.

In the following section, the various technical developments are discussed in greater detail. As the developments that took place after the oil crisis were so far-reaching and varied, it is not possible to describe them in as great a detail as the development in the historical epochs. The following description limits itself to the general tendencies and presents the most important cases.

First described are the state-supported developments of wind turbines. The best sources for historical details are the reports issued annually since 1985 by the IEA (International Energy Agency) wind energy programme.

National projects often made contributions to the IEA programme. Almost simultaneously with the state-supported development of large wind turbines, small pioneering companies developed small wind turbines. The consequent extension and enlargement of these wind turbines formed the foundation of the present market. In the following, current developments such as wind farms, offshore farms and the connection to the power grid are discussed.

### *1.5.1 The State-Supported Development of Large Wind Turbines*

The first experiments were carried out in Denmark and formed a collaborative project between Denmark and the US. As already mentioned, although the wind turbine in Gedser was taken out of operation in 1966, it was not pulled down. The first step to a resuscitation of wind power development was the restarting of the wind turbine in Gedser in 1977 (see Figure 1.28).

The results of the mutual Danish-American measurements and tests served as a starting point both for the development of the wind power research programme of NASA, as well as for Danish research and economic activities. The design principles of Ulrich Hütter were also an important component of the American research and development programme. Besides Denmark and the US, important research and development programmes were being kicked into life in the late 1970s in the Netherlands, Germany, Sweden, the UK, Canada, and later in Italy as well as Spain. Smaller programmes, or rather projects, were also in existence in Austria, Ireland, Japan, New Zealand and Norway. The first group of countries adopted the development of large wind turbines. The two main questions in the conception of the first large pilot plants were:

- What potential was offered by wind turbines with vertical axles (Darrieus rotor) in comparison with wind turbines with horizontal axles?
- What strategy was to be followed in order to develop cheap wind turbines in the medium term?

Should one first adopt the more risky but also potentially more advantageous direction to light, fast- running turbines with corresponding rotor concepts? Or should one go first for reliability and step-by-step improvement of the already-tested designs from before 1960?

**Figure 1.28** Gedser wind turbine in the early 1990s [8]

The US, the Netherlands, the UK and Germany carried out a systematic analysis of the potential of horizontal axle plants compared with plants with a vertical axle. From the start Canada focused on plants with vertical axles and Denmark was the only country that followed the first strategy. The first large wind turbines were put into operation in 1979 (Nibe 1 and 2 in Denmark) and the last purely experimental, non-commercially operated wind turbine was completed in 1973. In total, in the various countries about 30 pilot-only plants that had strong state support were built.

Tables 1.2 and 1.3 provide an overview of a selection of these wind turbines. The commercial prototypes are also shown. Figures 1.29 to 1.33 show some of these wind turbines, whose technical designs were very diverse. Many innovations of the past (Table 1.1) were newly designed and implemented. Substantial improvements were achieved by incorporating glass-fibre reinforced plastics into the rotor structure, and new electrical conversion systems were utilised.

The finite element method (FEM), even if not as developed as today, was used for improving the design of the sensitive components of the wind turbine, especially the structure of the hub. The basics of comprehensive design methods were very incomplete. In aerodynamics there were at best only imprecise simulations of flow separations, three-dimensional effects, aeroelastic modelling, and so on. The same applied to wind description at the rotor level, the effects of turbulence on performance, and the mechanical loading as well as the modelling of the flow tails.

**Table 1.2** Selection of state-supported pilot plants

| Wind turbines (land) | Rotor diameter, m | Rated capacity, MW | Year of start-up | Commercial successor |
|---|---|---|---|---|
| Nibe 1 (Nibe, Denmark) | 40 | 0.63 | 1979 | No |
| Nibe 2 (Nibe, Denmark) | 40 | 0.63 | 1979 | No |
| 25-m-HAT (Petten, Netherlands) | 25 | 0.4 | 1981 | No |
| 5 × MOD-0 (Sandusky, Ohio; Clayton, New Mexico; Culebra, Puerto Rico; Block Island, Rhode Island; Kuhuku Point, Oahu-Hawaii) | 38.1 | 0.1–0.2 | Since 1975 | No |
| WTS-75 (Näsudden, Sweden) | 38.1 | 0.1–0.2 | Since 1975 | No |
| WTS-3 (Marglarp, Sweden) | 75 | 2 | 1983 | No |
| WTS-4 (Medicine Bow, Wyoming, US) | 78 | 3 | 1982 | No |
| MOD-1 (Boone, North Carolina, US) | 61 | 1 | 1979 | No |
| 5 × MOD-2 (3 in Goodnoe Hills, Washington State; Medicine Bow, Wyoming; Solano, California, US) | 91 | 2.5 | 1980 | No |
| MOD-5B (Kahuku Point, Oahu-Hawaii, US) | 97.5 | 3.2 | 1987 | No |
| ÉOLE (Cap Quebec, Canada) | 100 | 4 | 1980(?) | No |
| GROWIAN (Kaiser-Wilhelm-Koog, Germany) | 100.4 | 3 | 1982 | No |

**Table 1.3** First large European wind turbines – development and pilot series

| Wind turbines (land) | Rotor diameter, m | Rated capacity, MW | Year of start-up | Commercial successor |
|---|---|---|---|---|
| **European programme WEGA I** | | | | |
| Tjæreborg (Esbjerg, Denmark) | 61 | 2 | 1989 | No |
| Richborough (UK) | 55 | 2 | 1989 | No |
| AWEC-60 (Cabo Villano, Spain) | 60 | 1.2 | 1989 | No |
| **European programme WEGA II** | | | | |
| Bonus (Esbjerg, Denmark) | 54 | 1 | 1996 | Yes |
| ENERCON E-66 (Germany) | 66 | 1.5 | 1996 | Yes |
| Nordic (Sweden) | 53 | 1 | 1996 | No |
| Vestas V63 | 63 | 1.5 | 1996 | Yes |
| WEG MS4 | 41 | 0.6 | 1996 | No |
| **THERMIE European presentation programme** | | | | |
| Aeolus II (Germany and Sweden) | 80 | 3 | 1993 | No |
| Monoptoros | 56 | 0.64 | 1990 | No |
| NEWECS 45 (Stork, Netherlands) | 45 | 1 | 1991 | No |
| WKA-60 (MAN, Helgoland, Germany) | 60 | 1 | 1989 | No |
| NEG-MICON (Denmark) | 60 | 1.5 | 1995 | Yes |
| NedWind (Netherlands) | 53 | 1 | 1994 | Yes |

**Figure 1.29** Left: Heidelberg wind turbine with vertical axle in Kaiser-Wilhelm-Koog [8]; right: GROWIAN wind turbine in Kaiser-Wilhelm-Koog [8]

**Figure 1.30** Left: 25-M HAT wind turbine in operation in Petten, the Netherlands; middle: Canadian EOLE wind turbine with Darrieus rotor; right: WTS-75 wind turbine in Näsudden, Gotland, Sweden [8]

Included in the wind turbine concepts were, among others:

- Rotors with one to three rotor blades for wind turbines with horizontal axes, and two or three rotor blades for plants with vertical axles.
- Rigid hubs, teetering hubs and movable hubs.

**Figure 1.31** Left: Nibe wind turbine in Jutland, Denmark; right: WEST wind turbine with single-blade rotor in the foreground and two-blade plant in the background in the Alta-Nurra pilot field, Sardinia, Italy [8]

**Figure 1.32** MOD-2-wind turbine in Solano, California, US [8]

**Figure 1.33** Disassembled AWCS-60 in Kaiser-Wilhelm-Koog, Germany [8]

- Rigid rotor blades, stall control and complete or partial control of the blade adjustment angle.
- (Almost) constant and variable revolution transfer systems.

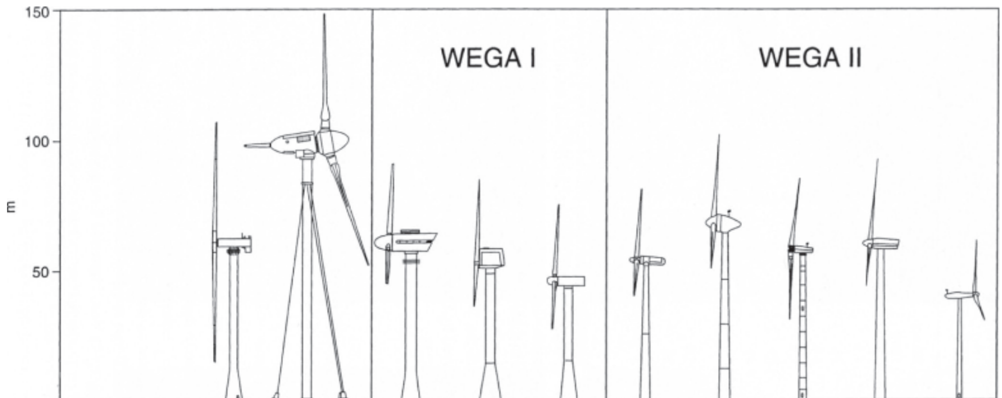
In addition, a spectacular series of installation techniques were used. The methods ranged from the conventional installation with the aid of a crane, to the use of the tower of the plant as a lifting device for platforms that were used to position the motor housing and the rotor blades.

After a modest start with regard to financial means, by 1988 the European programme started to strengthen support for the development of large wind turbines. These changes in politics were preceded by exhaustive discussions with scientists and representatives of the industry on the optimum industrial strategies and market potentials.

The results of these talks were that the manufacturers, who were already active earlier in the production of smaller plants and who had a serious interest in commercialising large wind turbines, reacted to the initiative of the European Commission and closed contracts for the development and construction of the first commercial prototypes of megawatt wind turbines. The participation of commercial companies in this programme changed the industry permanently. The programme for testing and evaluation, financed by individual governments and implemented by large construction and aviation concerns, slowly came to an end. The physical end for some wind turbines was quite spectacular: MOD 2, GROWIAN and Aelous II were dynamited.

The design philosophy of the commercial prototypes was based on the gradual enlargement of smaller plants, and was developed and commercialised by some of the pioneer companies that survived a serious crisis in the 1980s.

The most successful wind turbines at the start were not the most advanced, fast-running models, but rather those that possessed many features of the well-known ‘Danish concept’. This concept was based on the blueprint of the Gedser wind turbine. Figure 1.34 offers an overview of the WEGA I and II European programmes.




| Rated Power | 2500 kW | 3000 kW | 2000 kW | 1000 kW | 1200 kW | 1000 kW | 1500 kW | 1000 kW | 1500 kW | 600 kW |
|---|---|---|---|---|---|---|---|---|---|---|
| Rotor Diameter | 91 m | 100 m | 61 m | 55 m | 60 m | 54 m | 66 m | 53 m | 63 m | 41 m |
| Year of Construction | 1981 | 1982 | 1989 | 1989 | 1989 | 1996 | 1996 | 1996 | 1996 | 1996 |
| Location | USA | Germany | Tjaereborg, DK | Richborough, GB | Cabo Villmo, E | Tjaereborg, DK | Germany | Sweden | Danmark | United Kingdom |
| Type | MOD-2 | GROWIAN | ELSAM 2MW | HOWDEN 1MW | AWEC-60 | BONUS 1MW | ENERCON E-66 | NORDIC 1MW | VESTAS V63 | WEG MS4 |

**Figure 1.34** Overview of the large wind turbines developed in Europe [21]. Reproduced with permission of Keesing Media Group

The WEGA and THERMIE programmes ushered in the steady expansion of wind turbines (see Figure 1.35). Typical for this development phase was the consistent expansion of the smaller, commercially successful wind turbines. Many of the advanced technical designs such as teetering hubs, idlers, and fast-moving rotors with one or two rotor blades were given up by the industry. Their first prototypes were rather conservative as the customers were primarily concerned with reliability and not so much with advanced systems with potential for future cost savings. The innovations that were later developed differentiated themselves from the first generation of plants. The greatest further development was the performance electronic converter, as it allowed much improved control of the turbines. With these conversion systems, together with control of the blade adjustment angle and advanced multiparameter control strategies, the modern plants correspond to the demands of the power grid. Critical development and design procedures and the use of new materials led to a reduction in weight and thus to a reduction in the costs of power generation.

With the enlargement of the wind turbines, there was also an immense increase in the market volume of the wind turbine (see Figure 1.36). The product life of a particular type of wind turbine, when based on the turbine capacity, is usually six years and has extended with the growth of the turbine size since 2002 [20].

Technical knowledge has increased especially in the fields of aerodynamics, the modelling of flow loops in wind farms, aeroelasticity, finite element modelling, construction dynamics, measuring techniques, system modelling and control techniques.

The purely analytical results needed to be certified, whereby, besides laboratory installations, experimental wind turbines were also erected on the open air. The laboratory installations consisted mainly of test rigs for rotor blades, experimental stands for materials, as well as test rigs for drive trains and wind tunnels. Most of these research arrangements originated from

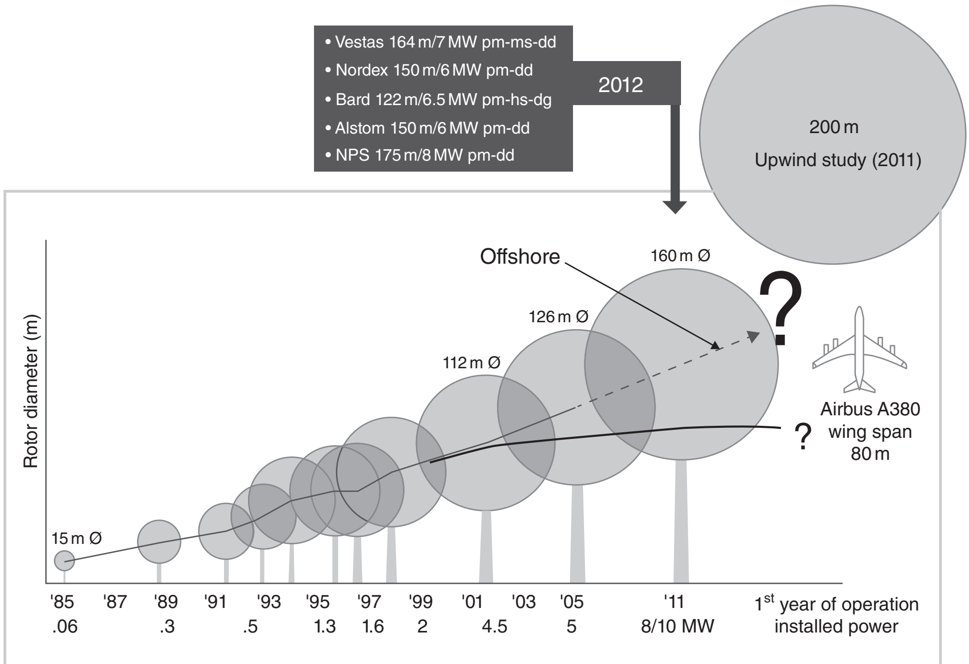



**Figure 1.35** Enlargement trend of modern wind turbines

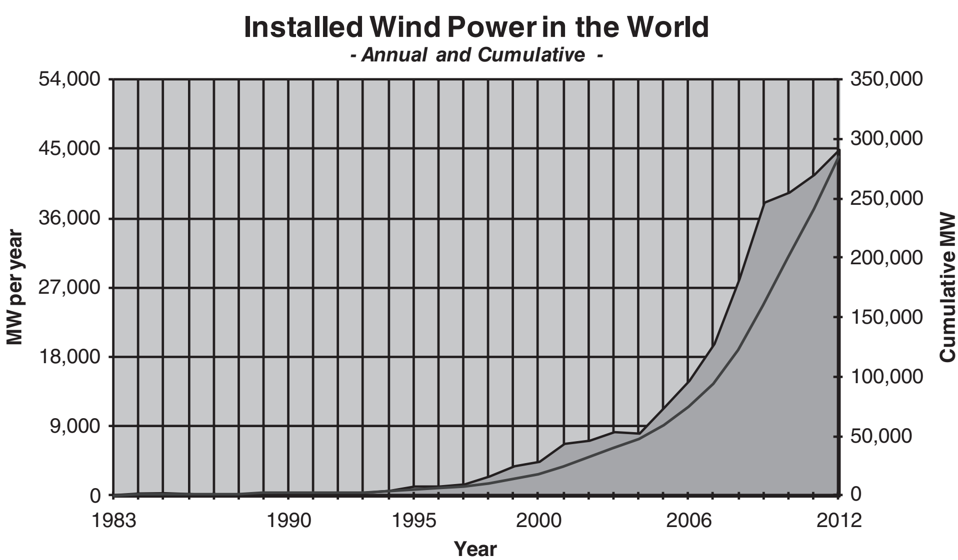



**Figure 1.36** Growth of the world market for wind turbines

national initiatives, and the European projects sometimes received support from the European Commission. The most important pilot plants for wind turbines in the open air were:

- MOD-0 (38 m in diameter, one and two-blade rotors, US): adjustable rigidity of the carrier structure, Uniwecs (16 m diameter, two-blade rotor, idler, Germany): the configuration of the hub was able to be changed by means of computer-controlled hydraulics (individual swivelling rotor blades, teetering hub, fixed hub) and damping and rigidity parameters were adjustable.
- 25 m HAT (25 m diameter, two-blade rotor, upwind turbine. Netherlands. The properties of the generator load are fully adjustable in that a direct current generator and DC–AC converter are used.
- NREL, Phase II, III, IV turbines (Boulder, US).
- Risø, TELLUS Turbine (Denmark).
- TUD Open Air Facility (10 m diameter, two-blade rotor, upwind turbine, Netherlands). The fully equipped rotor blade for pressure distribution measurement was also able to be tested in a wind tunnel in order to permit a comparison with exactly determined flow conditions in a wind tunnel.
- Mie University (Japan).
- Imperial College and Rutherford-Appleton Laboratory (RAL) (UK).

### *1.5.2 The Development of Smaller Wind Turbines*

In order to fully understand modern wind energy and its marketing success, one must also consider the role of the wind energy pioneers. This refers to individual persons as well as small companies.

Even before the oil crisis, pioneers constructed small wind turbines for their houses and small businesses in order to provide themselves with power (see Figure 1.37). In certain respects the pioneers followed a trade that was developed during the Second World War. Many built wind turbines for power supply as the power grid collapsed.

Several do-it-yourself attempts from this time of the war are still in existence. Some of these developed designs went into industrial manufacture. Examples of this are the Lagerwey turbine (see Figure 1.38 [Henk Lagerweij and Gijs van de Loenhorst, Netherlands]), Enercon (Alois Wobben, Germany), Enertech (see Figure 1.39, Bob Sherwin, US), and Carter (see Figure 1.40, Jay Carter, US). The Americans followed the tradition of Jacobs, but seen as a concept, the design was fairly innovative. In Denmark, members of the Smedemesterforeningen built small plants connected to the grid and mostly according to the well-known ‘Danish design’. From this pioneering work there developed companies such as Vestas, Bonus, NEG and Micon.

In order to support the efforts of the smaller companies to improve their products and to increase their commercial success in the US and the Netherlands, the governments organised tenders for the development of small, cheap wind turbines. However, these were not successful as the demand for this type of wind turbine with low capacities slowly sank in favour of the medium-sized plants connected to the grid. It was the Danish manufacturers who started to sell their plants on a large scale in their local markets and in various European countries. At the same time they exported very successfully to the US.

**Figure 1.37** Dutch do-it-yourself pioneer in the field of wind energy, Fons de Beer, with his passively controlled wind turbine [8]

**Figure 1.38** The early passively controlled wind turbine by Lagerwey van de Loenhorst with variable speed. Diameter: 10 m [8]

With increasing demand for large wind turbines, the manufacturers increased the capacities of their well-known concepts step by step. At the start of the 1990s they achieved the same size as the smaller plants supported by the state in the 1980s. With the support of the European Commission (WEGA and THERMIE programmes), it was possible for them to improve their designs, to test their plants and to write success stories. This was a necessary condition for successful market introduction. At this point the two, originally separated, lines of development

**Figure 1.39** Enertech wind turbine in a Californian wind farm [8]

**Figure 1.40** J. Carter's passively controlled idler [8]

merged into one. Because of the demand for very large wind turbines, the enlargement trend continued as these seemed to be potentially more competitive in the offshore region.

Almost none of the pioneer companies from the 1970s and 1980s emerged from this phase unchanged. Some went bankrupt and others were successful. They either remained completely independent (ENERCON) or, as independent companies, attracted the attention of foreign investors (Vestas). Others merged or were taken over by larger companies. Examples of well-known mergers are NEG and Micon.

### *1.5.3 Wind Farms, Offshore and Grid Connection*

Together with the increasing capacity of wind turbines, wind energy projects (wind farms) (see Figure 1.42) increased to such an extent that their total capacity rose from one megawatt to several hundred. In order to plan wind farms efficiently, it was first necessary to have knowledge of handling wake flows and flow conditions within the wind farm. Research in these areas began at the start of the 1980s with the physical analysis of wake flows and experimental investigations in wind tunnels (see Figure 1.41). This research field became of increasing

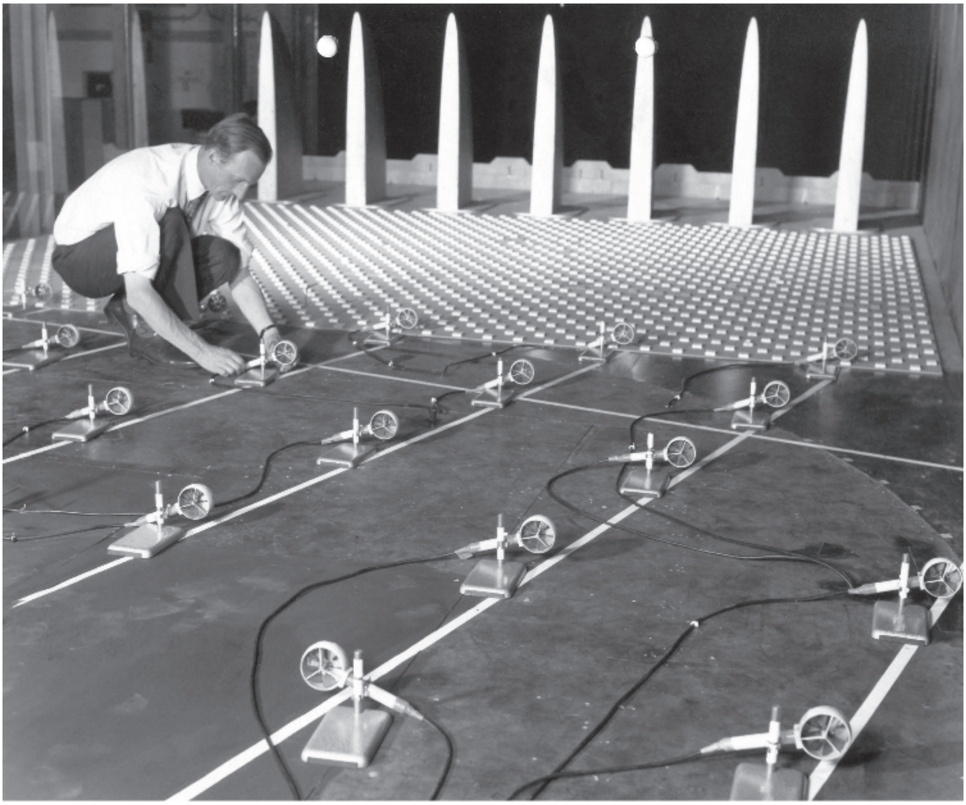


**Figure 1.41** Early wind farm measurements carried out by David Milborrow, Electrical Research Association, UK. Photo: ERA

importance from the first investigations on flow conditions in wind farms. External influences such as wind shear, intensity of turbulence and the stability of the atmosphere play a large role in the distribution of flows. As these influences are very different on land and offshore, the economic planning of offshore wind farm depends to a large extent on the investigation results on the flow conditions in wind farms.

The importance of offshore wind energy became greater as the best sites for wind energy generation on land in northwest Europe were already developed. Offshore is the only possibility for coastal countries to increase the contribution of wind energy for energy supply (>20%). A further reason for the growing importance of offshore wind energy is public resistance to the erection of wind turbines in protected and old landscapes, especially in the UK and Sweden. The potential of offshore wind energy was recognised right at the start of the modern wind energy era. Offshore wind energy has been investigated since 1978 within the framework of the IEA wind energy programme (see Figure 1.43).

In 1991 the first large commercial offshore wind farm with a total capacity of 4.95 MW was erected 2.5 km from the coast of Vindeby in Denmark. This comprised 11 Bonus wind turbines of 450 kW each. The second Danish offshore wind farm was erected at Tuno Knob in 1995.

**Figure 1.42** Multimegawatt plant of ENERCON, North Germany [5]

This wind farm has a total capacity of 5 MW and is made up of 10 Vestas wind turbines of 500 kW each. Both wind farms were erected in protected and flat waters. The first offshore wind farm near Copenhagen, Middelgrunden, was erected with the help of landscape architects and has a total capacity of 40 MW. It comprises 20 Bonus wind turbines that produce 2 MW each, are arranged in a curve and at a water depth of between 5 and 10 metres.

The first step in the direction of wind energy utilisation in the rough environment (see Figure 1.44) of the North Sea was taken in 2002 with the erection of the Horns Rev Offshore Wind Farm. The installed capacity was 160 MW, making it the first wind farm whose total capacity exceeded 100 MW. The farm comprised 80 wind turbines of 2 MW each, lying between 14 and 17 km from the coast at a water depth of 6–14 m. One at a time, more countries have joined the offshore community. In the middle of 2012 there were wind turbines with a total capacity of 4100 MW. These were spread over the following countries: Denmark, Sweden, the Netherlands, the UK, Ireland, Belgium, Germany and China.

The rapid growth in wind farm capacity is shown by the following figures:

| | |
|---|---|
| Average capacity: | 43 MW/farm |
| Average capacity of the 10 smallest, older wind farms | 8 MW/farm |
| Average capacity of the 10 largest, newer wind farms | 198 MW/farm |

Taking into account the capacities of offshore wind energy, the European states are planning further offshore wind farms, and this in an area without an existing electrical infrastructure. In this way the necessity of a new concept for grids becomes clear. This necessity becomes

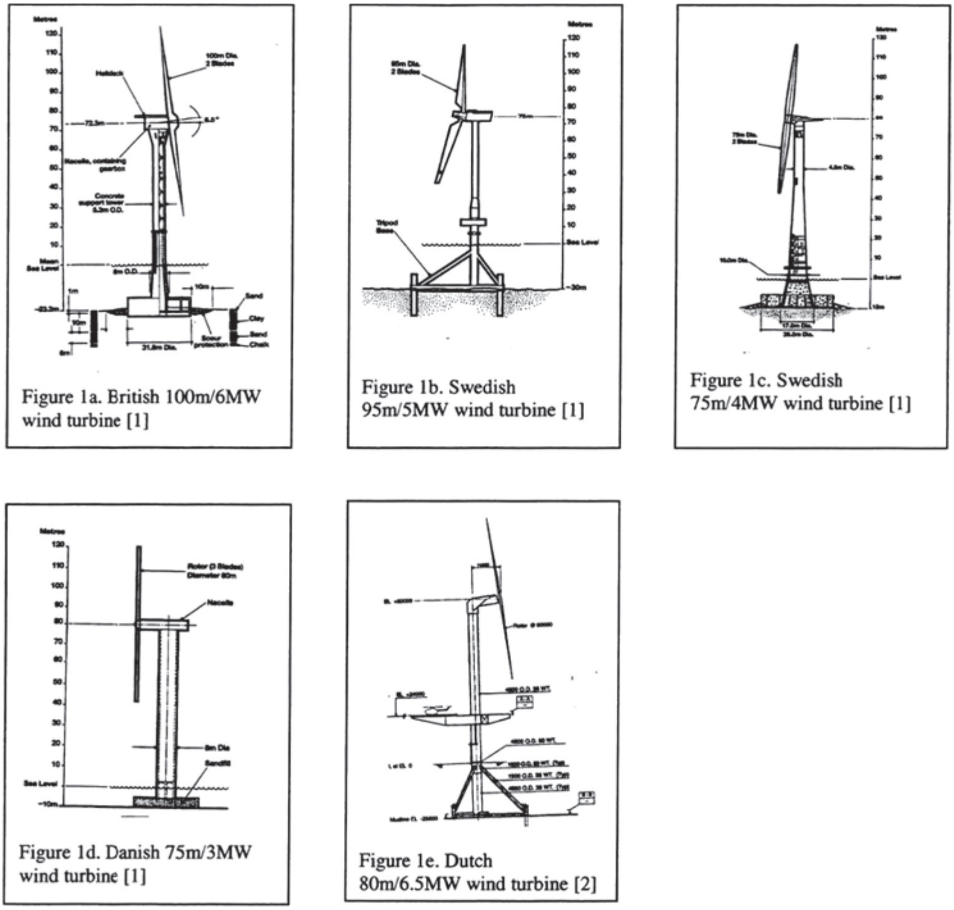


Figure 1a. British 100m/6MW wind turbine [1]

Figure 1b. Swedish 95m/5MW wind turbine [1]

Figure 1c. Swedish 75m/4MW wind turbine [1]

Figure 1d. Danish 75m/3MW wind turbine [1]

Figure 1e. Dutch 80m/6.5MW wind turbine [2]

**Figure 1.43** Offshore technology has been investigated since 1978 within the framework of the IEA-LS-WECS programme. The participating countries were Denmark, the Netherlands, Sweden, the UK and the US

more urgent with a view to future renewable sources of energy of variable power. This affects mainly wind turbines, concentrated solar energy plants and hydroelectric plants. As the lead time for extension of grids is very long, usually ten years or more, the expansion of the grid should have already started ten years ago in order to meet today's demands. The expansion of the grids could and should have been a part of the implementation, but this was not the case. It is clear that the bottleneck for further expansion of offshore wind energy is the grid.

## *1.5.4 International Grids*

Looking back, there arises the interesting question of whether the programmes instituted by the governments of 1979 were useless, as there were no directly resulting commercial applications.

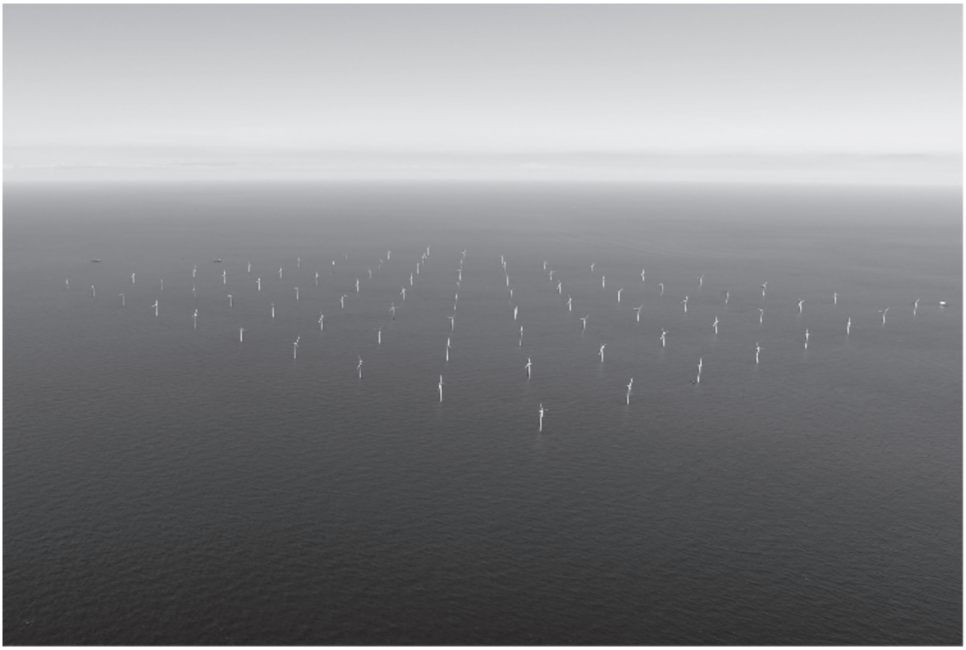


**Figure 1.44** 160 MW Horns REV Offshore wind farm in the North Sea in Esbjerg, Denmark. Photo: ELSAM

The answer would be 'Yes' if, between 1979 and 1985, there were companies that were large enough to carry the risks inherent in the market introduction of large wind turbines. However, these companies did not exist at the time. The companies that would have been in a position to tread such a risky path were at that time not interested in the commercial introduction of large wind turbines.

The answer would be 'No' of one takes into account the enormous quantity of collected data on design and operation that was gained from accidents and events. The manner in which this knowledge contributed to the new generation of wind turbines cannot be directly proven as this development did not take place in sequential steps. The learning process was carried out by experts who changed to the private sector and brought their knowledge with them. Added to this there were also conferences (e.g. organised by the EWEA, the European Commission and the AWEA) and seminars (e.g. organised by IEA).

The national research associations constantly created establishments for the collection of expert knowledge on wind turbines. These establishments (at the start, the national research laboratories Risø, ECN, SERI/NREL), universities and newer university networks such as ForWind and CEWind in Germany were supported in the long term by national governments. Without these institutions, the access to knowledge on wind turbines would have been locked up or even lost. The interconnection of the various aspects of this knowledge, such as resources management, structural dynamics, electrical and mechanical energy transmission and others, would also have been lost.

The fact that this knowledge is still coherent, up-to-date and accessible is due in large part to the degree of organisation of the scientific world and the intensive contacts between science and industry. In this, governments played only a minor role. Although they and the European Commission promoted the cooperation, it was the wind energy sector that started or coordinated many initiatives, distributed contracts and developed strategic scientific programmes. Examples of these initiatives from Europe are the EWEA (European Wind Energy Association), EUREC (European Renewable Energy Agency), EAWE (European Academy for Wind Energy) and MEASNET (Measurement Quality Assurance Network). In comparison to today's national associations, which have been in existence for a long time, these international networks present a new dimension.

### *1.5.5 To Summarise*

When one follows the long path of history, from the start of the use of windmills by the Persians up to the large-area usage of wind energy, one can differentiate two very successful periods: within the first period (1700–1890) the use of wind energy allowed the industrialisation of parts of Northern Europe, especially in the Netherlands. In the second period (after the oil crisis of 1973), wind energy was of increasing importance worldwide. The close meshing of theory and practice in the development of the technology, the introduction of reliable market incentives and political support were shown to be key to the success of today's developments in the wind energy sector.

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