1

History of Wind Energy

> *The fast growing world-wide wind industry is basically using the concept developed in Denmark from 1975 to 1979* (Maegaard 2009, p. 51).

1.1 Introduction

People have utilized the wind to power various types of devices and vessels since the dawn of civilization. Primary applications prior to the twentieth century were pumping water, grinding grain, and sailing ships. In all cases, some type of airfoil is utilized to capture the kinetic energy of the wind and convert that energy into some kind of mechanical action that produces work useful for human activities. Various rigid or soft wings, blades, sails, chutes, vanes, fins, and tails serve to generate lift and to provide stability.

Sailing was and continues to be the most widespread use of wind power in nearly all countries and cultures around the globe. The original scale for wind speed was devised for this purpose in 1805 by Sir Francis Beaufort of the British Royal Navy (Table 1.1). Although modified for other units, this wind scale remains the global standard.

Windmills of many types and sizes are ubiquitous around the world primarily for pumping water, grinding grain, sawing wood, and running diverse machinery. Windmills may have been used in Persia as early as the seventh century and likely by the tenth century AD (Beedell 1975; Musgrove 2010). These were somewhat similar to waterwheels turned on side, so the wheel rotates horizontally on a vertical axle. The Chinese likewise have used horizontal windmills since at least the thirteenth century (Fig. 1.1).

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Table 1.1 Beaufort wind scale for categories 0–10 in relation to wind energy.

Rank	Wind*				Beaufort	Surface effects	Wind energy
	knots	m/s	km/h	mph			
0	<1	0.5	1.8	1.2	Calm	Smoke rises straight up, sea and lake mirror-like surface	Turbines shut off
1	1–3	1.5	5.4	3.5	Light air	Smoke drifts, wind cannot be felt, smooth water surface	Turbines shut off
2	4–6	3.0	10.8	6.9	Light breeze	Wind felt on face, leaves rustle, ripples on water surface	Minimal
3	7–10	5.1	18.0	11.5	Gentle breeze	Leaves and twigs flutter, small flags extended, small waves	Moderate
4	11–16	8.2	29.1	18.4	Moderate breeze	Wind raises dust, branches move, small waves, numerous whitecaps	Good
5	17–21	10.7	38.2	24.2	Fresh breeze	Small trees sway, many whitecaps, some spray	Good
6	22–27	13.9	49.1	31.1	Strong breeze	Branches move, lines whistle, whitecaps everywhere	Excellent
7	28–33	17.0	60.1	38.0	Near Gale	Whole trees moving, resistance felt walking against wind	Excellent
8	34–40	20.6	72.8	46.0	Gale	Large trees move, walking difficult, large waves, howling sound	Excellent
9	41–47	24.2	85.5	54.1	Strong gale	Slight structural damage occurs, slate blows off roofs	Dangerous
10	48–55	28.3	100.1	63.3	Storm	Trees broken or uprooted, considerable structural damage	Turbines shut off

Range of wind speed (*) for each category given in knots (nautical miles per hour); equivalent upper limit for each category also given in meters per second (m/s), kilometers per hour (km/h), and miles per hour (mph). Wind energy is indicated for operation of large, modern wind turbines. Aber et al. (2015).

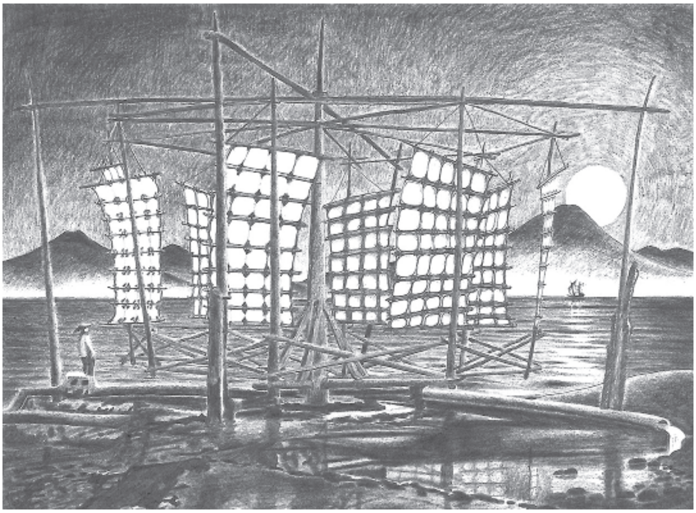

Figure 1.1 Sketch of traditional Chinese windmill for pumping water. Carl von Canstein / Wikimedia Commons / CC BY-SA 3.0.

1.2 Traditional Windmills—European and American

Traditional windmills first came to Europe around 1100 and spread from France to other regions (Thorndahl 2005). The earliest written reports date from 1180 in France and 1185 in England, and the oldest illustration comes from 1270 (Beedell 1975). In all cases, these were so-called post mills (Fig. 1.2). The sails rotate on a wheel in a near-vertical position on a near-horizontal axle, and the whole body may be turned on a central post to face the wind in any direction. This arrangement is clearly quite different from Persian or Chinese windmills, which suggests the European windmill was an independent innovation.

From this beginning, European windmills developed into much larger and more complex devices including tower, smock, and polder mills. During the next several centuries tens of thousands of windmills were constructed across Europe, and the technology was exported to America and elsewhere. The era of windmills lasted until the early twentieth century, some eight centuries, which is a remarkable achievement for any human technology (Fig. 1.3).

All traditional European windmills operate on the same basic principles. The sails of the wheel face into the wind and act much like ship sails or airplane wings. The common sail consists of cloth stretched over a wooden framework that is inclined at an angle (pitch) to the plane of the wheel. The pitch of the sail causes it to drive forward and, thus, turn the wheel. In early windmills, the sails were set at a fixed pitch of ~20° (Beedell 1975). However, the outer tip of the sail travels much faster than the inner portion. It was discovered that pitch could be twisted along the sail to take advantage of this. The so-called weathered sails have pitch ~20° in their inner portions and flatten to pitch of only ~5° toward their tips.

Figure 1.2 Egeby Stubmølle (post mill) was built in 1787. The mill is rotated manually with the long tail pole (to right). It is no longer in service, but has been restored and functional since 1999. Island of Bornholm, Denmark.

Figure 1.3 Klostermøllen near Vestervig in northwestern Jutland, Denmark. A typical Dutch-style windmill; it was built in 1860 and continued in service until 1960. The mill was restored to its original state in the late 1980s. Further restorations were necessary after storm and lightning damages.

The rate of rotation for practical work is typically 12–15 revolutions per minute (rpm) or one full rotation every four to five seconds at wind speeds of 4–10 m/s (see Table 1.1). More rapid rotation could lead to structural damage to the windmill. Hence, some means are necessary to control excessive speed in strong wind (>15 m/s). This may be accomplished in several ways. The simplest way with early post mills was to rotate the sails parallel to the wind. A mechanical brake was soon added that allowed the miller to slow and stop the wheel with one sail in the six o'clock (downward) position. The cloth cover then could be reefed (folded back) to reduce its surface area (Fig. 1.4). This had to be done for all sails to accommodate the wind speed, a laborious process that might be repeated several times during the day to adjust for changing wind conditions.

Beginning in the late eighteenth century, spring sails and patent sails were developed with shutters or flaps that were adjusted automatically using springs or weights to govern the rate of rotation (Beedell 1975). The so-called flap-shutter blades allowed the miller to adjust easily for variable wind speed and to turn the mill on and off at will. Another important innovation was the fantail. Positioned on the back side, the fantail is mounted vertically at right angle to the main wheel.

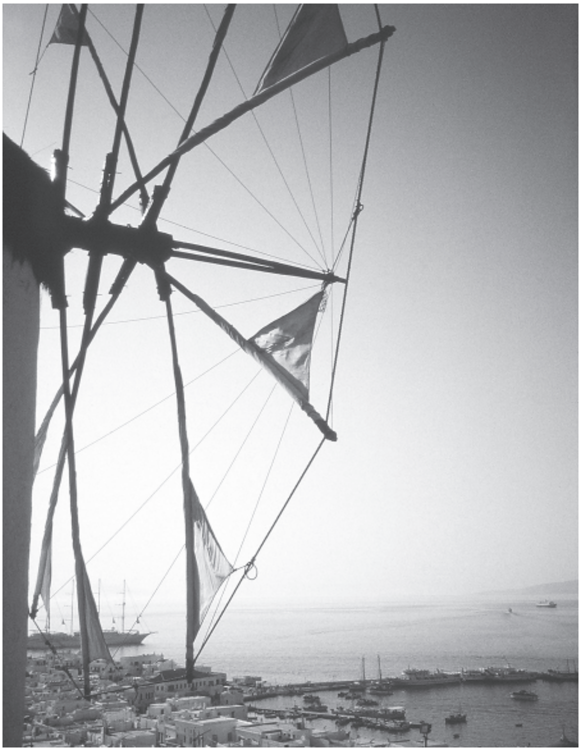

Figure 1.4 Close-up view of windmill wheel, Greek island of Mykonos in the Aegean Sea. The canvas sails are mostly reefed to reduce rotation speed. The earliest of these windmills date from the 1500s. Note the elaborate construction with braces and stays to reinforce the wheel. Similar windmills are known from other countries, such as Portugal (Autocar 1961). This technique was repeated on Danish wind turbines in the mid-twentieth century. Photo by R.K. Aber.

When the wind shifts to one side, the fantail begins to spin, and it drives a mechanism that turns the mill cap automatically into the wind again.

Fantails and flap-shutter blades represent the ultimate development of traditional European windmills by the turn of the twentieth century (Fig. 1.5). Typical mills of this type utilize only about 6% of potential wind energy (Thorndahl 2005). Such mills had an average power output of ~10 kilowatts (kW) with a maximum up to 40 kW (Musgrove 2010). At 10 kW, the mill was equivalent to the muscle power of 150–200 people.

Traditional European-style windmills also were built across the United States and Canada. A general impression is that such windmills were common only along the eastern seaboard, but they were actually quite numerous from coast to coast (Fig. 1.6). While European-style windmills were common, American windmill innovation took a completely different direction beginning in the mid-1800s. The prototype multi-bladed windmill was invented by Daniel Halladay in 1854 at Ellington, Connecticut (Baker 1985). Rapid development of diverse designs by many companies followed immediately.

Figure 1.5 Aarsdale Mølle, a smock, Dutch-style windmill on the island of Bornholm, Denmark. (Left) Flap shutters in closed position and blades turning in counterclockwise direction, (Right) flap shutters in open position and blades not turning. Note variation in pitch along length of blades and the fantail on back side of mill. This mill was built in 1877, and the original sail blades were replaced with flap-shutter blades in 1919–1921. The mill still operates today, although not on a regular basis.

Figure 1.6 Old Dutch Mill in Wamego, Kansas. The stone-tower mill was built in 1879 by a Dutch immigrant, J.B. Schonhoff, and used for grinding wheat and corn. The mill was taken down and rebuilt in Wamego in 1925 as a historical monument. The sail frames are non-functional decorative structures.

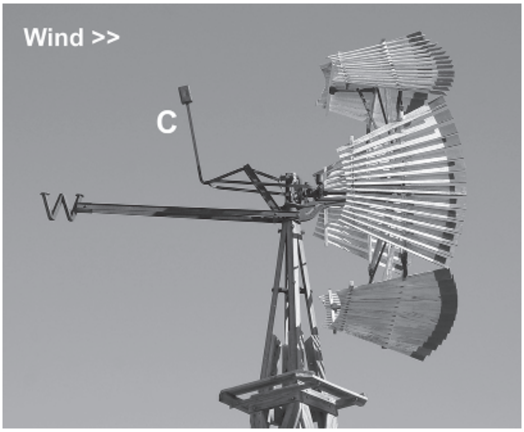

Figure 1.7 Side view of restored Raymond vaneless windmill at Lincoln County Museum, Kansas. The W counterbalance arm points into the wind, and the blade sections are tilted in the downwind direction. The counterweight (C) controls the tilt of the blades; shown here in a position for strong wind. This model was among the most common vaneless windmills across the U.S. Midwest and Great Plains in the late 1800s and early 1900s (Baker 1985).

The early windmills were mostly of the sectional-wheel type in which sets of closely spaced blades fold backward as wind speed increases, thereby controlling the rate of rotation. Some type of spring or counterweight governs the tilt of the blades. Some designs employed a large tail vane to point the bladed wheel into the wind; others were vaneless (Fig. 1.7). The main alternative to sectional wheels is the solid wheel in which all the blades are held rigidly and do not fold. Rate of wheel rotation is governed in various ways with a side vane, offset vane, or off-centered wheel.

Many variations of both sectional- and solid-wheel windmills were manufactured during the late 1800s and early 1900s. Early versions were made largely of wood with wheel diameters typically in the range 2–9 m and giant windmills up to 18 m in diameter (Baker 1985). The superiority of steel began with systematic experiments in 1882–1883 by Thomas Perry at the U.S. Wind Engine and Pump Company in Batavia, Illinois. Based on thousands of tests, he devised the now-familiar wind wheel (wind rose) with curved steel blades set at a specific angle within a rim that offered minimal resistance to the wind (Fig. 1.8). This wheel proved far more efficient than existing wooden wheels. Perry joined forces with LaVerne Noyes to form the Aermotor Company in 1888, which in relatively short time became the largest and best-known maker of American windmills.

In contrast to European windmills, American windmills have many blades in their wheels, at least a dozen to >100 blades in some models. According to Musgrove (2010), *the number of blades has little effect on the power output, for the power in the wind flowing through the rotor can be efficiently intercepted using any number of blades* (p. 53–54). However, the number of blades does influence torque and minimum wind speed needed to start the wheel turning. More blades result

Currie Windmills

In the late 1800s and early 1900s, windmills in Kansas pumped groundwater for railroad steam locomotives and small towns as well as thousands of farms and ranches. Most windmill manufacturers were located in states to the east, but as many as 50 companies may have built windmills in Kansas (KHS 2014). The Currie windmill was among the best known and long lived from the 1880s to 1950s, manufactured first at Manhattan, then Topeka from around 1900 until the late 1940s, and finally at Salina.

Currie windmills had a reputation for durability. The wind-rose wheels came in three sizes of 6-, 8-, and 10-foot diameters. Bearings were hard wood, a steel band encircled the wheel blades, and the tail vane was large and distinctive. Currie windmills were exceptionally low in cost and became known as the *poor man's windmill* (KHS 2014). They were quite common in Kansas as well as many other states. Currie windmills are preserved in several museums today, and the tradition continues with modern mini-Currie windmills made for garden displays and weathervanes.

Historic farmstead of D.R. Beckstrom, who moved to Greeley County in westernmost Kansas in 1892 (C. Shepherd, pers. com. 2023). The Currie windmill has a large wheel with 30 blades. Notice the wooden water barrels at the bottom. The mill presumably dates from the 1890s, as it appears to show Manhattan as the manufacturing city. Undated image obtained from the Horace Greeley Museum in Tribune.

in a higher starting torque at low wind speed, which is particularly useful for operating reciprocating water pumps. Aermotor and similar geared windmills could pump water at wind speeds as low as 2 m/s (Baker 1985).

The success of the American windmill was exported and copied widely in other countries, particularly Argentina, Australia, Brazil, Canada, China, India,

Figure 1.8 Baker Monitor W Series, back-geared, self-oiling windmill restored at Lakin, Kansas. The wheel has 15 fixed, curved steel blades. The distinctive vertical vane was introduced around 1940 and continued to be made into the 1960s. Note the bladed wheel is slightly off centered; as wind speed increases the wheel tends to turn toward the vane, thus regulating the rate of wheel rotation. As wind speed decreases, a governor spring pulls the wheel to face the wind again (Baker 1985).

Mexico, New Zealand, South Africa, Uruguay, and Venezuela, to name a few. Large windmills of the Halladay type were designed, built, and installed in Denmark by N.J. Poulsen in the 1870–1880s (Christensen 2009). By 1930, as many as six million American windmills had been built (Musgrove 2010). However, the Great Depression of the 1930s was a blow that many windmill companies could not survive, and American windmills reached a low ebb in the mid-twentieth century.

This situation turned around with sharp increases in energy costs beginning in the 1970s and since. Water-pumping windmills once again became common for both new equipment and maintaining older models in service. Also restoring antique windmills became popular (Fig. 1.9). The long-term success of the American windmill is due to several factors, most importantly American windmills are self-regulated and run autonomously with minimal human attention (Baker 1985).

1.3 Generating Electricity—Late 1800s to Mid-1900s

Electricity is ubiquitous in the modern world; so much so, that we take it for granted nearly everywhere. We simply "plug in" to the wall socket, put batteries into our portable devices, or connect the car to a fast-charging station. Yet widespread availability and use of electricity are hardly more than a century old.

Figure 1.9 Jasper Windmills, an open-air exhibit in southwestern Minnesota, restores and displays antique windmills from the United States and several other countries including some rare and unusual types.

The concept of utilizing the wind to generate electricity goes back at least to the 1860s. For example, several successful efforts were made by Prof. James Blyth of Anderson’s College (now Strathclyde University), Scotland, in 1887–1914, and in the United States by Charles Brush of Cleveland, Ohio, in 1888–1908 (Price 2005; Musgrove 2010).

The most important of these early efforts with long-term significance took place in southwestern Denmark under the leadership of Poul la Cour (1846–1908). A scientist, teacher, and inventor, he obtained governmental support to build an electricity-generating windmill at Askov in 1891. A second, larger windmill was constructed in 1897, on the basis of extensive experiments in a wind tunnel he designed. La Cour formulated many of the basic tenets of modern wind power, and his protégé, Johannes Juuls, innovated the basic concepts of modern wind turbines half a century later.

The period 1900–1920 is known as the first “golden age” of wind energy in Denmark (Christensen and Thorndahl 2012). By the end of World War I, approximately one-quarter of rural Danish power stations relied on wind turbines of the la Cour type. When la Cour’s 1897 Askov windmill was destroyed by fire in 1929, it was replaced with a Lykkegaard model that had a decidedly modern look—four metal-covered blades mounted on a steel-truss tower (Musgrove 2010).

World War I stimulated rapid aeronautical developments for wings and propellers. These concepts were applied soon to Danish wind turbines in the form of the Agricco windmill, which proved to be considerably more efficient than

Poul la Cour

Danish developments were in progress under the leadership of Poul la Cour (1846–1908). A meteorologist, teacher, and prolific inventor, known as the Danish Edison, he obtained governmental funding to build an electricity-generating windmill at Askov in southwestern Denmark in 1891. Batteries were unreliable and expensive at the time, so his idea was to use the electricity to electrolyze water and produce hydrogen and oxygen gases, which could be stored and later burned for lighting (Nissen 2009; Christensen and Thorndahl 2012).

The first windmill, built by N.J. Poulsen, was quite traditional with four canvas-covered sails and two fantails. These sails were soon changed to adjustable shuttered or flap-blades; the flaps opened automatically if the wind was too strong. In 1897, la Cour teamed with the architect P.V. Jensen-Klint and the millwright Christian Sørensen to design and build a larger windmill with further funding from parliament (Christensen 2017). Sørensen had developed a "conical wind rotor" which was installed with six blades.

Windmills built by Poul la Cour for generating electricity at Askov, southwestern Denmark. First mill (right) was erected in 1891 and had a diameter of 11.6 m with four flap blades. The second mill (left) was built in 1897 and was 22.8 m in diameter. The picture dates from that year and shows the six-bladed conical wind rotor of Christian Sørensen.

(*Continued*)

Poul la Cour (Continued)

However, this setup gave so many problems that la Cour switched after only eight months to a more-conventional four-blade design (Thorndahl 2005). This led to a long and bitter debate between Sørensen and la Cour (Quistgaard 2009), but investigation showed the four-blade design was more effective than the conical wind rotor.

La Cour invented many mechanical and electrical devices for improved capture and storage of wind energy during the last decade of the nineteenth century. He tested the aerodynamics of windmill blades and model windmills in wind tunnels and confirmed the long-held belief that the blade-swept (rotor) area was a key factor for the mill's working capacity (Nissen 2007). Based on his experiments, la Cour formulated the classic relationship:

$$\text{Work} = \text{constant} \bullet \text{blade} - \text{swept area} \bullet \text{wind speed}^3$$

The cube of wind speed means that a slight increase in wind speed yields a large increase in electricity generation. He introduced the American blade type with flaps. Traditional Dutch windmills utilize only about 6–8% of potential wind energy, but la Cour's mill utilized 23% (Thorndahl 2005). He furthermore discovered that fewer blades (4) gave greater power output than more blades (6, 8, 16). On the basis of wind-tunnel testing, la Cour developed principles for his *ideale mølle* (ideal windmill). La Cour had a social vision that wind-generated electricity would help modernize rural Danish life in the early twentieth century.

In order to promote this goal, he offered a prize in 1901 for the ideal mill. Two prize winners were millwrights Ole Jensen and Niels Hansen. The latter began producing windmills under the name Lykkegaard, and this firm continued to manufacture windmills in the la Cour tradition until 1957 (Christensen and Thorndahl 2012). Lykkegaard mills were also exported to France and Venezuela. During WWII (1940–1943), some 60 large flap-blade windmills were installed for generating electricity throughout Denmark (Christensen 2017). The building that supported la Cour's 1897 windmill survives as the Poul la Cour Museum.

traditional windmills or Lykkegaard turbines (Table 1.2). However, ready availability of imported oil and coal following World War I lessened the demand for wind power; production of the Agricco ended in Denmark in 1926, and manufacturing rights were sold to a Dutch company that continued production a few more years (Christensen 2008).

Table 1.2 Efficiency of Danish wind turbines for harnessing potential wind energy, early and mid-1900s.

Turbine type	Date	Blades and rotor (m)	Capacity (kW)	Turning method	Air brake method	Efficiency (%)
La Cour-type Lykkegård	1914–1945	4 blades and 7–18	5–30 DC	Fantail	Flaps in blades	20–25
Jensen & Vinding Agricco	1918–1925	4–6 blades and 5–12.5	5–40 DC	Fantail	Blade pitch control	40–45
F.L.S. Aeromotor	1940–1945	2 or 3 blades and 17.5–24	50–70 DC	Fantail	Spoilers on blade backs	30–40
Juul's Vester Egesborg	1950	2 blades and 7.65	15 AC	Electric motor	Flaps at tips of blades	40–50
Juul's Bogø	1952	3 blades and 13	45 AC	Electric motor	Flaps at tips of blades	50–55
Juul's Gedser	1957	3 blades and 25	200 AC	Electric motor	Flaps at tips of blades	40–50

Thorndahl (2005, Tables 1 and 2, p. 14–15).

Sporadic efforts were made elsewhere early in the twentieth century to harness wind energy for generating electricity. One of these took place at San Gorgonio Pass, California, a site that now hosts a large wind-energy complex. Dew Oliver, a colorful Texas inventor, built what he called a "blunderbuss" at the pass in 1926 (Baker 1985). He claimed it worked, but his scheme to build hundreds of similar turbines and power all of southern California eventually failed, and he was convicted of fraud. Another large and more successful wind turbine of this vintage was the Russian 100 kW generator at Balaclava on the Crimean Peninsula in the northern Black Sea. It was constructed in 1931 and operated for a decade until it was damaged in World War II (Musgrove 2010).

Marcellus and Joseph Jacobs began experiments to make a small, efficient wind generator in the 1920s on their Montana ranch. They soon arrived at a three-bladed configuration with a tail vane; rotational speed was controlled by variable blade pitch that was adjusted by a centrifugal governor (Musgrove 2010). The primary role was to charge batteries for operating light bulbs, radios, and small appliances. The company moved to Minneapolis in 1931, and some 20,000 small wind generators were sold before production ceased in the late 1950s. However, production restarted in 1980 and continues into the twenty-first century (Fig. 1.10; Jacobs 2019).

Agricco Windmill

Danish windmills had a renaissance and new development of blade profiles as a result of World War I, namely the propeller mill patented by the engineers Johannes Jensen and Poul Vinding. The *Agricco-mølle* was presented in 1919. It represented a new generation of windmills that featured blades based on airplane wings. Blades had steel frames with wooden ribs, and the turbine was self-directed into the wind. Rotor speed was adjusted by turning the entire blade, in other words, pitch regulation. Rotor diameter varied from 8.5 to 16.5 m, and blade number was four, five, or six.

The aerodynamic design of windmill blades in Denmark was well ahead of other countries around 1920 in terms of both techniques and scientific understanding. Government testing in 1923 showed that Agricco mills were more efficient at high wind than la Cour's ideal mill and at low wind were more effective than wind-rose rotors. Agricco windmills utilized 43% of potential wind energy (Thorndahl 2005).

An asynchronous generator was perfect for windmill operation to produce AC current directly into the grid system, although only a few Agricco mills were sold for electricity production. The timing of Agricco was unfortunate, however, as the market for new mills was on the way down after World War I, and the factory was liquidated in 1925 (Christensen 2017). Agricco windmills proved robust, and some continued in service until the 1960s, although only a few skeletons remain today.

Agricco windmill on the island of Bornholm, Denmark. Five-bladed model with twin fantails erected on the base of an older Dutch-style mill in Olsker. This mill was in service from 1927 until the late 1960s (Christensen 2016). Seen here as it appeared in 1979.

Figure 1.10 Jacobs wind turbines in Hawaii circa 1989. Paul Gipe / Wikimedia Commons / CC BY-SA 4.0.

In the 1930s, Palmer C. Putnam, a New England engineer and geologist, became interested in industrial-scale wind power for generating electricity. He convinced the S. Morgan Smith Company to finance the construction of a large wind turbine at Grandpa's Knob in the Green Mountains of Vermont (Baker 1985; Musgrove 2010). The turbine had twin blades with a rotor diameter of 175 feet (53 m) standing on a steel-truss tower, by far the largest wind turbine built up to that time with a maximum output of 1.25 megawatts (MW). The Smith–Putnam wind turbine began operation in 1941, but it suffered numerous mechanical failures and was eventually abandoned shortly after World War II.

The war and its immediate aftermath marked a time of severe restrictions for materials, fuel, and labor in many countries, which curtailed further wind-energy developments during the 1940s. The war-time need for wind power stimulated the F.L. Smidth & Co.'s Aeromotor development in Denmark. Designed by Helge Claudi Westh (1904–1992), these two- and three-bladed turbines were mounted on reinforced concrete towers (Thorndahl and Christensen 2009). The largest turbines had rotors 24 m in diameter with 70 kW capacity. These turbines proved quite significant for subsequent work by Johannes Juul in the 1950s.

Johannes Juul (1887–1967) took up the cause for further development of wind energy. Juul had been a student of la Cour's in the first class for wind electricians at Askov in 1904 (Christensen and Thorndahl 2012). He conducted wind-tunnel experiments and built a series of prototype turbines that culminated with the Gedser turbine in southeastern Denmark. The Gedser wind turbine was put into continual, unattended operation in 1958, and it generated grid power for a decade. Juul's innovations proved to be pivotal for modern turbine design (Thorndahl 2009), and without question the Gedser turbine had great influence for continued development of the wind industry in Denmark and elsewhere (Musgrove 2010).

Johannes Juul and the Gedser Wind Turbine

A direct line extends from Poul la Cour's windmills at Askov to modern Danish electricity generating wind turbines via Johannes Juul (1887–1969), who was a pupil in the first course for rural electricians in 1904 (Thorndahl 2005). From 1905 to 1925, Juul held various electrical positions in Denmark and Germany. In 1926, he accepted a position with SEAS (Sydøstsjællands Elektricitets Aktieselskab), where he had the freedom to conduct independent research.

In 1947, at age 60, Juul began the work that would make him world famous in the wind-energy community. He built a wind tunnel in 1948 to test blade profiles. At least 25 different blade types were tested, which showed that quite small deviations had great significance. Air brakes and spoilers could be integrated into blades. Juul reached conclusions in 1949 about the ideal blade and mill. From numerous sketches, he clearly favored a three-bladed rotor with brake flaps in the blade tips.

The first research wind turbine was erected at Vester Egesborg in 1949, and a second mill was built in 1952 at Bogø, both in southeastern Denmark. Blade regulation had proven to be the weak point with contemporary windmills in England and the United States. Juul's solution with brake flaps in the blade tips was simple, less expensive, and more stable than pitch regulation for the whole blade. Juul had solved the problem of regulating rotation speed, and in 1952 he got a patent for this technique.

In 1954–1955 plans were developed for a large 200 kW research wind turbine, and Parliament provided money from the Marshall Plan for wind-energy research (Thorndahl 2005). Gedser, at the southern tip on the island of Falster in southeastern Denmark, was chosen as the location, because personnel at SEAS had the most experience with the previous experimental windmills.

Much foreign interest was shown for *Gedsermøllen* when it was completed in 1957. The main aspects included a 24-m-diameter rotor with three blades and two braking systems, namely blade-tip brake flaps and a mechanical brake. The 200 kW asynchronous generator was designed to complement blade size and wind conditions in the vicinity. The tower was 25 m tall made of concrete with three buttress ribs on the sides. All aspects of mill design and construction were compromises in order to minimize cost.

The windmill opened in 1957, the same year that Juul retired. After some minor adjustments and measurements the mill was fully operational in spring 1958. The Gedser turbine ran continuously until 1967 and produced 2,240,000 kWh of electricity (Thorndahl 2005). Juul concluded in 1962 that wind energy could:

Johannes Juul and the Gedser Wind Turbine (Continued)

- Save cost of generating electricity over foreign fuels.
- Achieve reserve energy for steam-power plants when weather is windy and cold.
- Create a work market for building of wind-power facilities.
- Achieve economic distribution by Danish wind power working together with Norwegian and Swedish hydropower.
- Create a market for export of Danish wind-power facilities to the rest of Europe.

It took two more decades to prove that Juul was correct. However, he died in 1969 without realizing the full potential of his vision. State support for wind energy research ended in 1962. Interest in wind energy was minimal in Denmark at this time. Fossil fuels were cheap, and nuclear energy was just around the corner. In 1965 Jylland and Fyn, and earlier Sjælland, were connected via undersea cables to cheap and reliable Swedish hydropower.

Gedser turbine nacelle and blades restored and displayed at the Danish Energy Museum. Blades have steel beams with wooden cross ribs, and the blade surface is covered with aluminum sheets. Turbine blades have cross braces and struts for extra support; these braces were oversized to protect the blades from storm damage. Note the blade-tip flap brakes.

(*Continued*)

Johannes Juul and the Gedser Wind Turbine (Continued)

All this changed with the oil crisis in 1973. The Gedser turbine was the only large mill in the world that had operated without significant interruption for 10 years. DEFU (Dansk Elværkers Forenings Udredningsudvalg) and ERDA (U.S. Energy Research and Development Administration) agreed to restore the Gedser mill, which was renovated in 1977 and ran again until 1979. Thus, the Gedser turbine spanned more than 20 years of operation and measurements.

The Gedser wind turbine represents the **Danish Concept**, which includes a three-bladed rotor mounted upwind from the tower, dual aerodynamic and mechanical braking systems, and asynchronous AC generator connected directly to the electricity grid. In the 1970s, Gedser was the starting point for further development of both large and small Danish wind turbines.

Key criteria behind Juul's construction at Gedser were simplicity, safety, and low cost. Gedser was a success in comparison to contemporary ambitious wind turbines in other countries. Those elegant turbines suffered many technical problems, but Gedser was not elegant and it did work. Juul had carried out practical experiments and had upscaled smaller mills into the large Gedser turbine. Gedser represents today one of the most important technological Danish innovations since WWII and the basis for the modern worldwide wind industry.

Like Denmark, France, Germany and the United Kingdom experimented with AC-generating, grid-connected wind turbines during the 1950s and 1960s (Musgrove 2010). Several large wind turbines were designed and tested at inland and coastal sites as well as small islands, such as the Orkneys and Isle of Man. A noteworthy series of turbines was designed by Lucien Romani in France (Cavey 2024). He founded the Bureau des études scientifiques et techniques (BEST) in 1946 and produced a series of increasingly large wind turbines known as BEST–Romani aerogenerators.

Among the most remarkable turbines of this era were those developed by Ulrich Hütter at the Technischen Hochschule Stuttgart (now University of Stuttgart), Germany. Hütter was an aircraft designer who began field-testing wind turbines based on propeller designs in 1940. Continued experiments resulted in a 34-m-diameter, two-bladed turbine in 1957 (Fig. 1.11). He was the first to employ fiberglass to construct self-supporting blades that were extremely long and thin. Hütter's work had decisive influence on subsequent Danish developments at Tvind.

At this time, large turbines were quite few in number, located in relatively isolated spots, and generally did not attract much attention from the public in terms of their

Figure 1.11 Allgaier–Hütter StGW-34 model, two-bladed, 100 kW wind turbine located at Stötten, ~80 km east of Stuttgart, Germany (1958). With a rotor diameter of 34 m, it was the first turbine with fiberglass blades. Courtesy of H.H. Dörner.

appearance or potential environmental impacts. In fact, the environmental movement as we know it today hardly existed. Most international treaties and national laws regarding air, water, wetlands, wildlife, pollution, climate, and other environmental issues were still in the future. Thus, the emphasis on developing wind energy was focused almost entirely on practical and economic questions of electrical and aerodynamic engineering.

By the 1960s, however, vast oil reserves of the Middle East were flooding the world with low-cost fuel, nuclear energy was growing, and the perceived need for wind energy waned (Musgrove 2010). The Gedser wind turbine was shut down in 1967. The Allgaier–Hütter, BEST–Romani, and other large wind turbines suffered similar fates, as the general public and policy makers firmly believed that cheap oil and nuclear energy would be unlimited and have no environmental consequences.

These assumptions soon would change dramatically. When the United Kingdom withdrew from the Persian Gulf region in 1971, the politics of petroleum changed, and the first great oil crisis was triggered barely two years later. A second oil crisis in 1979 and nuclear disasters at Three Mile Island, Pennsylvania, in 1979 and Chernobyl, Soviet Union (now Ukraine), in 1986 further drove public opinion and policy decisions regarding energy resources. Yet, it would take much of the late twentieth century for the modern wind industry to emerge as a leading source for renewable, non-polluting energy.

1.4 Generating Electricity—Late 1900s

Interest in and development of wind energy had reached a low ebb by the end of the 1960s. The Yom Kippur War in 1973 triggered OPEC to reduce oil production, which led to shortages and rapid price increases, and high oil prices continued through the 1970s. Many countries recognized the need to develop renewable, domestic, safe, and non-polluting forms of energy. Research was conducted on many potential energy sources, namely solar, geothermal, wave and tidal, and wind. In the 1970s, however, wind was considered an unlikely prospect for generating substantial electrical power compared with other renewable energy sources.

1.4.1 Developments in the 1970s

Several relatively small wind-energy programs were started nonetheless in Denmark, Germany, Netherlands, Sweden, United Kingdom, and United States (Musgrove 2010). Among the most important wind-energy developments during the 1970s and 1980s were those in Denmark and the United States. The Danish government and electric utilities wanted to build nuclear power stations as quickly as possible. However, many grass-roots organizations sprang up in opposition to nuclear energy and in support of renewable energy sources, namely solar and wind.

Lars Albertsen proposed a new Danish word, *vedvarende energi*, meaning sustainable or renewable energy (Grove-Nielsen 2023). Many Danish entrepreneurs, teachers, and inventors began to experiment with wind turbines, particularly in Jutland in the mid-1970s. Among the most important of these were small turbines built by Christian Riisager and the large turbine at Tvind.

Erik Grove-Nielsen became involved with wind turbines as a young man in 1977 to build fiberglass turbine blades, and he set up Økær Vind Energi (Grove-Nielsen 2023). In 1978 Grove-Nielsen and his wife, Tove, came to a decision that would have long-lasting consequences, namely blades that would rotate in a clockwise direction. Future Økær customers—Vestas, Bonus, Nordtank, and Enercon—followed the clockwise pattern, which set the industry standard.

Nordvestjydsk Institut for Vedvarende Energi (NIVE) was founded in Thisted in 1977 and led by the charismatic Preben Maegaard (1935–2021). The aim was to establish decentralized production of wind turbines. NIVE developed the so-called *Smedemestermølle* (Blacksmith turbine) with the idea that it could be produced in small machine shops across the country (Fig. 1.12). Økær Vind Energi supplied fiberglass blades that rotated in a clockwise direction. Like the Riisager turbine, it had twin fantails to point the main rotor into the wind. Rated output was 22 kW; later models increased to 60 and 100 kW.

Christian Riisager

Christian Riisager (1930–2008), a carpenter, was prominent among the Danish wind-turbine innovators in the mid-1970s. He already had built a small 7.5 kW turbine to provide electricity for his home garden near Herning in central Jylland. Without permission, Riisager and his wife Boe connected this turbine to the electric grid in 1975 and made their meter run backward (Thorndahl 2011). This unofficial experiment led to formal rules for individuals to sell electricity to the utility grid system.

The Riisagers teamed with Erik Nielsen in 1976, and they began manufacturing wind turbines in Herning. The blades were constructed of laminated wood by Riisager himself, and turbines were sold in sizes ranging from 10 to 45 kW (Grove-Nielsen 2023). Riisager and other windmill pioneers found parts for their machines from junk yards and auto chop-shops. Gears, brakes, crankshafts, differentials, and other parts were repurposed for windmills to generate electricity. They also found solutions from older mills, such as fantails (Christensen 2017).

Riisager turbine at the Danish Energy Museum. The rotor consists of three blades upwind from the tower and twin fantails to turn the rotor into the wind. In keeping with windmill tradition, the blades turn in the counterclockwise direction—nearly all other modern turbines rotate clockwise as viewed from upwind.

(*Continued*)

Christian Riisager (Continued)

Riisager turbines followed the general design of the earlier Gedser turbine (Thorndahl 2005). His turbines were, in fact, miniature versions of the giant Gedser windmill, except that his did not have brake flaps in the blade tips. Three blades rotated upwind from the tower, and twin fantails kept the rotor facing into the wind. An induction generator connected to the grid was held at constant speed, which also maintained constant rotor speed for the fixed-pitch blades (Musgrove 2010).

Riisager sold production rights in 1979 to a new company, Windmatic. He also entered into other partnerships, and Riisager-clone turbines were manufactured under such names as Erini, Oxholm, and Sonebjerg (Thorndahl 2011). By 1980 about 120 Riisager windmills were around Denmark.

Riisager sold a 55-kW turbine to the Faroe Islands in 1980, and in 1981 the Riisager family moved to Miðvágur in the Faroes and began making larger wind turbines of 90–130 kW capacity (Thorndahl 2011). These carried the Riisager name and had slimmer blades, new gears, and were tested in wind speeds up to 60 m/s. Blade materials were wood, fiberglass, and stainless steel. Finally the Riisagers made sure to patent their wind turbine.

In 1985, Riisager began to develop a 200-kW turbine, but the project encountered economic difficulty, and Riisager returned to his original avocation as a carpenter. The Riisagers did not become rich through building wind turbines, but they were instrumental in starting the Danish wind industry in 1975 and helping to develop it well into the 1980s (Grove-Nielsen 2023).

Windmatic 65 kW turbines with 14-m-diameter rotors and hub height of 18 m. Designed by Christian Riisager. In the former Los Vaqueros Windfarm, north of Livermore, California, as they appeared in 2012.

Tvind Wind Turbine

> *The importance of the building of the Tvind Turbine was immense – at a crucial time in history, where Denmark was going to decide, whether we should embark on building nuclear power stations in the country, or not* (Grove-Nielsen 2023).

In the 1970s, Denmark faced a major dilemma and engaged in political debate whether to begin development of nuclear energy. This was an intensely polarizing issue that lasted into the 1980s. The Tvind Schools had been founded as an alternative Folk High School in 1970 with governmental support as a teachers' training college. The people at Tvind, led by the charismatic teacher Amdi Petersen, were strongly opposed to nuclear power and made the decision to build a megawatt-sized wind turbine to provide power for the school complex (Maegaard 2009; Christensen and Thorndahl 2012).

A call was sent out for volunteers—both students and professionals. The basic design was modeled on Juul's Gedser wind turbine of 1957. For technical advice, they turned to Ulrich Hütter to learn about the fiberglass blades in his turbine at Stötten, Germany. They received help from several other professionals, utilized second-hand parts, and did most of the construction themselves with volunteer labor. Construction began in 1975. The base and 53-m-tall tower are made of reinforced concrete. The nacelle is made of welded steel and contains the gearbox, generator, and the hydraulic pitch-control and emergency-stop systems. Blades were lifted into position by Klose Cranes, which later became the major company for erecting turbines all over Denmark (Grove-Nielsen 2023).

The 2.0 MW Tvind wind turbine was completed in 1978, and for many years it was the largest wind turbine in active service anywhere in the world. The Tvind turbine rotor has three self-supporting fiberglass blades, 54 m in diameter, mounted downwind from the tower. The Tvind turbine *introduced the blade technology of the future. It became the industry standard and the core technology in the decisive breakthrough for Danish wind turbine producers in the following years* (Maegaard 2009, p. 48). Its blades were replaced in 1993. For this long-term achievement, the Tvind wind turbine was awarded the European Solar Prize in 2008.

In 2023, after 45 years in operation, the turbine showed serious signs of its age. Water leakage in the nacelle had caused rusting and corrosion of the generator support frame and other components. The turbine was taken offline to perform maintenance and repairs. The renovation consisted of cleaning and sandblasting with dry-ice (CO_2) pellets. The generator was lifted, and the undercarriage was replaced with new stainless-steel supports. Marine waterproofing was the final step to seal and protect the turbine (E. Værge, pers. com. 2023). It is anticipated the Tvind wind turbine will have many more decades of service.

In addition to the large turbine, the Vestjydsk Energi Kontor (Western Jylland Energy Office) was set up at Tvind in 1976 by two young engineers, Jens B. Gjerding and Søren Kahlke. The purpose was to aid and give advice to turbine

(*Continued*)

Tvind Wind Turbine (Continued)

self-builders. They designed the small 11 kW PTG turbine and its 4.5-m-long fiberglass blades. PTG followed windmill tradition and Riisager turbines by rotating counterclockwise. Furthermore, Tvind played a prominent role in Denmark's eventual decision in 1985 not to develop nuclear energy (Maegaard 2009). Without doubt, the Tvind wind turbine inspired Danes to experiment with wind power, and it stimulated numerous, independent developments by inventive self-builders.

Tvind wind turbine near Ulfborg, western Denmark, as it appeared in 2012. The concrete tower is supported by a conical foundation also of reinforced concrete. The distinctive paint scheme was applied to celebrate the turbine's 25th anniversary in 2003.

Early blades had no aerodynamic braking capability and were subject to runaway failures. Grove-Nielsen was convinced by fellow builder and customer, Henry Jørgensen, to adopt the tip-brake technique of Juul's Gedser turbine. Økær developed a new 7.5-m-long blade, under the name AeroStar, in 1980. This blade was utilized by many companies including Danregn (Bonus) and Nordtank in early California wind farms. These blades were still in service and operating 40 years later.

Figure 1.12 Økær 5-m-long fiberglass blades on a 22 kW Smedemestermølle of the Riisager type. Note the blades turn in a clockwise direction. Restored and displayed at the Renewable Energy Museum, Denmark.

Late in 1978, Økær blades with air brakes were delivered to the Herborg Vind Kraft (HVK) turbine designed by Henrik Stiesdal and built by Karl Erik Jørgensen. This turbine was similar in many respects to the Riisager style, but without fantails. The HVK employed a wind sensor and yaw motor to point the rotor into the wind, and blades rotated clockwise as viewed from upwind. The HVK turbine embodied the so-called *Danish concept* and was the basis for continued turbine development. By the end of 1979, Vestas had signed a licensing agreement for the HVK turbine and had begun commercial production.

Thus, by the end of the 1970s, Denmark had moved through an extremely rapid and innovative phase of wind-energy development. Countless experiments were undertaken by inventors and self-builders using diverse materials, varied construction techniques, and numerous turbine and blade designs. Many small companies provided a supply chain of specialized components for manufacturing and installing commercial wind turbines based on the HVK model, which emerged as the Danish standard. This standard consisted of three fiberglass blades rotating in a near-vertical plane on a near-horizontal axis upwind from the tower with an asynchronous generator supplying electricity to the grid system (Maegaard 2009). Autonomous controls and independent braking systems provided safe operation.

These efforts were aided by freely sharing technology. *No single patent or property right blocked the innovative process in this new industry* (Maegaard 2009, p. 47). Furthermore an investment subsidy of 30% for purchase of approved wind turbines was enacted in 1979, which spurred domestic sales (Madsen 2009). This subsidy gradually was reduced over time to 10% and then eventually terminated in 1989. Additional incentives included a national recommendation to local municipalities and counties to support wind energy, and access by small wind turbines to the utility grid system. This was a remarkable social achievement, in stark contrast to normal economics, that placed Denmark into a position of leadership as the wind industry grew worldwide during the 1980s.

In the United States, the first Earth Day was celebrated on April 22, 1970. This was followed by nearly 20 major statutes enacted during the decade dealing with clean air and water, endangered species, and other environmental issues. The influential physicist Amory Lovins called in 1976 for increased reliance on renewable energy resources—solar, wind, biofuels, and geothermal—for generating electricity. The premier wind research project in the United States was conducted by NASA at the Glenn Research Center in Sandusky, Ohio, beginning in 1974 (Grove-Nielsen 2023). Sponsored mainly by the Department of Energy, most of the funding went to major aerospace and electrical engineering companies (Ragheb 2023).

The result was a series of increasingly large experimental and operational turbines from Mod-0 through Mod-5B (Fig. 1.13). All employed two-bladed rotors patterned after the earlier Smith–Putnam and Ulrich Hütter designs. Some rotors were upwind and others downwind from the tower. Early models had truss towers; later ones had tubular steel towers (Fig. 1.14). In all, some 13 turbines were built and installed across the United States from Hawaii to Puerto Rico, and one went to Sweden.

The Mod turbines suffered a series of operational problems and equipment failures, and showed slight promise for eventual commercial success. The program demonstrated the difficulty of engineering successful large wind turbines by aeronautical manufacturers that had little experience in this technology. The Mod-series models, in fact, could not compete for reliability and efficiency with smaller Danish wind turbines of the time (Musgrove 2010). The Mod-series program ended in the late 1980s.

President Carter was keen to develop alternative energy resources. Federal energy legislation under his administration included three key components, all enacted in 1978—Energy Tax Act, Powerplant and Industrial Fuels Act, and Public Utilities Regulatory Policy Act (PURPA). Together these tax incentives added up to 50% in California, and PURPA guaranteed that electricity could be sold at a favorable price. U.S. Windpower, which already had built its first wind

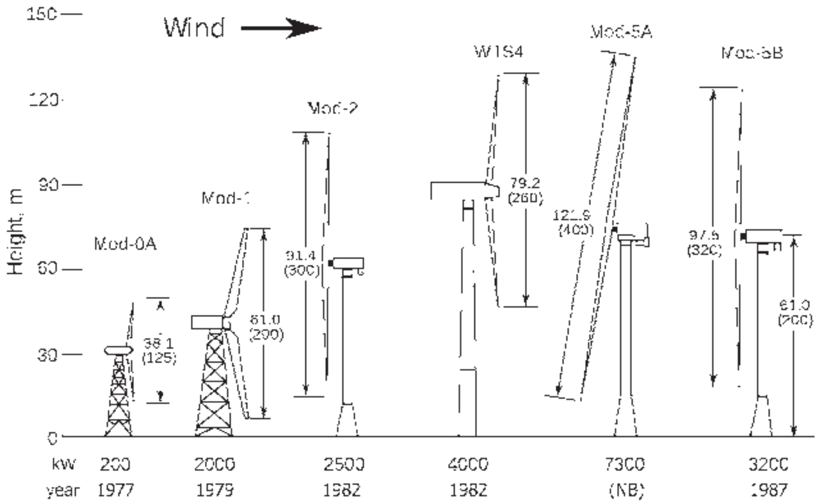

Figure 1.13 Schematic diagram to scale of NASA Mod-series wind turbines. Rotor diameters and hub heights given in meters (feet), rated capacity in kilowatts (kW), and year of first installation. NB = not built. NASA image obtained and adapted from Wikimedia Commons https://commons.wikimedia.org/

Figure 1.14 NASA Mod_0 wind turbine at Plum Brook Station, Sandusky, Ohio (1976). Downwind, two-bladed rotor was 38 m in diameter, hub height 30 m, and rated output 100 kW. Note the person at lower left for scale. NASA on The Commons/Wikimedia Commons/Public Domain.

Figure 1.15 U.S. Windpower turbines at Paterson Pass in the Altamont Pass wind-energy complex as seen in 2012. The turbines have three fiberglass blades with variable pitch mounted downwind from the tower. Rotor diameter is 17 m with nominal output of 100 kW (Musgrove 2010).

farm at Crotched Mountain, New Hampshire, quickly realized the potential tax and sales advantages in California. The company began leasing land at Altamont Pass and erected the first 100 wind turbines in 1981 (Fig 1.15). Thus began the California wind boom.

1.4.2 Developments in the 1980s

Many other companies quickly followed in California with leasing land, obtaining zoning approval, contracting with local utilities, raising financing, and erecting wind turbines by the hundreds and then thousands in the early 1980s. For a good return on investment, two factors were critical—reliable turbines and a windy location (Musgrove 2010). Three mountain passes well known for strong wind became the primary locales for California wind-farm development, namely Altamont Pass situated on ridges of the Diablo Range east of San Francisco Bay, Tehachapi Pass located between the southern end of the Sierra Nevada Mountains and the Tehachapi Mountains, and San Gorgonio Pass situated close to Palm Springs and next to the San Jacinto Mountains.

Within five years, more than 12,000 wind turbines had been installed in California representing more than 30 different models (Musgrove 2010). U.S. Windpower turbines proved generally reliable; however, most other turbines of American design and manufacture suffered widespread failures. Beginning in 1983, California wind-energy developers increasingly sought Danish turbines that already had established a reputation for robust, reliable service. Wind turbines rapidly covered hill sides and ridge tops, like mushrooms sprouting after a spring rain (Fig. 1.16).

Figure 1.16 Overview of the Patterson Pass wind farm which was commissioned in 1985 with several hundred Bonus and Nordtank turbines, as seen in 2012. Altamont Pass vicinity, east of Livermore, California.

Lattice steel towers were the norm at the beginning of the 1980s decade. Nordtank, a Danish company that made tank vehicles, introduced welded-steel tubular towers for wind turbines in 1980 (Madsen 2009). Within a few years, other turbine makers had adopted this type of tower because it was visually more acceptable to most people (Musgrove 2010). Peter Mørup, the head of Nordtank manufacturing, left the company in 1983 and co-founded Micon with his brother.

Danregn Vindkraft was founded in 1980 by Peter Stubkjær Sørensen and Egon Kristensen. The early Danregn turbine was inspired by the Smedemester design and had many similarities. The company name soon was changed to Bonus. By the mid-1980s Vestas, Bonus, Nordtank, and Micon had become the leading Danish manufacturers of wind turbines that had gained a reputation for dependable performance (Musgrove 2010). It should be noted these companies had their origins in agricultural and transportation manufacturing, wherein reliable equipment is paramount, and they drew on the shared, grass-roots efforts from the 1970s.

The Nordic Folkecenter for Renewable Energy was founded in 1983 by Maegaard near Hurup, Denmark. The center is a museum for early wind turbines and provides technology transfer and pilot projects in many countries around the world. By this time more than 20 Danish companies produced wind turbines, and government subsidies were in place for purchase of turbines. Thus, the grass-roots era of wind-turbine development had come effectively to its end by the early 1980s.

The United States, however, failed to renew tax incentives for wind energy in 1986, which led to financial collapse for the Danish turbine industry the following year. Most companies (except Bonus) went into bankruptcy. All were reorganized, downsized, and managed to continue. The Danish government encouraged consolidating many small suppliers into larger integrated companies that would compete on the international market. The convergence of innovation, manufacturing, and public policy that resulted in Danish wind-energy success during the 1970–1980s is an example of *bricolage*, a French term that refers to resourcefulness in the creation of a new technology from diverse sources and available resources (Nielsen 2009).

The environmental movement had gained considerable momentum and widespread acceptance during the 1970s. Many of the strongest supporters followed the *small is beautiful* philosophy (Graetz 2011). This movement was especially opposed to nuclear power and also to large hydropower projects. Wind power remained the most promising alternative means for generating electricity; however, environmentalists were not particularly happy with the prospects for expanded wind energy. According to Graetz (2011, p. 123), *wind turbines are neither small nor beautiful.*

Lucrative tax credits in the United States attracted all types of investors seeking financial shelters; wind farms were regarded by some as "tax farms" (Graetz 2011). Along with serious investors came fraudulent and unscrupulous scoundrels. The most notorious case involved International Dynergy, which equipped a wind farm in southern California with used helicopter blades attached to broken turbines in an effort to fool tax appraisers.

Under the Reagan administration, federal tax credits expired at the end of 1985, and California tax credits ended a year later. Meanwhile oil prices declined sharply in 1986, and concerns arose about bird mortality, particularly at Altamont Pass. Public desire for wind energy diminished, and permitting of new wind farms became more difficult (Musgrove 2010). These factors in combination busted the California wind boom. Still, California utilities had long-term contracts to purchase electricity from wind farms, which allowed the industry to continue, albeit at a much slower pace than prior to 1986. U.S. Windpower survived on electricity sales, and in 1988 it was reorganized as Kenetech that diversified and expanded into new wind-energy markets.

James Hansen, a NASA climatologist, is often considered the father of global warming. In 1987, he testified before the U.S. Congress concerning the role of atmospheric carbon dioxide and other greenhouse gases for global warming (Graetz 2011). He warned that climatic change could dramatically impact global environments and the world's human population. Although a scientific and political consensus was still in the future, the potential impact of burning fossil fuels was clear, and the need to develop renewable, non-polluting sources of energy became more urgent.

1.4.3 Developments in the 1990s

By 1990, the Danish concept had proven superior for routine, dependable generation of electricity from the wind under wide-ranging circumstances and conditions. Efficient, low-cost manufacturing techniques had been worked out, so that Denmark was well positioned to dominate the wind-energy market during the 1990s. One key to improved economics was increasingly large turbines, which had reached 25–27 m in rotor diameter and 150–250 kW output. By 1996, Vestas had achieved 20% of the world market with Bonus, Nordtank, and Micon each around 10% for a total of half the global market in wind turbines (Musgrove 2010). The latter two companies merged in 1997 to form NEG Micon.

Already the Danish government began to recognize limits for land-based wind farms. The world's first offshore wind farm was constructed at Vindeby in 1991 in shallow seas of relatively protected waters between islands of southern Denmark (Fig. 1.17). Offshore wind farms, although more expensive to construct, produce substantially more electricity than land-based wind farms because of stronger and more consistent wind. Most of the land area of Denmark, for example, has average wind speeds at 100 m height of 7–9 m/s; whereas, much of the surrounding sea is 9–10 m/s (GWA 2023). By the end of the decade, Denmark had formulated plans to build large offshore wind farms.

Figure 1.17 Vindeby turbine preserved and displayed in the Danish Energy Museum. Blades are 17 m long, the tower originally stood 33 m tall, and generating capacity was 450 kW. Note the brake flaps in the blade tips. From the world's first offshore wind farm erected in 1991 and taken offline in 2017.

Figure 1.18 Pair of Tacke turbines at Swarzewo, northern Poland, as seen in 1998. Tacke Windtechnik was the second leading German manufacturer of wind turbines in the 1990s.

Europe was poised for rapid expansion of wind energy during the 1990s. Germany and Spain enacted feed-in tariff laws for sale of renewable energy to large utilities, which led to exponential growth of their wind industries (Musgrove 2010). Gamesa and Acciona emerged as major turbine manufacturers in Spain; Gamesa entered the wind industry in 1993 in partnership with Vestas. In Germany, most turbines were installed near the North Sea and Baltic Sea coasts. As in Denmark, turbine dimensions grew steadily, reaching megawatt size by the end of the decade. The main German turbine makers were Enercon and Tacke (Fig. 1.18). Tacke, however, fell on economic difficulties and declared bankruptcy in 1997. It was bought by Enron Wind and subsequently acquired by General Electric in 2002.

The feed-in tariff laws in Denmark, Germany, and Spain had been highly successful for stimulating the wind industries in those countries. The United Kingdom, in contrast, took a different approach that proved quite disappointing (Musgrove 2010). The Non-Fossil Fuel Obligation (NFFO) was devised during 1989–1990 primarily to support the higher cost of producing nuclear energy by placing a levy on electricity generated with fossil fuels. Only a small portion of proposed British wind farms were approved and eventually constructed.

By the end of 2000, the total U.K. capacity was just 410 MW compared with 2,300 MW in Denmark, 2,400 MW in Spain, and 6,100 MW in Germany (Musgrove 2010). By the late 1990s, the lack of NFFO success was evident, and the government moved to replace it. The result was the Renewable Obligation (RO), a complex process that required utilities to sell electricity generated from renewable energy resources; it began early in the twenty-first century.

Both China and India have quite large potentials for wind energy. India began early development in the mid-1980s with financial support from Denmark. In the mid-1990s, both national and state governments provided generous financial incentives for wind energy, which exceeded a total capacity of 1,000 MW in 1999. The Indian market stimulated domestic production, and Suzlon emerged as a major builder of wind turbines. China likewise began limited wind-energy development in the late 1980s also with financial support from Denmark. However, China's pace of wind-energy growth remained slow during the 1990s. Goldwind produced its first Chinese turbine in 1998 with German technical help.

Following the collapse of the California wind boom, growth of wind energy stagnated in the United States. Between 1990 and 1997 installed capacity increased by a trivial 90 MW (Musgrove 2010). The federal Production Tax Credit (PTC) of 1992 was an attempt to increase use of renewable energy technologies; financial support was linked to a project's long-term energy output rather than its capital cost. The PTC revived the U.S. wind industry, which began a modest recovery during the decade. The most successful venture during this period was the wind farm developed on Buffalo Ridge in southwestern Minnesota.

Buffalo Ridge

Buffalo Ridge is the most conspicuous drainage divide in the north-central United States. The ridge is a glacial landform, known as the Bemis Moraine, that accumulated along the western edge of the Des Moines ice lobe about 14,000 years ago. The Bemis Moraine extends from eastern South Dakota, across southwestern Minnesota, and into northwestern Iowa. Buffalo Ridge marks the eastern margin of the Prairie Coteau, a glacial upland that drains into the Missouri River basin. Buffalo Ridge is the divide, east of which drainage heads into the Minnesota River and eventually Mississippi River basin. The ridge exceeds 600 m elevation toward its northern end at Summit, South Dakota, some 300 m above the Minnesota River valley to the east.

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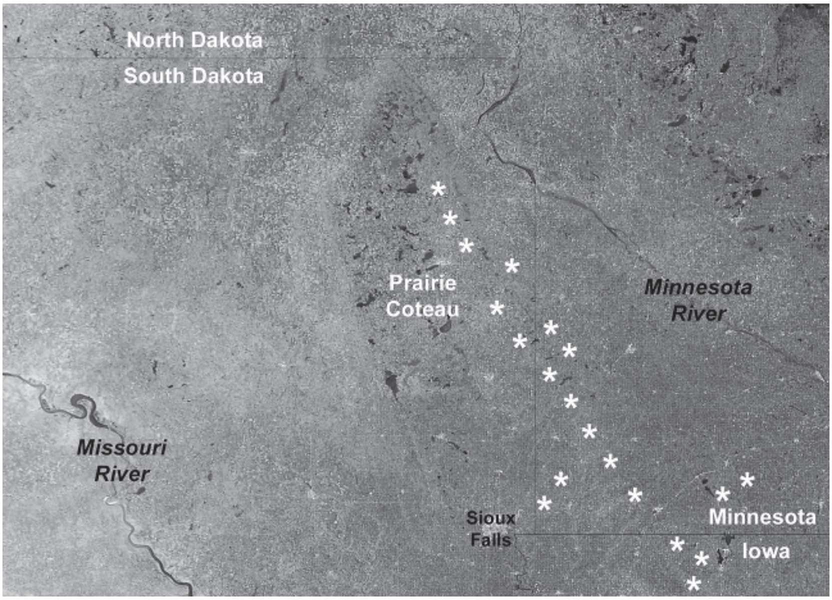
Buffalo Ridge (Continued)



Satellite image of the Great Plains region in the north-central United States. Numerous wind farms (*) are positioned along Buffalo Ridge on the eastern margin of the Prairie Coteau upland in South Dakota, Minnesota, and Iowa (Hoen et al. 2018–2025). MODIS natural-color image, Terra satellite, September 3, 2002. NASA / Public Domain.

This prominent drainage divide was an early target for wind-energy development during the 1990s. When Northern States Power requested to expand its nuclear-waste storage, Minnesota required that it add 425 MW of wind power to its generating inventory. Kenetech turbines were used in the first phase of development in 1994. These were followed by Zond turbines in the second phase completed in 1998. Zond was bought by Enron and renamed Enron Wind. Meanwhile Kenetech, once the world's largest manufacturer of wind turbines, suffered continuing engineering problems and went bankrupt in 1996.

Wind farms have proliferated along Buffalo Ridge and the Prairie Coteau since then from near Summit, South Dakota, to Worthington, Minnesota, a distance of more than 200 km, and continuing southward into Iowa. More than 2,700 turbines are arrayed in these wind farms in South Dakota and Minnesota (Hoen et al. 2018–2025). Multiple generations of operational wind farms and turbines range in age from the late 1990s to early 2020s, including the original Zond/Enron turbines from 1998. These turbines demonstrate the trend through time for larger sizes and capacities. Meanwhile, some of the oldest and smallest turbines have been removed.

Buffalo Ridge (Continued)

Kenetech KVS-33 wind turbines on Buffalo Ridge near Lake Benton, southwestern Minnesota, as seen in 1996. Rotor diameter is 33 m, and output is 300–360 kW. Between 1992 and 1996, about 700 of these turbines were installed at sites across the United States and in Costa Rica (Carlin et al. 2001).

Older and newer turbines on Buffalo Ridge near Lake Benton. (Left) Vestas 0.66 MW turbines in the Ruthton Wind Farm date from 2001. Rotor diameter is 47 m, and total height is 88.4 m (290 feet). (Right) GE Wind 2.82 MW turbines of the Buffalo Ridge wind farm were installed in 2022 surrounding the Ruthton vicinity. Rotor diameter is 127 m, and total height is 152.4 m (500 feet).

Besides Minnesota, several other states began to require utilities to provide electricity generated with renewable energy through some form of Renewables Portfolio Standard (RPS). This came about mainly because of growing concerns about greenhouse gases and climate change, and development of new wind-energy facilities began to pick up in the late 1990s. But the PTC was allowed to lapse in 1999, which once again stalled wind-power developments. The PTC was soon renewed, but did not have any practical effect until 2001. This stop-and-go cycle of financial incentives for wind energy was symptomatic and highlights the lack of a coherent, long-term energy policy at the federal level, a problem that still continues.

Part of the problem was strong opposition to wind energy by those with vested interests in fossil fuels as energy sources. For example, in 1999 the American Association of Petroleum Geologists (AAPG) rejected the likelihood that human activity, namely burning fossil fuels, has any influence on global climate change (Bean 2012). AAPG has since softened its position on this subject, but opposition to development of wind energy remains strong even today among many in the fossil-fuel industries.

1.5 Wind Energy—Early Twenty-First Century

In 1990, the global wind-power capacity was just 2,000 MW. Ten years later, total capacity had reached 17,700 MW (Musgrove 2010). Still, wind energy was a niche enterprise at the beginning of the twenty-first century. Since then, wind energy has expanded dramatically around the world for varied reasons. Many countries provided financial incentives to increase the domestic production of renewable and non-polluting energy in order to lessen their use of fossil fuels and nuclear energy as well as to decrease their dependence on unreliable foreign energy sources.

The use of wind power for generating electrical energy has grown phenomenally during the past quarter century. Total installed wind-power capacity worldwide by the end of 2023 had exceeded 1,000 gigawatts (GW) led by China (441.9 GW) and the United States (148.0 GW), which together accounted for more than half of global wind-generating capacity. Germany and India were the next leading countries followed by Spain and the United Kingdom (Table 1.3). Maegaard et al. (2013) and Aber et al. (2015) presented summaries for history and status of wind energy in many countries around the world.

In the United States, renewal of the PTC combined with RPS mandates in more than 25 states led to rapid increases in wind energy starting in 2001 (Fig. 1.19). The goal to control greenhouse gases and climate change came to the forefront of energy and policy debates, particularly under the administrations of President Obama and President Biden. In particular, the Inflation Reduction Act of 2022 addressed energy security and climate change, although the issue remains a low priority for many citizens.

General Electric (GE) entered the wind industry with purchase of Enron Wind's manufacturing assets in 2002 to form GE Wind Energy (Musgrove 2010). It developed

Table 1.3 Top 12 countries for wind-energy generating capacity including both onshore and offshore installations.

Country	Installed (GW)	Country	Installed (GW)
China	441.9	Brazil	29.1
United States	148.0	France	20.8
Germany	69.5	Canada	17.0
India	44.7	Sweden	16.3
Spain	31.0	Turkey	11.7
United Kingdom	30.1	Australia	12.9

Rounded values in gigawatts (GW) as of end 2023. Adapted from IRENA (2024).

Figure 1.19 Gray County Wind Farm, built in 2001, was the first large array of turbines in Kansas. It has 170 Vestas V47 turbines with a combined capacity of 112 MW. These turbines are relatively small and closely spaced compared with newer models. Kite aerial photograph (2006).

an earlier Tacke design for a 1.5-MW turbine that was installed at many wind farms across the country (Fig. 1.20). GE became the dominant maker of wind turbines in the United States. In 2024, GE Vernova was spun off from its parent, and the new company deals primarily with renewable energy worldwide. Its headquarters is located in Massachusetts (GE Vernova 2024).

Vestas and Siemens also continued to supply the U.S. market as well as Gamesa, Mitsubishi, and Suzlon. The sight of wind-turbine components in transit on special truck trailers and railway carriages became commonplace, especially in the Great Plains region (Fig. 1.21). New wind farms proliferated, and existing wind farms were expanded. International companies built manufacturing plants in the United States to supply the rapidly growing market—Vestas in Colorado, and Siemens in Kansas and Iowa.

Figure 1.20 Spearville Project, built in 2006, is equipped with GE Wind 1.5 MW turbines amid agricultural fields. These GE Wind turbines were made in the United States; they are descendants of the Tacke turbine made in Germany during the 1990s. Kite aerial photograph with D. Leiker and C. Unruh (2007).

Wind-energy capacity grew quickly in both China and India, and China surpassed the United States to become the world's leading producer. China has expanded aggressively for offshore wind farms, which now account for more than 8% of total Chinese wind-energy capacity, but India has yet to build any offshore

Figure 1.21 Turbine-blade logistics in Kansas. (A) Highway transport by oversized tractor–trailer truck; blades are typically about 50–60 m long, (B) temporary storage in the BNSF Railway depot at Emporia. Vertical view of Gamesa blades in tight-packing arrangement. Service truck shows size of blades. Kite aerial photograph with D. Leiker.

Figure 1.21 (Continued)

(B)

wind farms (GWEC 2024a). Six of the ten largest wind-turbine manufacturing companies are located in China (Table 1.4).

Germany maintained its dominance of European wind energy, and the United Kingdom expanded considerably with offshore wind farms, which now make up nearly half of its total capacity (GWEC 2022). Siemens (a German company) acquired Bonus Energy in 2004, which was renamed as Siemens Wind Power. Gamesa and

Table 1.4 Top 10 wind-turbine companies generating capacity supplied for 2023.

Company	**Country**	**Capacity**
Goldwind	China	16.7
Envision	China	15.9
Vestas	Denmark	12.7
Windley	China	10.5
Mingyang	China	10.2
Siemens Gamesa	Spain	7.7
GE Vernova	United States	7.6
SANY	China	7.5
Nordex group	Germany	6.9
Dongfang	China	5.6

Six of the ten companies come from China, which is also the largest consumer for wind turbines. Values given in gigawatts (GW) rounded.
Adapted from GWEC (2024b).

Figure 1.22 EHN turbines harvest wind energy on a prominent ridge near Pamplona, northern Spain. Photo courtesy of J.T. Aber (2012).

Figure 1.23 Middelgrunden wind farm in the Øresund strait between Denmark and Sweden. A single, curved alignment; commissioned in 2001 with 20 Bonus 2.0 MW turbines. This wind farm is highly visible to the public given its location near Copenhagen, Denmark. Arnoldius/Wikimedia Commons/CC BY-SA 3.0.

Siemens merged in 2017 to form Siemens Gamesa Renewable Energy (SGRE) with headquarters in Spain.

Acciona Windpower built its first wind farm in Spain in 1994 and since expanded rapidly. In 2005, Acciona bought full ownership of EHN, a leading Spanish developer of wind energy (Fig. 1.22). Nordex was founded in Denmark in 1985, part of the Danish revolution in wind energy (Nielsen 2009), but then Nordex moved to Germany in 1992. Nordex and Acciona merged in 2016 with headquarters in Germany.

During the first decade of this century, Danish development moved increasingly toward large wind farms, both on land and offshore into the surrounding seas (Fig. 1.23). Offshore wind turbines typically produce about 50% more electricity than comparable onshore turbines, which justifies the higher cost of building offshore wind farms (Musgrove 2010). As of 2022, offshore wind turbines provided 2.3 GW of capacity, approximately one-third of Denmark's total wind power.

Onshore, meanwhile, the government offered incentives to replace many smaller, older turbines with fewer, larger turbines. Denmark and its neighbor Sweden continue to lead the world in per-capita wind-generated electricity with nearly 3.3 kWh per person (Ember 2024), and Vestas remains among the world's largest wind-energy companies (Table 1.4). As the foregoing discussion illustrates, the early twenty-first century was a period of tremendous expansion of wind energy worldwide as well as an interval of mergers and consolidation within the wind industry.

1.6 Summary

People have utilized the wind to power various types of devices and vessels since the dawn of civilization. The classic European windmill first appeared in the twelfth century in France and England and spread rapidly thereafter. The era of such windmills lasted until the early twentieth century, some eight centuries. In the middle nineteenth century, windmill innovation took a completely different direction in the United States. The continuing success of the American windmill is due to several factors—ease of manufacturing, shipping, assembly, routine maintenance, and autonomous operation.

Generating electricity with windmills began in the late nineteenth century in several locations. The most important developments were achieved in Denmark by Poul la Cour in the 1890s and beginning of the twentieth century. His innovations may be traced forward into the modern wind industry. Johannes Juul's wind turbine at Gedser, Denmark, and Ulrich Hütter's fiberglass blades are particularly noteworthy for demonstrating many technical aspects that would become industry standards later in the twentieth century.

As cheap oil and nuclear energy became widely available in the 1960s, the perceived need for wind energy reached a low ebb, and most wind-energy projects were shut down. At this time, the public and policy makers believed that cheap energy was unlimited and without environmental consequences, but these assumptions changed quickly with a series of oil crises and nuclear disasters beginning in the 1970s.

Among the most important wind-energy developments during the 1970s and 1980s were those in Denmark and the United States. By the end of the 1970s, Denmark had moved through an extremely rapid and innovative phase of wind-energy development, which led to the so-called Danish concept for modern wind turbines. A modest wind-energy program in the United States was initiated in the 1970s with a series of increasingly large Mod turbines, and a combination of federal and state tax incentives set off the California wind boom in the early 1980s.

The California wind boom crashed when tax credits expired in 1985 (federal) and 1986 (state). Concerns about greenhouse gas emissions from burning fossil fuels began to emerge as part of the debate about energy resources. During the 1990s, one key to improved economics was increasingly large turbines. Danish companies had a combined share of roughly half of the world market for wind turbines, and Denmark began to experiment with offshore development of wind farms.

The early twenty-first century was a period of tremendous expansion of wind energy worldwide as well as a time of mergers and consolidation within the wind industry. Many countries provided financial incentives, and by 2023 global wind-energy capacity exceeded 1,000 GW. China, United States, Germany, India, Spain, Brazil, and the United Kingdom emerged as the largest producers.

Offshore wind farms were pioneered by Denmark and have expanded considerably particularly for China and the United Kingdom. Denmark and Sweden continue to lead the world in per-capita wind-energy production, and Vestas remains among the largest company for manufacturing wind turbines. Thus, wind power has emerged from unlikely prospects based on the Danish concept to become a major source for renewable, non-polluting energy worldwide in the twenty-first century.

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