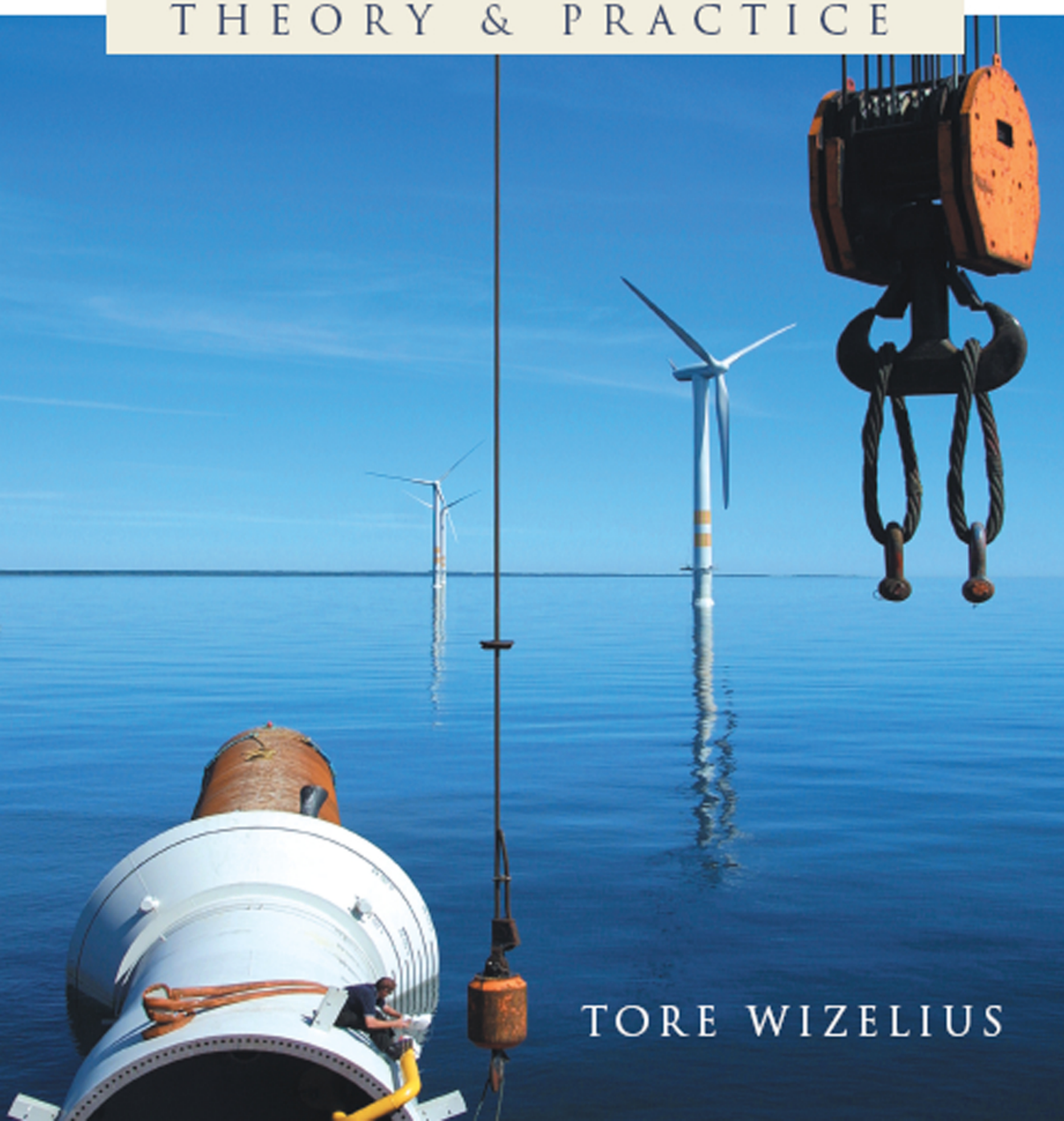
DEVELOPING WIND POWER PROJECTS

THEORY & PRACTICE



TORE WIZELIUS

Developing Wind Power Projects

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Theory and Practice

Tore Wizelius

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Preface

You don't have to be an engineer to install a wind turbine – there are reliable wind turbines available that are ready to use, and installation is often included in the price. However, to be able to choose the right kind of turbine for the right place, obtain the necessary permissions and get a reasonable economic return on the investment, it is necessary to have a sound knowledge of meteorology, environment laws and economics and a basic understanding of how wind turbines work.

To design and build a wind turbine it is not enough to be an engineer. It takes at least five engineers with different specialities: one mechanical engineer, one electrical engineer, one aeronautical engineer for design of the rotor blades, one computer engineer to design the control system and, finally, a building engineer to design the foundations.

Furthermore, to work with wind power it is not sufficient to learn how a wind turbine operates from a technical point of view. It is just as important to be able to estimate the wind resources at a specific site: the energy content of the wind should always be the basis for a wind power project.

Commercial wind turbines today cost around a million euros or more, so it is necessary to understand the project economics to ensure that the investment will be profitable. It is also necessary to gain the relevant permissions from the appropriate authorities. Therefore it is important to know what impact wind turbines could have on the environment and to be familiar with the laws and regulations that govern the decisions made by the authorities. Finally, the local community should also give their consent. To gain approval for a wind power plant it is vital to inform those who will be affected by the installations and to take their views into serious consideration.

This book aims to provide guidance and the information required to develop commercial wind power plants, through a combination of theory and practice. Laws, rules and project economics will vary in different countries, and change so often that these aspects are described in general terms. The reader should check the specific regulations for the country they are working in.

The Swedish edition of this book, published in 2003, was produced with support from the Swedish Energy Agency, which has contributed to the dissemination of knowledge about wind power not only in Sweden but also internationally. I would like to express my gratitude to Professor Ann-Sofi Smedman at Uppsala University, who has scrutinized the facts in Chapters 4, 'The Wind' and 5, 'The Power of Wind'; to Björn Montgomerie, wind power researcher at FOI (the Swedish defence research agency), who has checked the facts in Chapters 6, 'Conversion of Wind Energy' and 8, 'The Wind Turbine Rotor'; and to my own former teacher Göran Sidén at Halmstad University, who has checked the facts in Chapter 10, 'Electrical and Control Systems'. For this English edition I have updated several facts and figures and the chapters in Part IV, 'Wind Power and Society', have been completely rewritten.

I feel greatly in debt to Paul Gipe, whose eminent books on wind power I have read repeatedly. They have not only been a valuable source of knowledge, but also a great inspiration for my own writing, and I hope that I too have managed to explain things in a comprehensible manner. Gipe's latest book, *Wind Power*, is a masterpiece in both form and content and a book that everyone interested in wind power should read.

I am just as grateful to David Milborrow, who has had the patience to check both facts and the English language in my translated manuscript. I have followed his expert analyses, published in *Windpower Monthly*, for years, and have included some diagrams based on his research in this book. Any faults that may remain in the book are, of course, solely my responsibility.

Tore Wizelius

PART I

Introduction to Wind Power

Wind power is a renewable energy source that has developed rapidly since the end of the 1970s. This has been achieved by an energy policy that has created a market for renewable energy and by research and technical development. In these few decades wind power has developed from an alternative energy source to a new fast-growing industry which no longer needs subsidies and manufactures wind turbines that produce power at competitive costs. This introduction describes this development.

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1
Wind Power Today and in the Future

Wind turbines catch kinetic energy in the wind and transform it into other forms of energy: mechanical work in water pumps and windmills or electric power in modern wind turbines. The wind is a renewable energy source; the wind is set in motion by the differences in temperature and air pressure created by the sun's radiation on Earth. Wind turbines produce clean energy, don't need any fuel transport that can be hazardous to the environment, don't create air pollution and don't leave any hazardous waste behind.

The sun, the wind and running water are all renewable energy sources, in contrast to coal, oil and gas, which depend on fossil fuels from mines or oil and gas fields. In many countries, for example Sweden, hydropower has already been fully developed. The technology to use direct solar radiation with solar collectors and photovoltaic (PV) panels is still waiting for a commercial breakthrough that is expected to come during the first decade of this millennium. Wind power is the new renewable energy source that has seen the most successful development so far.

Modern wind turbines are efficient, reliable and produce power at reasonable cost. Furthermore, the wind power industry is growing very fast, with the leading companies having increased their turnover by 30–40 per cent per year in the first years of this decade. Simultaneously the cost per produced kWh has become lower for each new generation of wind turbines that has been introduced on the market.

From the early 1980s the size of wind turbines has doubled approximately every four years. The largest commercial turbines today have hub heights of 110 metres, rotors with a diameter of 110 metres and a rated power of 3.6MW. The next generation, with a rated power of 5MW, have already been built as prototypes. If this development continues, wind turbines may have a rated power of 10MW by 2010.

The technology in the wind turbines has developed in several ways. The control systems have become cheaper and more advanced, new profiles for the rotor blades can extract more power from the wind, and new power electronic equipment makes it possible to use variable speed and to optimize the capacity of the turbines.

Just as wind turbines have grown in size, so installations have also become larger and larger. In the early days of wind power development, turbines were installed one at the time, often next to a farm. After a few years they were installed in groups of 2–5 turbines. Today large wind farms are built, on land and off shore, with the same capacity as a conventional power plant. The largest wind farms in Europe consist of up to one hundred turbines.

A problem with the wind as an energy source is that the wind always varies. When the wind slows or stops, power has to be produced by other power plants. This could lead to the conclusion that it will always be necessary to have a back-up capacity with other power plants with the same capacity as the wind power connected to the power system. If this were true, wind power would be very expensive. However, since wind power only constitutes one part in a large power system, this is not necessary at all. A moderate share of wind power in a system does not need any back-up capacity at all, since it already exists in the power system. In Sweden, for example, power companies can simply save water in the hydropower dams when the wind blows, and use this saved hydropower when the wind drops.

In a power system power consumption varies continually, during each day as well as during seasons. Every power system has a regulating capacity to adapt power production to actual power consumption. This can be used to adapt the system to the variations in the wind – and the output of wind turbines – as well. When the wind power penetration (that is the share of electric power produced by wind in a power system) increases to 10–20 per cent, it may be necessary to regulate the wind power as well, by reducing power from wind turbines in situations with low load (consumption) and high production, or by keeping a power reserve to be used to balance power production with consumption at short notice. Few countries, however, have yet reached such penetration levels.

Fast market growth

During the development from small single turbines connected to farms to large wind farms with the capacity of large-scale power plants, wind power has become more competitive: the power produced by wind turbines has grown cheaper. Today the cost of power produced by wind turbines (in places with good wind conditions) is competitive with the cost of power produced by oil, coal, gas or nuclear fuel in *new* power plants. Within this decade wind power could become the cheapest energy source available.

To lower the cost of wind power still further takes mass production of turbines. To attain this, the market has to grow. And indeed it is growing very fast. Germany, Denmark, Spain and the UK, as well as India and China and the US, are installing wind power plants on a large scale.

During the last few years the German market has grown fastest. Germany passed pioneering Denmark in 1994 with respect to installed wind power capacity and currently has the most wind power installed in the world. German manufacturers are now competing with the Danish industry. Both Germans and Danes

BOX 1.1 WIND POWER STATISTICS

To indicate how much wind power there is in a country, the total installed capacity is used as a measure. Every wind turbine has a rated power (maximum power) that can vary from a few hundred watts to 5000kW (5MW). The number of turbines does not give any information on how much wind power they can produce. How much a wind turbine can produce depends not only on its rated power, but also on the wind conditions. To get an indication of how much a certain amount of installed (rated) power will produce per year, this simple rule of thumb can be used: 1MW wind power produces 2GWh/a on land and 3GWh/a offshore.

1TWh (terawatt hour) = 1000GWh (gigawatt hours)
1GWh = 1000MWh (megawatt hours)
1MWh = 1000kWh (kilowatt hours)
1kWh = 1000Wh (watt hours)

International information on wind turbine installations is available at *www.windpower-monthly.com* (the Windicator), *www.ewea.org* and *www.ieawind.org.*

have found new large export markets in India and China. Spain has installed several thousand MW in the last few years, and in the US large wind farms are installed on the large plains in the Midwest and on the west coast. In Denmark and Germany development on land has now reached a level where it is harder to find new sites for wind turbines and consequently growth in their domestic markets

Table 1.1 *Global wind power capacity in 2005 (MW)*

Country	Installed in 2005	Total 2005
Germany	1798	18,247
Spain	1764	10,027
US	2424	9124
India	1430	4430
Denmark	4	3128
Italy	452	1717
UK	465	1353
China	496	1260
Netherlands	141	1219
Japan	144	1040
Other	2192	7436
Total	**11,310**	**58,981**

In 2005, 11,310MW of new wind power was connected to the world's power grids. Total installed power increased to almost 60GW, an increase of 24 per cent from 2004.

Source: World Wind Energy Association (2006) has declined. Thus in 2004 Spain took the lead in terms of most installed capacity in a year. In short, most of the growth so far has been concentrated in a few countries and there is still an immense potential for market growth in countries where development has hardly taken off – Australia, Brazil, Ireland, Canada, Poland, Norway, to mention a few.

There are also ambitious plans to develop wind power plants offshore. Several offshore wind farms are already installed in Denmark, the UK, the Netherlands and Sweden. Denmark has decided that wind power shall produce 50 per cent of the electric power in the country by 2030, a significant increase from the 20 per cent today, and the development of large offshore wind farms necessary to realize this ambitious target has already started. The UK has also started an ambitious plan for offshore development.

2
Historical Background

The ancient Greeks had no windmills, and while they used sails on their ships to harness the power of the wind, their knowledge of wind power generally was weak. The Greeks, the Romans and the Vikings used square sails, and steered using oars instead of rudders, which made it hard to keep a straight course when the wind came from the side and avoid drifting away in the direction of the wind. Therefore their ships had large crews – they needed many strong oarsmen and galley slaves to reach a destination within a reasonable time. When winds increased to storm force, the sails were taken down, a simple method of *power control*. In other words they had respect for the unpredictable and unreliable wind that could turn even the best of ships into disabled wrecks.

Exactly how long man has known how to utilize wind for work is unknown, but some kinds of windmills were probably used in China and Japan some 3000 years ago. The first historically well-documented windmill dates from AD947, in Persia, close to the border with Afghanistan. There, as in many other places on Earth, the wind varies according to a regular pattern. Some times of the year the wind always blows from the sea inland, through a pass. Those who built the windmill didn't have to worry about the wind direction.

This windmill had a vertical axis, on which mats were mounted. This is the same principle as for a small watermill. To make it rotate, half of the rotor has to be protected from the wind. This was easily done, since the wind always came from the same direction. A wall surrounded the mill, with one opening facing the wind, so that the wind only hit the mats on one side of the axis. Power control was simple. If the winds blew too hard, a door was closed. At the back there was no wall at all, to utilize the power of wind the air must be able to get away behind the turbine (see Figure 2.1).

By the end of the 12th century the first windmills in Europe had been built on the Mediterranean coast and in northern France. These demonstrate a radical change of technology: while the Persian windmills had a vertical axis, these had a horizontal one.

To be able to build a horizontal axis windmill, another fundamental technological item has to be used – the cogwheel. The power has to be transformed from the horizontal to the vertical axis for the millstones to be turned around. The cog-

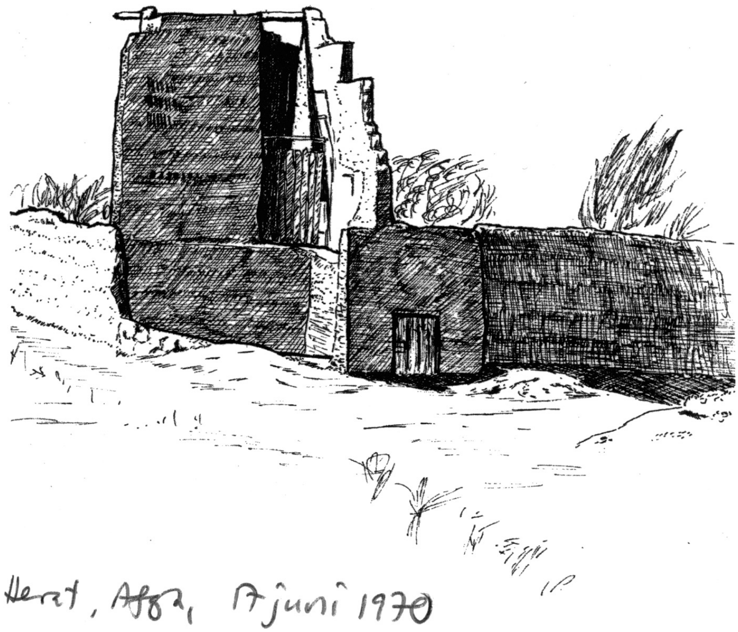

Figure 2.1 *Persian windmill*

The Persian vertical axis windmill is sited inside a building where a wall screens off the part of the rotor that turns into the wind.

Source: Bo Göran Johansson

wheel had, however, already been invented and was used in watermills. To transfer this technology to windmills was a simple matter.

With a horizontal axis and a vertical rotor, a new technical problem has to be solved – how to direct the rotor towards the wind. The windmills used in the Mediterranean area, which are still used on Crete, for example, were built with a stone tower. The rotor and the shaft were made of wood, and the wind was caught by sails made of cloth (see Figure 2.2). The rotor was made with quite thin wooden bars and had a low weight. The top of the tower was constructed like a 'cap' and could be turned.

The windmills in northern Europe, in France, the Netherlands and the UK, were at this time so-called post mills. The whole mill was mounted on a strong stand, with a vertical wooden log, so that the whole mill could be turned and the rotor directed towards the wind. It was heavy work. A man could turn the mill using a lever, but if it was too heavy, an ox was used to turn the mill into the wind.

Windmills started their march into Europe in the 13th century and soon became one of the most important power sources, a position maintained until the end of the 19th century. By the middle of the 19th century, when the number of mills reached its peak, there were some 9000 windmills in the Netherlands,

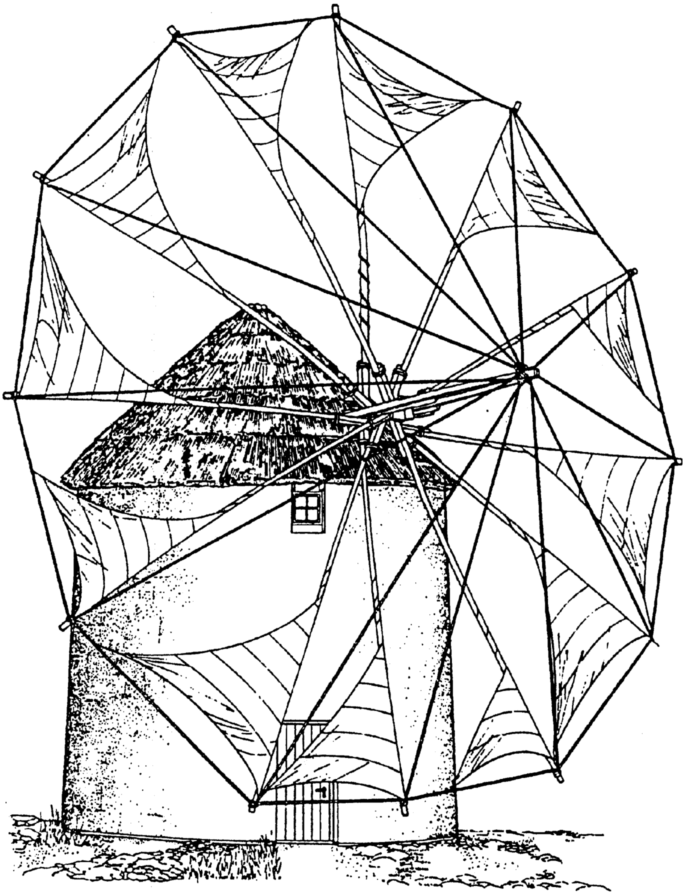

Figure 2.2 *Mediterranean windmill*

To transmit power from a water wheel to a millstone, you need cogwheels. The same technology is used in horizontal axis windmills. The type used in the Mediterranean area has a revolving cap and a rotor with sails.

Source: Hills (1996)

18,000 in Germany, 8000 in England, 3000 in Denmark and 20,000 in France. Those who have read Cervantes' novel *Don Quixote* know that there were also plenty of windmills in Spain. Before the steam engine was developed and modern industrialism took off, hydropower and wind power produced half of the power each, excluding horses and oxen.

The windmill as a symbol of freedom

During these centuries the windmill also played an important political role. 'The windmill was a tool for social development, the number of skilled mechanics increased, and it lessened the burden of women, they no longer had to mill their grain by hand,' writes British historian Edward Kealey, arguing that the windmill undermined feudal oppression and contributed to women's liberation.

During the 14th century the squires and the monasteries had exclusive rights to exploit and use watersheds, and in that way had a watermill monopoly. And they used this monopoly position to exploit the farmers. The wind, however, belonged to all, and the power in the wind was free. Farmers and artisans built windmills, and thus liberated themselves from one of the burdens of the feudal society. These times were characterized by social unrest. For the growing liberation movement, the windmill became both a tool and a symbol of the idea of freedom that spread and threatened the foundations of medieval society.

During the following centuries the simple stock mill underwent impressive technological development. The Dutch, especially, were masters of windmill engineering. They developed a brand new concept that utilized the same principle as the Mediterranean windmill, with a revolving 'cap'.

The windmills also grew in size. Mills with 20–30 metre brick towers and 20–30 metre rotor diameters were built; these produced some 25–30kW. The total power produced by all the windmills in Europe at the peak of the windmill era was 1500MW, a level that wind power did not reach again until 1988.

The windmills in northern Europe usually had four rotor blades, with the outer part built as an 'espalier'. When the mill was about to be used, the blades were covered with wooden plates or with sailcloth. When the wind got too strong, reducing the cover on the blades could regulate power. There were also advanced versions with adjustable 'Venetian blinds'. The windmills were not in use continually but were started when the miller was about to start milling grain and when there was suitable weather.

The windmill engineers also developed an automatic yaw mechanism, the so-called Dutchman. This was made of a wind wheel (or two, one on each side of the tower) that was mounted perpendicular to the rotor. The wind wheel was connected to a cogwheel on the tower by a gear drive. When the wind direction changed so that the rotor was hit from a side angle, this wind wheel was activated and started to turn. The wind wheel turned the 'cap' of the windmill until the rotor again was directed towards the wind. In that position no wind could hit the wind wheel and it stopped turning (see Figure 2.3).

Windmills were not only used to grind grain, although that was the most important application. Another important task they were used for was to pump water, thus contributing to land reclamation for agriculture. The rotor turned either a blade wheel or a water screw. Such wind driven pumps made it possible to increase the land area of the Netherlands. A large part of the country today

Figure 2.3 *The Dutchman*

Windmill technology developed over centuries. The simple stock mill that was used by farmers was further developed into the Dutch mill, which spread through Europe in different versions. The Dutch mill was a tower with a revolving cap and was not used only to grind grain, but also as a sawmill, rag mill and snuff mill and for flax dressing and other mechanical work. This technically advanced windmill – a Dutchman in Britain, with a wind wheel for turning the cap and rotor blades with Venetian blinds for automatic power regulation – is sited in North Leverton and is still in a usable condition.

Source: Hills (1996)

consists of drained seabed, so-called polders. There were also windmills that were used to saw timber, to stamp rag that was used to make paper and for many other applications. In the industrial area outside Amsterdam there were 700 windmills in the 19th century providing mechanical power to the factories.

Steam engines finally drove the windmills out of the market, but it was a surprisingly slow process, in fact taking a whole generation. Nevertheless, in the 20th century the windmill definitely had had its day and its role is now reduced to one of heritage. In the Netherlands, where the windmill has become an important national symbol, the authorities have set a goal to keep at least 1000 windmills in good shape and many of them are actually set to work a couple of days each year.

The wind wheel of the Wild West

On the other side of the Atlantic Ocean, on the American prairie, another kind of windmill played an important role: the wind pump, a wind wheel that was used for water pumping. According to the American historian Walter Prescott Webb there were three inventions that made it possible for man to colonize the prairie: the revolver, barbed wire and the wind pump. A common saying was: 'Women who can't fire a gun or climb a wind pump have no future here.' The prairie was described as a land where 'the wind pumps the water and the cows chop the wood' (since there was no wood dried cow dung was used instead of firewood).

The wind pump was mounted on a post or a truss tower. The pump was driven directly by an axle that was made to rotate by the wind. In the beginning, both the towers and the rotor blades were made of wood; only the axle and some other mechanical parts were made of iron. The pumps were installed next to the farms. They had to be oiled and greased regularly and when the winds increased they had to be turned out of the wind and a brake had to applied manually. They needed constant surveillance.

In the Midwest industrialization took off in the 19th century and in 1854 a wind pump with automatic power regulation, developed by Daniel Halladay, was introduced on the market. It had four twistable rotor blades and when the wind speed increased the force of the wind twisted the blades so that some of the wind passed through the rotor. The rotor was directed towards the wind by a wind vane. This wind pump could work without constant surveillance and could therefore be used to pump water for cattle far from the farmstead, which made it possible for farmers to increase their grazing land and increase the number of cattle (see Figures 2.4 and 2.5).

The market for wind pumps of different sizes grew fast. By the end of the 19th century there were 77 companies that manufactured these types of wind turbines in the US. And simultaneously technical development continued. Halladay's wind pump met market competition from the Eclipse model, which was simpler

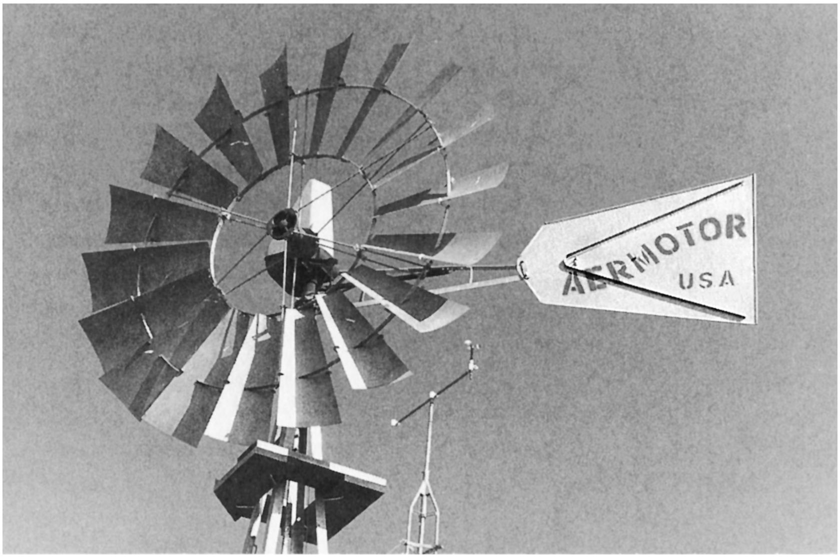

Figure 2.4 *Wind wheel as water pump*

This wind wheel from Aermotor was a result of the experiments conducted by the American engineer Thomas Perry, who had tested 5000 different rotor options. The rotor is almost solid (it covers almost the whole swept area) and the blades are slightly cup-shaped.

Source: Gipe (1993)

and had fewer moving parts. This model was, in turn, outshone by Aermotor, developed by the engineer Thomas Perry. Perry performed a large number of experiments to develop an efficient rotor, testing some 5000 different rotor options! His wind pump used a wind wheel, an almost solid rotor with a large number of inclined blades. The efficiency of this rotor was twice as high as competing models and could be manufactured at 20 per cent of the price.

During the 19th century the US railroad network developed fast and railroad tracks where built across the prairie. The steam locomotives needed to fill their water tanks at regular intervals, so next to railway stations out on the prairie very large wind wheels were built, up to 18 metres in diameter, to pump water.

Wind turbines for water pumping, usually wind wheels with around 2.5m rotor diameter, are still used in many parts of the world. In the 1990s there were around 600,000 wind pumps in use in Argentina, some 250,000 in Australia, 100,000 in South Africa and 60,000 on the American prairie. Today there are more than one million such wind-driven water pumps in use in the world.

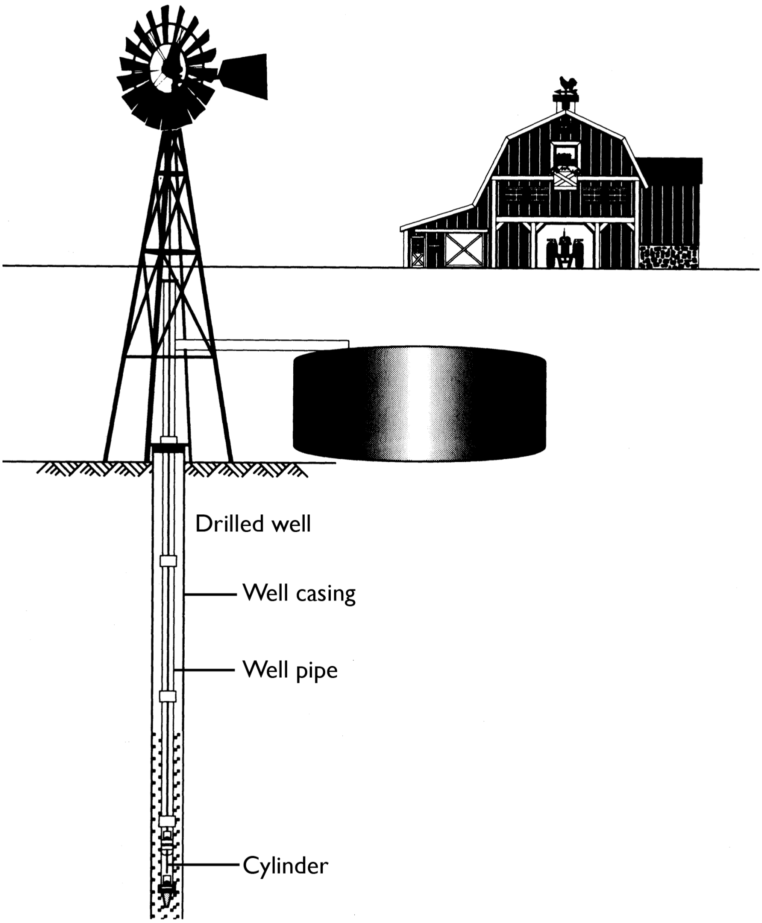

Figure 2.5 *The wind pump*

The wind pumps played an important role in the colonization of the Wild West.

Source: Gipe (1993)

Wind charger

In the 1930s a market for a completely different kind of wind turbine was developed. Electric power had made its entry, but in the early days of electrification, there were electric power grids only in the cities, where the generators were driven by coal, and as small 'islands' around hydropower stations. Large parts of the countryside were without electricity and there was not much demand for it either. In the cities, however, more and more electric appliances were being developed, radios being an example. In the countryside these used crystal receivers, which only needed a small battery, but when the 'real' radio was developed, even people in the countryside wanted to listen to it, and to do that they needed electricity.

To supply farmers in the countryside with electricity a new type of wind turbine was developed – the wind charger, which charged batteries. The aircraft industry had been established for some decades, and the manufacturers of these wind chargers utilized the new knowledge of aerodynamics to give the rotor blades suitable profiles so that the small two- or four-bladed turbines worked like aircraft propellers, only the other way around. These so-called fast runners, with a rotor tip speed five to ten times faster than the wind speed, had a sufficiently high rotational speed to drive a generator without a gearbox. The rotor was connected to a small generator and the current was fed to batteries, which in turn were used to supply radios and light bulbs with electricity. Without battery back-up the radio would be silent during calm days.

The radio manufacturer Zenith and the wind turbine manufacturer Wincharger joined in a marketing campaign to spread these new commodities across the countryside. There were hundreds of thousands of wind chargers operating in the US and several thousands in countries like Denmark and Sweden.

When the electric power grid was finally developed in the countryside the market for wind chargers died. This kind of small wind turbine for electric power generation and battery charging is still manufactured, and has a niche market for different kinds of off-grid applications, being used on oil platforms, in light houses, for radio transmitters and in research stations in the arctic, and nowadays also on sailing boats and caravans used for leisure (see Figure 2.6).

Grid-connected wind turbines

The Danes have always been early starters when it comes to wind power. In 1892, with financial support from the state, Professor Paul la Cour built the first wind turbine for electric power production. It produced DC power and used batteries for energy storage, just like the American wind chargers. The Danish turbines, however, were much larger in size. In 1908 there were 72 wind turbines of 10–20kW online and at the end of the Second World War there were 18 turbines with a nominal power of 45kW. After the Second World War the Danes also tried to connect wind turbines to the power grid.

A turbine with 200kW nominal power and an AC generator was built in Gedser and was put online in 1957 (see Figure 2.7). Simultaneously a wind measurement programme was started to survey the wind resources in Denmark.

In Vermont in the US a gigantic prototype was built in the 1940s, dubbed Grandpa's Knob. This turbine had a rotor diameter of 53 metres and a nominal power of 1250kW. It was online for 1100 hours and fed power to the grid.

Figure 2.6 *Battery charger*

Excenter, an American farm windmill for battery charging, was also sold in Europe. One of these was used at a farm on Gotland, Sweden for several decades. Now it stands as a statue in front of Gotland University.

Source: Tore Wizelius