Understanding WIND POWER TECHNOLOGY
Theory, Deployment and Optimisation

Editor: Alois Schaffarczyk

Understanding wind energy technology has progressed enormously over the last decade. In coming years it will continue to develop in terms of power ratings, performance and installed capacity of large wind turbines worldwide, with exciting developments in offshore installations. Designed to meet the training needs of wind engineers, this introductory text puts wind energy in context, from the natural resource to the assessment of cost-effectiveness, and bridges the gap between theory and practice. The thorough coverage spans the scientific basics, practical implementations and the modern state of technology used in onshore and offshore wind farms for electricity generation.

Written by experts with in-depth experience in research, teaching and industry, this text conveys the importance of wind energy in the international energy-policy debate, and offers clear insight into the subject for postgraduates and final year undergraduate students studying all aspects of wind engineering. Understanding Wind Power Technology is also an authoritative resource for engineers designing and developing wind energy systems, energy policy-makers, environmentalists, and economists in the renewable energy sector.

Key features:
- provides in-depth treatment of all systems associated with wind energy, including the aerodynamic and structural aspects of blade design, the flow of energy and loads through the wind turbine, the electrical components and power electronics including control systems;
- explains the importance of wind resource assessment techniques, site evaluation and ecology, with a focus of project planning and operation;
- describes the integration of wind farms into the electrical grid and includes a whole chapter dedicated to offshore wind farms;
- includes questions in each chapter for readers to test their knowledge.

Translated by Gunther Roth, Adliswil, Switzerland

Editor: Alois Schaffarczyk, University of Applied Sciences, Kiel, Germany
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THEORY, DEPLOYMENT AND OPTIMISATION

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Although nearly 20,000 windmills dotted Germany’s landscape by the end of the eighteenth century, the era of modern wind energy began in 1983 when the aptly-named GROWIAN prototype (a German abbreviation for Grosswindanlage, or ‘large wind turbine’) started operation in the German state of Schleswig-Holstein. By the end of 2011, almost 23,000 modern wind turbines had been erected in Germany and supplied nearly 10% of the country’s electricity demand. It took only 30 years for the modern wind industry to develop to the extent that turbines the size and power of the once-colossal GROWIAN had become standard and mass-produced.

At the request of the Carl Hanser Verlag publishing company and under the umbrella of CEwind eG – the consortium for wind energy research between Schleswig-Holstein’s universities – authors from the wind community in Schleswig-Holstein and the Netherlands have collaborated to compile this introductory text on wind energy. Over 11 chapters the interested reader will become familiar with the modern state of this technology.

This text begins with a brief history and then supplements this with an explanation of the importance of wind energy in the international energy policy debate. Following chapters then introduce the aerodynamic and structural aspects of blade design. Then the focus shifts to the flow of energy and loads through the wind turbine, through the powertrain and also the tower-foundation system, respectively. Next, the electrical components such as the generator and power electronics are discussed, including control systems and automation. Following is an explanation of how wind turbines are integrated into the electricity grid, despite the highly fluctuating nature of both this energy source and the grid load; this particular topic is especially relevant for Germany’s transition to renewable energy. The final topic covers one of the youngest and most promising aspects of wind energy: offshore technology.

Kiel, February 2012

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1

The History of Wind Energy

Jos Beurskens

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 because of 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.
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 1.1** Historical development of the use of wind as a source of energy. The first and last periods have had the greatest effects on society
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 1.2** 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
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].

**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
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]
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 1.8 ‘Koker’ windmill from South Holland. Photo (right) from [8]

Figure 1.9 The development of the classical ‘Holland mill’
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 industry 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.
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 genera-
tors. 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).
Figure 1.12  Page from Scientific American magazine, 20 December 1890. Reproduced with permission of Scientific American/Wikimedia Commons