"Blowin' in the Wind"

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The title of this article may suggest that it constitutes a tribute to the recent Nobel Prize in Literature and a sweet remembrance of our 20s for those of us who are now in our 60s. That could be the case. After all, scientists and technicians live in a diversified and interconnected world where culture, art, and civil actions are interdependent with technology. However, regardless of my esteem for Mr. Bob Dylan, this column deals with exploiting wind for energy, a long-term challenge to humanity, much longer than the time cannon balls flew.

WINDMILLS WERE FIRST USED AS PRODUCTIVE DEVICES IN EASTERN PERSIA IN THE NINTH CENTURY OR SOME TIME EARLIER.

Humans first harnessed wind for sailing. In the sixth millennium BC, boats sailed the Persian Gulf to trade Ubaid pottery [1]. Since the fourth millennium BC, Egyptian reed boats sailed the Nile upstream, boosting trade among cities and promoting national unity. Sailing ships were vital for early Mediterranean traders, Minoans from the third millennium BC, and Mycenaeans and Phoenicians from the 12th century BC, voyaging as far as the British Islands, the Gulf of Guinea, and Somalia. Wind allowed the Romans and Chinese to consolidate their empires sailing seas and rivers. Wind blew Viking sails to Labrador and Newfoundland. In the 16th century BC, it pushed Lapita people to colonize the Pacific Ocean atolls, a millenarian conquest that was completed in about the tenth century AD, when Eastern Polynesia and Easter Island were reached. It was again the power of wind that made possible the oceanic navigations of the explorers who discovered other continents then unknown in Europe in the 16th–18th centuries, starting with Christopher Columbus. Sails were also used for overland mobility, in high-speed chariots reported in China in the sixth century AD and one millennium later in Europe [2].

The exploitation of wind power to operate a machine appeared much later than sailing. An early account was given by Heron of Alexandria in the first century AD, describing a windmill for pumping air pressure in a musical organ [3]. Starting in the eighth century, similar entertaining uses of the windmill and wind power were made in Baghdad for the amusement of the Abbasid caliphs. Windmills were first used as productive devices in eastern Persia in the ninth century or some time earlier. These were half-screened, vertical-axis, direct-drive machines for grinding corn or raising water. They spread to China, India, and the Islamic world. In the early 12th century, a horizontal axis version came into use in the Mediterranean lands where the wind blows in a constant direction, from the Cyclades islands to Spain, in a design that can still be found around there (Figure 1) [4]. In the same century, the wooden post mill appeared in northern Europe. Being mounted on a post, it could be oriented in the wind's direction by acting on a rudder. It could be placed far from rivers and creeks and used when the water froze, and it also allowed farmers to escape the mill right that ensured only feudal lords with the ownership of water mills. Around the end of the 13th century, this design evolved into the tower-type mill, with a brick or stone tower and a wooden rotating turret, suitable to produce much higher power thanks to larger blades, which spread particularly in The Netherlands, being used for grinding grain, pumping water, and

FIGURE 1 — A medieval Mediterranean windmill still standing in Formentera, Belearic Islands, Spain.

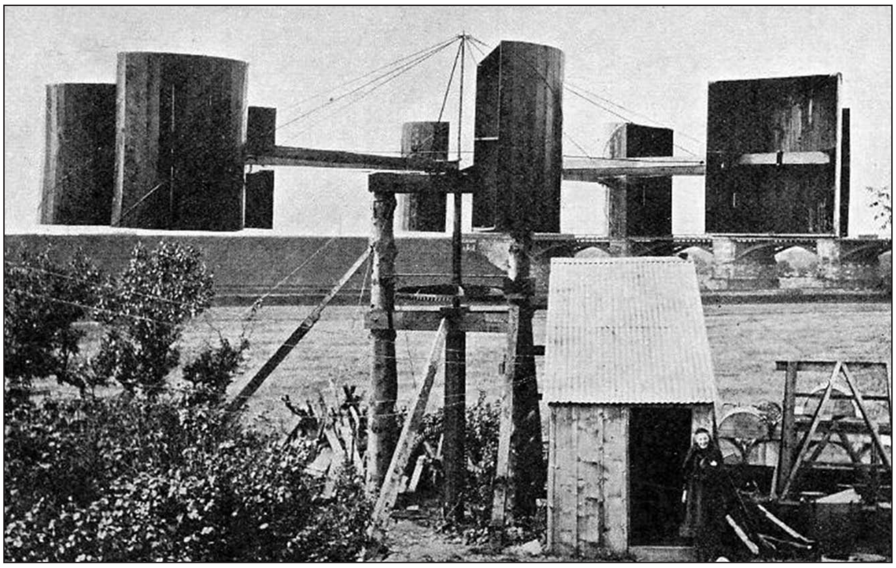

FIGURE 2 – The Blyth's wind turbine built by Blyth (not the first one of 1887) to power the lighting at his summer home in Marykirk, Scotland. For size evaluation, note the woman standing in front of the battery shed. (Photo courtesy of Wikimedia Commons.)

operating sawmills. It later evolved into the smock mill, a more advanced though basically similar design. In these mills, the wooden lattice blades had to be covered with more or less extended canvas sails, depending on the wind force. But they were always in danger of being destroyed by sudden storms.

In 1745, an Englishman, Edmund Lee, patented the fantail, a small wind wheel mounted at a right angle to the blades that feedback oriented them toward the wind. In 1772, Andrew Meikle (1719–1811), a Scot, replaced canvas sails with spring-controlled shutters, which were hand operated by means of a lever and could lose lift in the case of a storm. Meikle's shutters were improved in 1807 by civil engineer William Cubbit (1785–1861), with a mechanism to automatically adjust the shutter tilt without stopping the mill. An alternative device for adjusting the blade lift from inside the mill was invented by a Frenchman, Pierre-Théophile Berton, a few decades later. In 1787, Thomas Mead invented the lift tenter based on rotating spheres that, placed in rotation by the blades, raised and lowered, depending on the spinning speed, thus adjusting the distance between the grinder stones. The device inspired James Watt with the centrifugal governor for feedback regulating the steam supplied to his engine, patented in 1788. In turn, Watt's governor inspired the paper "On Governors," published by James Clerk Maxwell in 1868 [5], a seminal work in control theory. By the mid-19th century, such advancements had made wind an important source of energy, with 20,000 mills operating in France, 10,000 in Great Britain, and 12,000 in the Netherlands, and by 1900, about 2,500 provided mechanical power to pumps and mills in Denmark. Perhaps 6 million were in operation on farms around the American Midwest to power irrigation pumps in the period 1850–1900.

THE DEVELOPMENT OF A PRACTICAL RECHARGEABLE LEAD-ACID BATTERY WAS PIVOTAL FOR PIONEERING ELECTRICITY GENERATION FROM WIND POWER.

The development of a practical rechargeable lead-acid battery by Camille Alphonse Faure (1840–1898) in 1881 was pivotal not only for the viability of early electric cars but also for pioneering electricity generation from wind power [6]. In fact, in the same year, Sir William Thomson, later Lord Kelvin, wrote an overview on energy sources where he proposed that batteries could be used for assuring supply continuity against intermittent generation from renewables [7], but he concluded that windmills were too costly to be attractive as electric power generators for lighting, the most promising application at that time, after the invention of viable arc and incandescent lamps [8] and before the creation of electricity distribution by Thomas Edison [9]. Nevertheless, others explored the technology. The first successful wind electric turbine was built in 1887 by James Blyth (1839–1906), a Scot, as was William Thomson, and a professor at Glasgow and West of Scotland Technical College, which eventually became Strathclyde University. The machine was intended to recharge the Faure's accumulators that provided lighting at his holiday home in Marykirk, Scotland (Figure 2) [10]. It was provided with a vertical shaft with 4-m-high sails at right angles to each other and a flywheel that drove a dynamo by means of a rope [11].

Based on the Robinson anemometer design, reportedly, it was passively self-stalling against strong wind and could be quickly shut down. Blyth offered to light the local main street with such a device, but the people of Marykirk turned down the offer, as they deemed electricity "the work of the devil." However, the electric windmill was a success that earned Blyth prizes and recognition in the scientific community. It was demolished in 1914. The design was patented in 1891 and was licensed for an electric windmill that was built for Montrose Asylum in 1895.

In 1888, Charles F. Brush (1849–1929), one of the U.S. electrical lighting pioneers [8], built another very early successful wind generator for his residence in Cleveland, Ohio, resorting to the skills of his engineering company. The mill consisted of a horizontal-axis 144-twisted-blade rotor with a diameter of 17 m mounted on an 18-m-high iron lattice tower (Figure 3). The belt-driven dynamo generated a maximum power of 12 kW spinning at 500 r/min and was provided with a fully automated electric control system ensuring load voltage in the range of 70–75 V [12]. It was used for recharging a 408-cell battery and for powering electric lights, two of the arc type and about 100 incandescent, in

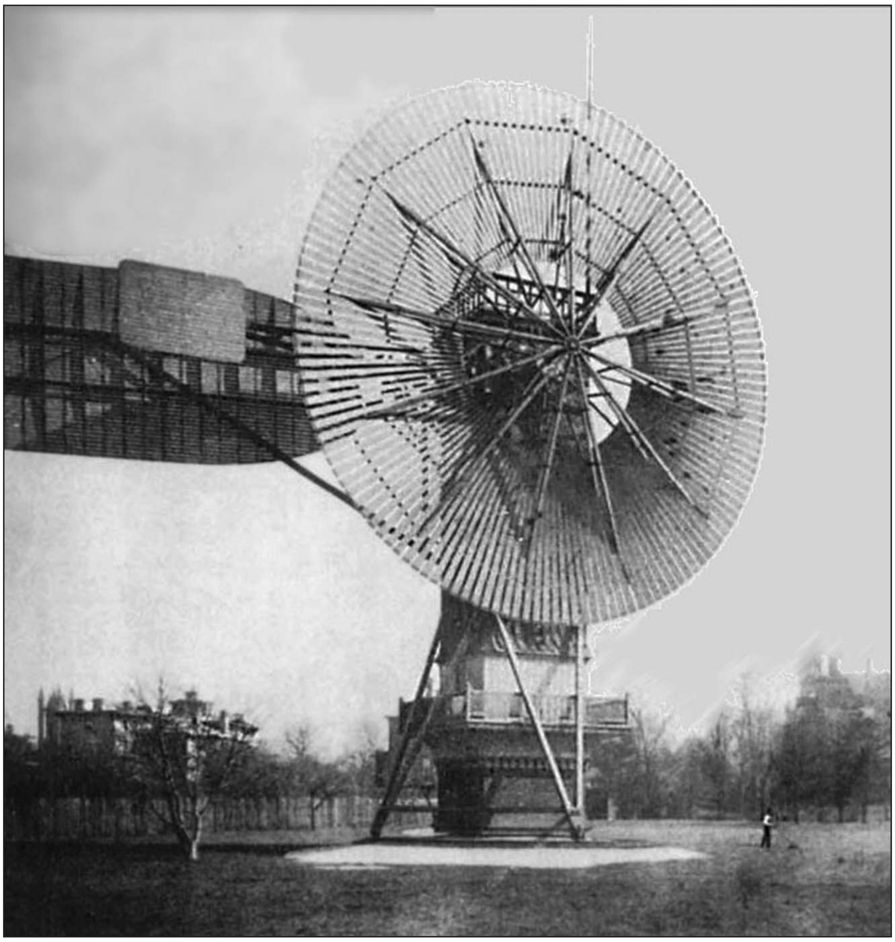

FIGURE 3 — The Brush's wind turbine of 1888 had a 17-m diameter, and the belt-driven dynamo generated a maximum power of 12 kW spinning at 500 r/min and was provided with a fully automated electric control system ensuring load voltage in the range 70–75 V. The large rectangular shape to the left of the rotor is the vane, used to move the blades into the wind. For size evaluation, note the gardener pushing lawnmower to right. (Photo courtesy of Wikimedia Commons.)

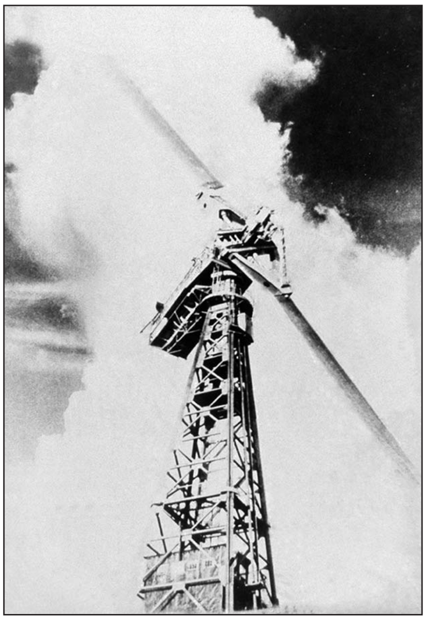

FIGURE 4 — The Smith–Putnam wind turbine on Grandpa's Knob in Vermont, circa 1941. It was the world's first megawatt-size power turbine. (Photo courtesy of Wikimedia Commons.)

addition to three laboratory motors. It operated until 1900, when it was replaced by a grid connection, and was disposed of eight years later.

In 1891, scientist and teacher Poul la Cour (1846–1908) built a wind generator to power a school at Askov, Denmark, that he endowed with a hydrogen generator (from water electrolysis) and a storage system and later with a regulator for stabilizing the output power, dubbed the *Kratostate* [13]. A successor version was used to provide light to the village of Askov. La Cour's pioneering work paved the way for wind power development in Denmark, where 72 electric wind generators rated 5–25 kW were in operation in 1908, with rotor diameter up to 24 m mounted on 25-m towers, and electric windmills grew to become important sources of power in Denmark in the first decades of the 20th century.

IN POSTWAR TIMES, CHEAP ELECTRICITY FROM FOSSIL FUELS AND NUCLEAR ENERGY PUT A TEMPORARY STOP TO THE DEVELOPMENT OF WIND GENERATORS.

In the United States, wind generators were industrially produced beginning in 1927 for lighting and battery charging in farms not yet reached by electricity distribution from central stations [14]. They featured steel lattice towers and, typically, two-blade rotors and were rated at hundreds to thousands of watts. Fluid-dynamic brakes were used to regulate the rotation speed. When electric grids were extended to rural areas in the United States starting in 1936, domestic sales collapsed, but there were still good market opportunities for wind turbines abroad. By 1936, small machines had become popular in Australia to service isolated users. Before World War II, two much larger turbines, provided with steel lattice towers, were built in the USSR and the United States. In 1931, WIME D-30, a 100-kW generator with a 30-m three-blade rotor atop a 30-m tower, was completed and connected to the 6.3-kV local power grid at Balaklava, near Yalta, Crimea. In 1941, a two-blade 1.25-MW turbine designed by P.C. Putnam was installed by the S. Morgan Smith Company at Castelton, Vermont (Figure 4). It was the first turbine to exceed 1 MW and operated for a short time before a failure of a blade put it out of service permanently. Similar experiments were conducted in Germany in the period 1930–1950.

During the war, several low-voltage small-power wind generators were built in northern Europe to provide power to final users who could no longer rely on dependable grid power. Generators from 5 kW to 100 kW were used in Denmark in that period.

In postwar times, cheap electricity from fossil fuels and nuclear energy put a temporary stop to the

FIGURE 5 — A wind turbine installed on the tidal island of Neuwerk, Germany, in 1946. It had a 15-m rotor atop a guyed steel lattice tower with mechanical transmission to an 18-kW generator located at ground level. It was provided with automatic rotor positioning depending on the wind velocity. (Photo courtesy of *IEEE Power & Energy Magazine*, vol. 7, no. 5, 2009.)

FIGURE 6 — The experimental 800-kVA BEST-Romani aerogenerator (wind turbine) put into operation in Nogent-le-Roi, France, in 1955. (Photo courtesy of Jean-Luc Cavey.)

development of wind generators, although a few exceptions occurred. In 1946, a turbine with a 15-m rotor atop a guyed steel lattice tower and mechanical transmission to an 18-kW generator located at the tower foot was installed in the tidal island of Neuwerk, Germany (Figure 5). It was provided with automatic rotor positioning depending on the wind velocity. This device resisted 144-km/h winds and operated over 20 years, supplying a lighthouse and residences with power, before being replaced by a submarine cable to the mainland [15]. A three-blade turbine with a lattice tower developed by John Brown Engineering, Glasgow, was installed in the remote Orkney Islands off northern Scotland in 1951. It was the first to be connected to a local grid in the United Kingdom, but it did not last long against the strength of storms. An 800-kVA experimental turbine operated at the Station d'Etude de l'Energie du Vent in Nogent-le-Roi, France, between 1955 and 1966 (Figure 6) [16]. An advanced wind generator was installed by Johannes Juul at Gedser, Denmark, in 1957. It featured a 24-m rotor with three blades (in place of the four then common in the country) and stall regulation and fixed the basic Danish design for the next local turbine architecture. At that time, major issues were operation at low wind speed, 5–20 m/s, and resistance against strong winds or storms.

When the 1973 oil crisis struck, several industrialized nations regarded nuclear energy as a viable alternative for power generation. The Tvind counterculture educational movement that flourished in Denmark in the 1970s rejected that option and turned its attention to wind power, building small turbines. A Tvind Mill Team was formed with teachers, students, and volunteers who, opposed by the official technological culture, worked for three years to design and construct Tvind Power, an innovative 2-MW turbine featuring a three-blade 54-m wingspan, pitch control, and a 54-m tubular tower [17]. It was the biggest in the world at the time of its commissioning in 1978 and nearly 40 years later is still in service. It demonstrated that multimegawatt wind generators were possible, pushed the country toward a leading position in wind energy, and set the background over which Vestas's and Siemens's wind technology was developed. Following the Danish example, other European countries undertook major initiatives in wind power development, notably Germany and Spain. In 1978, a Danish blade producer, Økær, distrustful of Tvind principles, started manufacturing blades that rotated clockwise, the opposite of the common direction at the time (and of that used in Tvind's turbines). Because Økær's blades were later adopted by the major turbine producers, clockwise rotation became standard.

IN 1974, NASA LAUNCHED A RESEARCH PROGRAM AIMED AT DEVELOPING LARGE UTILITY-SCALE WIND GENERATORS.

On the other side of the Atlantic Ocean, in 1974, NASA launched a research program funded by the National Science Foundation and later by the Department of Energy

FIGURE 7 — The NASA/Department of Energy MOD-5B wind turbine at Oahu, Hawaii. This 100-m diameter, two-bladed turbine was the largest in the world during the early 1990s. (Photo courtesy of Wikimedia Commons.)

FIGURE 8 — The Éole, a 4-MW 110-m Darrieus's vertical-axis wind turbine installed at Cap Chat, Gaspésie, Quebec, in 1987 is still the largest in the world. A fault in the base bearing put it permanently out of service in 1993.

aimed at developing large utility-scale wind generators that resulted in the construction of 13 experimental two-blade turbines in partnership with industrial companies by the mid-1980s [18]. Independently of European developers, they pioneered some innovative technologies later adopted in industrial multimegawatt machines, such as tubular tower, variable speed, composite materials for blades, and partial-span pitch control, together with other advanced engineering solutions. The United Technologies WTS-4 wind turbine, placed into operation in Medicine Bow, Wyoming, in 1982, was rated 4 MW, a world record held for 20 years. The 3.2-MW Boeing MOD-5B, installed in Ohau, Hawaii, in 1987, had a 97.5-m rotor on a 60-m tower that was the largest in the world (Figure 7). Transportation to the site was made easier by the sectioned blade design. However, these turbines did not go into mass production, and their development was hampered by a deflation in oil prices in the following years, until tax rebates were introduced for wind energy, notably in California.

The alternative concept of the vertical axis, exploited in early Persian windmills and in Blyth's first successful wind generator of 1887, was reintroduced by French aeronautical engineer Georges Jean Marie Darrieus (1888–1979) in 1931. Its major advantage is no need to be pointed into the wind and no need for a stiff tower, but it also presents some major disadvantages, such as no self-start and pulsing mechanical power, which can start potentially catastrophic resonant modes. Even though these drawbacks made Darrieus's turbine less competitive in the megawatt class, some of them were built. The largest was Éole, a 4-MW 110-m-high turbine installed in La Nordais wind farm at Cap Chat, Gaspésie, Quebec, in 1987 (Figure 8). It went out of service in 1993 due to a fault in the base bearing and was never repaired. Now, it still stands as a tourist attraction. After such outcomes, the vertical axis concept was relinquished in large-scale turbines, but it has achieved better success in medium and small-size devices, in the H-rotor and helical blade designs.

Until 1970, the standard generator was a squirrel-cage induction machine coupled with a multistage gearbox driven by aerodynamically controlled wind turbines to give a fixed speed system. In the 1970s, a major change derived from the advancements in power electronics that allowed variable speed systems to be developed. Two approaches have emerged: 1) a multistage gearbox with a doubly fed induction generator coupled to a small back-to-back power converter in the rotor circuit, and 2) a direct-drive low-speed synchronous machine coupled to a fully rated power electronic converter. These architectures have resulted in much more versatile wind generators that can provide the needed reactive power and frequency support in addition to active power. Recently, technology development has resulted in turbines in the class of 8 MW boding that a substantial contribution to a carbon-free energy future will be blowin' in wind.

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