

Wind turbine

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A **wind turbine** is a device that converts the wind's kinetic energy into electrical power.

Wind turbines are manufactured in a wide range of vertical and horizontal axis types. The smallest turbines are used for applications such as battery charging for auxiliary power for boats or caravans or to power traffic warning signs. Slightly larger turbines can be used for making contributions to a domestic power supply while selling unused power back to the utility supplier via the electrical grid. Arrays of large turbines, known as wind farms, are becoming an increasingly important source of intermittent renewable energy and are used by many countries as part of a strategy to reduce their reliance on fossil fuels.



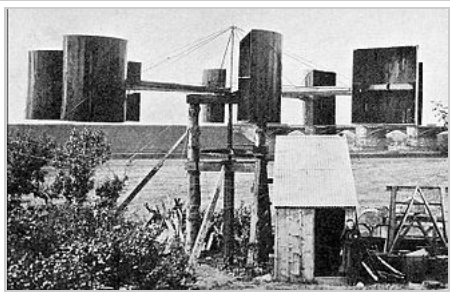
Offshore wind farm, using 5 MW turbines REpower 5M in the North Sea off the coast of Belgium.

Contents

- 1 History
- 2 Resources
- 3 Efficiency
- 4 Types
 - 4.1 Horizontal axis
 - 4.2 Vertical axis
- 5 Design and construction
 - 5.1 Unconventional designs
 - 5.2 Turbine monitoring and diagnostics
- 6 Materials and durability
- 7 Wind turbines on public display
- 8 Small wind turbines
- 9 Wind turbine spacing
- 10 Operability
 - 10.1 Maintenance
 - 10.2 Repowering
 - 10.3 Demolition
- 11 Records
- 12 See also
- 13 References
- 14 Further reading
- 15 External links

History

Windmills were used in Persia (present-day Iran) about 500-900 A.D.^[1] The windwheel of Hero of Alexandria



James Blyth's electricity-generating wind turbine, photographed in 1891

marks one of the first known instances of wind powering a machine in history.^{[2][3]} However, the first known practical windmills were built in Sistan, an Eastern province of Iran, from the 7th century. These "Panemone" were vertical axle windmills, which had long vertical drive shafts with rectangular blades.^[4] Made of six to twelve sails covered in reed matting or cloth material, these windmills were used to grind grain or draw up water, and were used in the gristmilling and sugarcane industries.^[5]

Windmills first appeared in Europe during the Middle Ages. The first historical records of their use in England date to the 11th or 12th centuries and there are reports of German crusaders taking their windmill-making skills to Syria around 1190.^[6] By the 14th century, Dutch windmills were in use to drain areas of the Rhine delta. Advanced wind mills were described by Croatian inventor Fausto Veranzio. In his book *Machinae Novae* (1595) he described vertical axis wind turbines with curved or V-shaped blades.

The first electricity-generating wind turbine was a battery charging machine installed in July 1887 by Scottish academic James Blyth to light his holiday home in Marykirk, Scotland.^[7] Some months later American inventor Charles F. Brush was able to build the first automatically operated wind turbine after consulting local University professors and colleagues Jacob S. Gibbs and Brinsley Coleberd and successfully getting the blueprints peer-reviewed for electricity production in Cleveland, Ohio.^[7] Although Blyth's turbine was considered uneconomical in the United Kingdom^[7] electricity generation by wind turbines was more cost effective in countries with widely scattered populations.^[6]

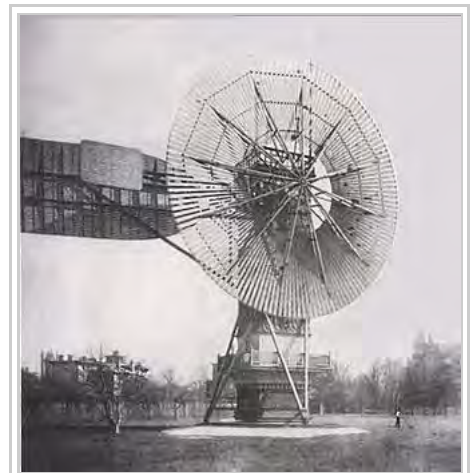
In Denmark by 1900, there were about 2500 windmills for mechanical loads such as pumps and mills, producing an estimated combined peak power of about 30 MW. The largest machines were on 24-meter (79 ft) towers with four-bladed 23-meter (75 ft) diameter rotors. By 1908 there were 72 wind-driven electric generators operating in the United States from 5 kW to 25 kW. Around the time of World War I, American windmill makers were producing 100,000 farm windmills each year, mostly for water-pumping.^[9]

By the 1930s, wind generators for electricity were common on farms, mostly in the United States where distribution systems had not yet been installed. In this period, high-tensile steel was cheap, and the generators were placed atop prefabricated open steel lattice towers.

A forerunner of modern horizontal-axis wind generators was in service at Yalta, USSR in 1931. This was a 100 kW generator on a 30-meter (98 ft) tower, connected to the local 6.3 kV distribution system. It was reported to have an annual capacity factor of 32 percent, not much different from current wind machines.^[10]

In the autumn of 1941, the first megawatt-class wind turbine was synchronized to a utility grid in Vermont. The Smith-Putnam wind turbine only ran for 1,100 hours before suffering a critical failure. The unit was not repaired, because of shortage of materials during the war.

The first utility grid-connected wind turbine to operate in the UK was built by John Brown & Company in



The first automatically operated wind turbine, built in Cleveland in 1887 by Charles F. Brush. It was 60 feet (18 m) tall, weighed 4 tons (3.6 metric tonnes) and powered a 12 kW generator.^[8]

1951 in the Orkney Islands.^{[7][11]}

Despite these diverse developments, developments in fossil fuel systems almost entirely eliminated any wind turbine systems larger than supermicro size. In the early 1970s, however, anti-nuclear protests in Denmark spurred artisan mechanics to develop microturbines of 22 kW. Organizing owners into associations and co-operatives lead to the lobbying of the government and utilities and provided incentives for larger turbines throughout the 1980s and later. Local activists in Germany, nascent turbine manufacturers in Spain, and large investors in the United States in the early 1990s then lobbied for policies that stimulated the industry in those countries. Later companies formed in India and China. As of 2012, Danish company Vestas is the world's biggest wind-turbine manufacturer.

Resources

A quantitative measure of wind energy available at any location is called the Wind Power Density (WPD). It is a calculation of the mean annual power available per square meter of swept area of a turbine, and is tabulated for different heights above ground. Calculation of wind power density includes the effect of wind velocity and air density. Color-coded maps are prepared for a particular area described, for example, as "Mean Annual Power Density at 50 Metres". In the United States, the results of the above calculation are included in an index developed by the National Renewable Energy Laboratory and referred to as "NREL CLASS". The larger the WPD, the higher it is rated by class. Classes range from Class 1 (200 watts per square meter or less at 50 m altitude) to Class 7 (800 to 2000 watts per square m). Commercial wind farms generally are sited in Class 3 or higher areas, although isolated points in an otherwise Class 1 area may be practical to exploit.^[12]

Wind turbines are classified by the wind speed they are designed for, from class I to class IV, with A or B referring to the turbulence.^[13]

| Class | Avg Wind Speed (m/s) | Turbulence |
|-------|----------------------|------------|
| IA | 10 | 18% |
| IB | 10 | 16% |
| IIA | 8.5 | 18% |
| IIB | 8.5 | 16% |
| IIIA | 7.5 | 18% |
| IIIB | 7.5 | 16% |
| IVA | 6 | 18% |
| IVB | 6 | 16% |

Efficiency



Wind turbine in Germany

Not all the energy of blowing wind can be used, but some small wind turbines are designed to work at low wind speeds.^[14]

Conservation of mass requires that the amount of air entering and exiting a turbine must be equal. Accordingly, Betz's law gives the maximal achievable extraction of wind power by a wind turbine as 16/27 (59.3%) of the total kinetic energy of the air flowing through the turbine.^[15]

The maximum theoretical power output of a wind machine is thus 0.59 times the kinetic energy of the air passing through the effective disk area of the machine. If the effective area of the disk is *A*, and the wind velocity *v*, the maximum theoretical power output *P* is:

$$P = 0.59 \frac{1}{2} \rho v^3 A$$

where ρ is air density

As wind is free (no fuel cost), wind-to-rotor efficiency (including rotor blade friction and drag) is one of many aspects impacting the final price of wind power.^[16] Further inefficiencies, such as gearbox losses, generator and converter losses, reduce the power delivered by a wind turbine. To protect components from undue wear, extracted power is held constant above the rated operating speed as theoretical power increases at the cube of wind speed, further reducing theoretical efficiency. In 2001, commercial utility-connected turbines deliver 75% to 80% of the Betz limit of power extractable from the wind, at rated operating speed.^{[17][18]}

Efficiency can decrease slightly over time due to wear. Analysis of 3128 wind turbines older than 10 years in Denmark showed that half of the turbines had no decrease, while the other half saw a production decrease of 1.2% per year.^[19] Vertical turbine designs have much lower efficiency than standard horizontal designs.^[20]

Types

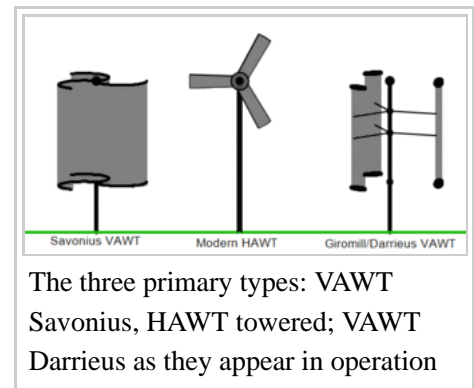
Wind turbines can rotate about either a horizontal or a vertical axis, the former being both older and more common.^[21] They can also include blades (transparent or not)^[22] or be bladeless.^[23] Vertical designs produce less power and are less common.^[24]

Horizontal axis

Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator.^[25]

Since a tower produces turbulence behind it, the turbine is usually positioned upwind of its supporting tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted forward into the wind a small amount.

Downwind machines have been built, despite the problem of turbulence (mast wake), because they don't need



an additional mechanism for keeping them in line with the wind, and because in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since cyclical (that is repetitive) turbulence may lead to fatigue failures, most HAWTs are of upwind design.

Turbines used in wind farms for commercial production of electric power are usually three-bladed and pointed into the wind by computer-controlled motors. These have high tip speeds of over 320 km/h (200 mph), high efficiency, and low torque ripple, which contribute to good reliability. The blades are usually colored white for daytime visibility by aircraft and range in length from 20 to 40 meters (66 to 131 ft) or more. The tubular steel towers range from 60 to 90 meters (200 to 300 ft) tall.

The blades rotate at 10 to 22 revolutions per minute. At 22 rotations per minute the tip speed exceeds 90 meters per second (300 ft/s).^{[26][27]} A gear box is commonly used for stepping up the speed of the generator, although designs may also use direct drive of an annular generator. Some models operate at constant speed, but more energy can be collected by variable-speed turbines which use a solid-state power converter to interface to the transmission system. All turbines are equipped with protective features to avoid damage at high wind speeds, by feathering the blades into the wind which ceases their rotation, supplemented by brakes.

Year by year the size and height of turbines increase. Offshore wind turbines are built up to 8MW today and have a blade length up to 80m.

Onshore wind turbines are installed in low wind speed areas and getting higher and higher towers. Usual towers of multi megawatt turbines have a height of 70 m to 120 m and in extremes up to 160 m, with blade tip speeds reaching 80 m/s to 90 m/s. Higher tip speeds means more noise and blade erosion.

Vertical axis

Vertical-axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. One advantage of this arrangement is that the turbine does not need to be pointed into the wind to be effective, which is an advantage on a site where the wind direction is highly variable. It is also an advantage when the turbine is integrated into a building because it is inherently less steerable. Also, the generator and gearbox can be placed near the ground, using a direct drive from the rotor assembly to the ground-based gearbox, improving accessibility for maintenance. However, these designs produce much less energy averaged over time, which is a major drawback.^{[24][28]}

The key disadvantages include the relatively low rotational speed with the consequential higher torque and hence higher cost of the drive train, the inherently lower power coefficient, the 360-degree rotation of the aerofoil within the wind flow during each cycle and hence the highly dynamic loading on the blade, the pulsating torque generated by some rotor designs on the drive train, and the difficulty of modelling the wind flow accurately and hence the challenges of analysing and designing the rotor prior to fabricating a prototype.^[29]

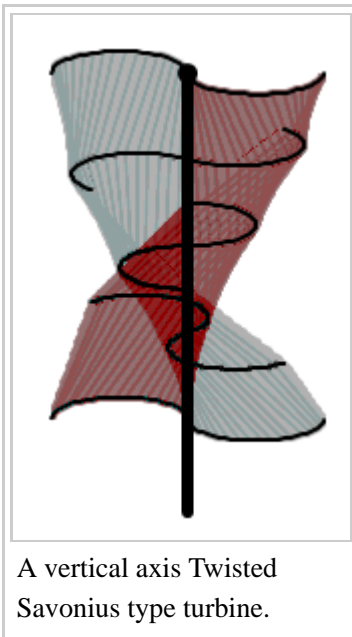
When a turbine is mounted on a rooftop the building generally redirects wind over the roof and this can double



Components of a horizontal axis wind turbine (gearbox, rotor shaft and brake assembly) being lifted into position



A turbine blade convoy passing through Edenfield, UK



A vertical axis Twisted Savonius type turbine.

the wind speed at the turbine. If the height of a rooftop mounted turbine tower is approximately 50% of the building height it is near the optimum for maximum wind energy and minimum wind turbulence. Wind speeds within the built environment are generally much lower than at exposed rural sites,^{[30][31]} noise may be a concern and an existing structure may not adequately resist the additional stress.

Subtypes of the vertical axis design include:

Darrieus wind turbine

"Eggbeater" turbines, or Darrieus turbines, were named after the French inventor, Georges Darrieus.^[32] They have good efficiency, but produce large torque ripple and cyclical stress on the tower, which contributes to poor reliability. They also generally require some external power source, or an

additional Savonius rotor to start turning, because the starting torque is very low. The torque ripple is reduced by using three or more blades which results in greater solidity of the rotor. Solidity is measured by blade area divided by the rotor area. Newer Darrieus type turbines are not held up by guy-wires but have an external superstructure connected to the top bearing.^[33]

Giromill

A subtype of Darrieus turbine with straight, as opposed to curved, blades. The cycloturbine variety has variable pitch to reduce the torque pulsation and is self-starting.^[34] The advantages of variable pitch are: high starting torque; a wide, relatively flat torque curve; a higher coefficient of performance; more efficient operation in turbulent winds; and a lower blade speed ratio which lowers blade bending stresses. Straight, V, or curved blades may be used.^[35]

Savonius wind turbine

These are drag-type devices with two (or more) scoops that are used in anemometers, *Flettner* vents (commonly seen on bus and van roofs), and in some high-reliability low-efficiency power turbines. They are always self-starting if there are at least three scoops.

Twisted Savonius

Twisted Savonius is a modified savonius, with long helical scoops to provide smooth torque. This is often used as a rooftop windturbine and has even been adapted for ships.^[36]

Another type of vertical axis is the Parallel turbine, which is similar to the crossflow fan or centrifugal fan. It uses the ground effect. Vertical axis turbines of this type have been tried for many years: a unit producing 10 kW was built by Israeli wind pioneer Bruce Brill in the 1980s.^[37]

Vortexis

The most recent advancement in Vertical Axis Wind Turbines has been the Vortexis VAWT, utilizing a pre-swirled augmented vertical axis wind turbine (PA-VAWT) designed for the purpose of developing a



Offshore Horizontal Axis Wind Turbines (HAWTs) at Scroby Sands Wind Farm, UK



Onshore Horizontal Axis Wind Turbines in Zhangjiakou, China

high efficiency VAWT concept that keeps the advantages of VAWT's compact size, lack of bias as to incoming wind direction, easy deployment and low radar cross section for use in mobile applications for the military, referred to in Special Operations as "Black Swan."^{[38][39]}

Design and construction

Wind turbines are designed to exploit the wind energy that exists at a location. Aerodynamic modeling is used to determine the optimum tower height, control systems, number of blades and blade shape.

Wind turbines convert wind energy to electricity for distribution. Conventional horizontal axis turbines can be divided into three components:

- The rotor component, which is approximately 20% of the wind turbine cost, includes the blades for converting wind energy to low speed rotational energy.
- The generator component, which is approximately 34% of the wind turbine cost, includes the electrical generator,^{[40][41]} the control electronics, and most likely a gearbox (e.g. planetary gearbox),^[42] adjustable-speed drive or continuously variable transmission^[43] component for converting the low speed incoming rotation to high speed rotation suitable for generating electricity.
- The structural support component, which is approximately 15% of the wind turbine cost, includes the tower and rotor yaw mechanism.^[44]

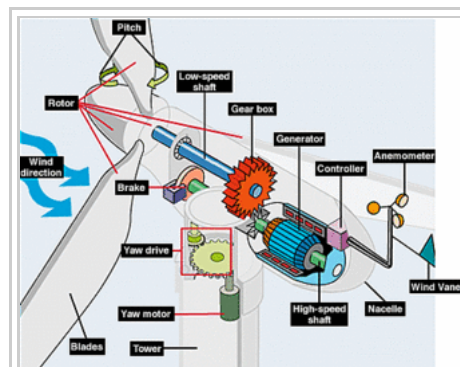
A 1.5 MW wind turbine of a type frequently seen in the United States has a tower 80 meters (260 ft) high. The rotor assembly (blades and hub) weighs 22,000 kilograms (48,000 lb). The nacelle, which contains the generator component, weighs 52,000 kilograms (115,000 lb). The concrete base for the tower is constructed using 26,000 kilograms (58,000 lb) of reinforcing steel and contains 190 cubic meters (250 cu yd) of concrete. The base is 15 meters (50 ft) in diameter and 2.4 meters (8 ft) thick near the center.^[45]

Among all renewable energy systems wind turbines have the highest effective intensity of power-harvesting surface^[46] because turbine blades not only harvest wind power, but also concentrate it.^[47]

Unconventional designs

An E-66 wind turbine in the Windpark Holtriem, Germany, has an observation deck for visitors. Another turbine of the same type with an observation deck is located in Swaffham, England. Airborne wind turbine designs have been proposed and developed for many years but have yet to produce significant amounts of energy. In principle, wind turbines may also be used in conjunction with a large vertical solar updraft tower to extract the energy due to air heated by the sun.

Wind turbines which utilise the Magnus effect have been developed.^[48]



Components of a horizontal-axis wind turbine



Inside view of a wind turbine tower, showing the tendon cables.

A ram air turbine (RAT) is a special kind of small turbine that is fitted to some aircraft. When deployed, the RAT is spun by the airstream going past the aircraft and can provide power for the most essential systems if there is a loss of all on-board electrical power,^[49] as in the case of the "Gimli Glider".

The two-bladed turbine SCD 6MW offshore turbine designed by aerodyn Energiesysteme, built by MingYang Wind Power has a helideck for helicopters on top of its nacelle. The prototype was erected in 2014 in Rudong China.

Turbine monitoring and diagnostics

Due to data transmission problems, structural health monitoring of wind turbines is usually performed using several accelerometers and strain gages attached to the nacelle to monitor the gearbox and equipments. Currently, digital image correlation and stereophotogrammetry are used to measure dynamics of wind turbine blades. These methods usually measure displacement and strain to identify location of defects. Dynamic characteristics of non-rotating wind turbines have been measured using digital image correlation and photogrammetry.^[50] Three dimensional point tracking has also been used to measure rotating dynamics of wind turbines.^[51]

Materials and durability

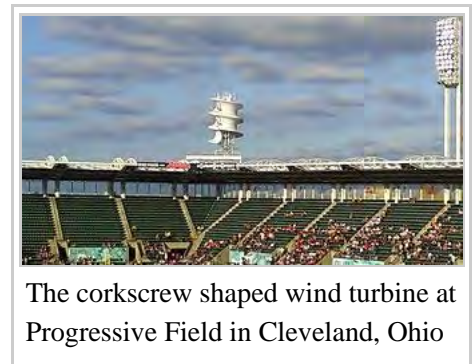
Materials that are typically used for the rotor blades in wind turbines are composites, as they tend to have a high stiffness, high strength, high fatigue resistance, and low weight.^[52] Typical resins used for these composites include polyester and epoxy, while glass and carbon fibers have been used for the reinforcing material.^[53] Construction may use manual layup techniques or composite resin injection molding. As the price of glass fibers is only about one tenth the price of carbon fiber, glass fiber is still dominant.

As competition in the wind market increases, companies are seeking ways to draw greater efficiency from their designs. One of the predominant ways wind turbines have gain performance is by increasing rotor diameters, and thus blade length. Retrofitting current turbines with larger blades mitigates the need and risks associated with a system-level redesign. By incorporating carbon fiber into parts of existing blade systems, manufacturers may increase the length of the blades without increasing their overall weight. For instance, the spar cap, a structural element of a turbine blade, commonly experiences high tensile loading, making it an ideal candidate to utilize the enhanced tensile properties of carbon fiber in comparison to glass fiber.^[54] Higher stiffness and lower density translates to thinner, lighter blades offering equivalent performance. In a 10-MW turbine—which will become more common in offshore systems by 2021—blade lengths may reach over 100 m and weigh up to 50 metric tonnes when fabricated out of glass fiber. A switch to carbon fiber in the structural spar of the blade yields weight savings of 20 to 30 percent, or approximately 15 metric tonnes.^[55] The compressive properties of carbon fiber do not differ significantly from those of glass fiber. It is therefore not economical to replace glass fiber components under compression with carbon fiber components.

While the material cost is significantly higher for all-glass fiber blades than for hybrid glass/carbon fiber



Counter rotating wind turbine (dual rotor)



The corkscrew shaped wind turbine at Progressive Field in Cleveland, Ohio

blades, there is a potential for tremendous savings in manufacturing costs when labor price is considered. Utilizing carbon fiber enables for simpler designs that use less raw material. The chief manufacturing process in blade fabrication is the layering of plies. By reducing the number of layers of plies, as is enabled by thinner blade design, the cost of labor may be decreased, and in some cases, equate to the cost of labor for glass fiber blades.^[56]

Materials for wind turbine parts other than the rotor blades (including the rotor hub, gearbox, frame, and tower) are largely composed of steel. Smaller wind turbines have begun incorporating more aluminum based alloys into these components in an effort to make the turbines more lightweight and efficient, and may continue to be used increasingly if fatigue and strength properties can be improved. Prestressed concrete has been increasingly used for the material of the tower, but still requires much reinforcing steel to meet the strength requirement of the turbine. Additionally, step-up gear boxes are being increasingly replaced with variable speed generators, increasing the demand for magnetic materials in wind turbines.^[52] In particular this would require an increased supply of the rare earth metal neodymium. Reliance on rare earth minerals for components has risked expense and price volatility as China has been main producer of rare earth minerals (96% in 2009) and had been reducing its export quotas of these materials.^[57] In recent years, however, other producers have increased production of rare earth minerals and China has removed its reduced export quota on rare earths leading to an increased supply and decreased cost of rare earth minerals, increasing the viability of the implementation of variable speed generators in wind turbines on a large scale.^[58]

Wind turbines on public display

A few localities have exploited the attention-getting nature of wind turbines by placing them on public display, either with visitor centers around their bases, or with viewing areas farther away.^[59] The wind turbines are generally of conventional horizontal-axis, three-bladed design, and generate power to feed electrical grids, but they also serve the unconventional roles of technology demonstration, public relations, and education.

Small wind turbines

Small wind turbines may be used for a variety of applications including on- or off-grid residences, telecom towers, offshore platforms, rural schools and clinics, remote monitoring and other purposes that require energy where there is no electric grid, or where the grid is unstable. Small wind turbines may be as small as a fifty-watt generator for boat or caravan use. Hybrid solar and wind powered units are increasingly being used for traffic signage, particularly in rural locations, as they avoid the need to lay long cables from the nearest mains connection point.^[60] The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) defines small wind turbines as those smaller than or equal to 100 kilowatts.^[61] Small units often have direct drive generators, direct current output, aeroelastic blades, lifetime bearings and use a vane to point into the wind.

Larger, more costly turbines generally have geared power trains, alternating current output, flaps and are actively pointed into the wind. Direct drive generators and aeroelastic blades for large wind turbines are being researched.



The Nordex N50 wind turbine and visitor centre of Lamna Winds in Hong Kong, China

Wind turbine spacing

On most horizontal windturbine farms, a spacing of about 6-10 times the rotor diameter is often upheld. However, for large wind farms distances of about 15 rotor diameters should be more economically optimal, taking into account typical wind turbine and land costs. This conclusion has been reached by research^[62] conducted by Charles Meneveau of the Johns Hopkins University,^[63] and Johan Meyers of Leuven University in Belgium, based on computer simulations^[64] that take into account the detailed interactions among wind turbines (wakes) as well as with the entire turbulent atmospheric boundary layer. Moreover, recent research by John Dabiri of Caltech suggests that vertical wind turbines may be placed much more closely together so long as an alternating pattern of rotation is created allowing blades of neighbouring turbines to move in the same direction as they approach one another.^[65]

Operability

Maintenance

Wind turbines need regular maintenance to stay reliable and available, reaching 98%.^{[66][67]}

Modern turbines usually have a small onboard crane for hoisting maintenance tools and minor components. However, large heavy components like generator, gearbox, blades and so on are rarely replaced and a heavy lift external crane is needed in those cases. If the turbine has a difficult access road, a containerized crane can be lifted up by the internal crane to provide heavier lifting.^[68]

Repowering

Installation of new wind turbines can be controversial. An alternative is repowering, where existing wind turbines are replaced with bigger, more powerful ones, sometimes in smaller numbers while keeping or increasing capacity.

Demolition

Older turbines were in some early cases not required to be removed when reaching the end of their life. Some still stand, waiting to be recycled or repowered.^{[69][70]}

A demolition industry develops to recycle offshore turbines at a cost of DKK 2–4 million per MW, to be guaranteed by the owner.^[71]

Records

Largest capacity conventional drive

The Vestas V164 has a rated capacity of 8 MW,^[72] has an overall height of 220 m (722 ft), a diameter of 164 m (538 ft), is for offshore use, and is the world's largest-capacity wind turbine since its introduction in 2014. The conventional drive train consist of a main gearbox and a medium speed PM generator.



A small Quietrevolution QR5 Gorlov type vertical axis wind turbine in Bristol, England. Measuring 3 m in diameter and 5 m high, it has a nameplate rating of 6.5 kW to the grid.

Prototype installed in 2014 at the National Test Center Denmark nearby Østerild. Series production starts end of 2015.

Largest capacity direct drive

The Enercon E-126 with 7.58 MW and 127 m rotor diameter is the largest direct drive turbine. It's only for onshore use. The turbine has parted rotor blades with 2 sections for transport. In July 2016, Siemens upgraded its 7 to 8 MW.^[73]

Largest vertical-axis

Le Nordais wind farm in Cap-Chat, Quebec has a vertical axis wind turbine (VAWT) named Éole, which is the world's largest at 110 m.^[74] It has a nameplate capacity of 3.8 MW.^[75]

Largest 1-bladed turbine

Riva Calzoni M33 was a single-bladed wind turbine with 350 kW, designed and built in Bologna in 1993.

Largest 2-bladed turbine

The biggest 2-bladed turbine is built by Mingyang Wind Power in 2013. It is a SCD6.5MW offshore downwind turbine, designed by aerodyn Energiesysteme.^{[76][77][78]}

Largest swept area

The turbine with the largest swept area is the Samsung S7.0-171, with a diameter of 171 m, giving a total sweep of 22966 m².

Tallest

A Nordex 3.3 MW was installed in July 2016. It has a total height of 230m, and a hub height of 164m on 100m concrete tower bottom with steel tubes on top (hybrid tower).^[79]

Vestas V164 was the tallest wind turbine, standing in Østerild, Denmark, 220 meters tall, constructed in 2014. It has a steel tube tower.

Highest tower

Fuhrländer installed a 2.5MW turbine on a 160m lattice tower in 2003 (see Fuhrländer Wind Turbine Laasow and Nowy Tomyśl Wind Turbines).

Most rotors

Lagerwey has build Four-in-One, a multi rotor wind turbine with one tower and four rotors near Maasvlakte. In April 2016, Vestas installed a 900 kW quadrotor test wind turbine at Risø, made from 4 recycled 225 kW V29 turbines.^{[80][81][82]}

Most productive

Four turbines at Rønland wind farm in Denmark share the record for the most productive wind turbines, with each having generated 63.2 GWh by June 2010.^[83]

Highest-situated

Since 2013 the world's highest-situated wind turbine was made and installed by WindAid and is located at the base of the Pastoruri Glacier in Peru at 4,877 meters (16,001 ft) above sea level.^[84] The site uses the WindAid 2.5 kW wind generator to supply power to a small rural community of micro entrepreneurs who cater to the tourists who come to the Pastoruri glacier.^[85]

Largest floating wind turbine

The world's largest—and also the first operational deep-water *large-capacity*—floating wind turbine is the 2.3 MW Hywind currently operating 10 kilometers (6.2 mi) offshore in 220-meter-deep water,



Fuhrländer Wind Turbine Laasow, in Brandenburg, Germany, among the world's tallest wind turbines



Éole, the largest vertical axis wind turbine, in Cap-Chat, Quebec, Canada

southwest of Karmøy, Norway. The turbine began operating in September 2009 and utilizes a Siemens 2.3 MW turbine.^{[86][87]}

See also

- Compact wind acceleration turbine
- Environmental impact of wind power
- Éolienne Bollée
- Renewable energy
- Tidal stream generator
- Wind lens
- Windbelt
- Windpump

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External links

- Harvesting the Wind (45 lectures about wind turbines by professor Magdi Ragheb (<https://netfiles.uiuc.edu/mragheb/www/NPRE%20475%20Wind%20Power%20Systems/>))
- Wind Projects (<http://www.projectfreepower.com/>)
- Make small wind turbine at home Complete video and image Guide by Newphysicist (<http://www.newphysicist.com/make-small-wind-turbine/>)
- Guided tour on wind energy (http://www.windpower.org/en/knowledge/guided_tour.html)
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- Wind turbine simulation, National Geographic (<http://environment.nationalgeographic.com/environment/global-warming/wind-power-interactive.html>)
- Airborne Wind Industry Association international (<http://www.aweia.org/>)
- Top 10 biggest wind turbines in the world (<http://ongreentech.com/10-biggest-wind-turbines/>)
- The Tethys database seeks to gather, organize and make available information on potential environmental effects of offshore wind energy development (<http://tethys.pnnl.gov/>)



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