Wind Energy

Mechanical Design Considerations
Upwind Machines

Upwind machines have the rotor facing the wind. The basic advantage of upwind designs is that one avoids the wind shade behind the tower. By far the vast majority of wind turbines have this design. On the other hand, there is also some wind shade in front of the tower, i.e. the wind starts bending away from the tower before it reaches the tower itself, even if the tower is round and smooth. Therefore, each time the rotor passes the tower, the power from the wind turbine drops slightly. The basic drawback of upwind designs is that the rotor needs to be made rather inflexible, and placed at some distance from the tower (as some manufacturers have found out to their cost). In addition an upwind machine needs a yaw mechanism to keep the rotor facing the wind.
Downwind Machines

Downwind machines have the rotor placed on the lee side of the tower. They have the theoretical advantage that they may be built without a yaw mechanism, if the rotor and nacelle have a suitable design that makes the nacelle follow the wind passively. For large wind turbines this is a somewhat doubtful advantage, however, since you do need cables to lead the current away from the generator. How do you untwist the cables, when the machine has been yawing passively in the same direction for a long period of time, if you do not have a yaw mechanism? (Slip rings or mechanical collectors are not a very good idea if you are working with 1000 ampere currents).

A more important advantage is that the rotor may be made more flexible. This is an advantage both in regard to weight, and the structural dynamics of the machine, i.e. the blades will bend at high wind speeds, thus taking part of the load off the tower. The basic advantage of the downwind machine is thus, that it may be built somewhat lighter than an upwind machine.

The basic drawback is the fluctuation in the wind power due to the rotor passing through the wind shade of the tower. This may give more fatigue loads on the turbine than with an upwind design.
Tip speed ratio

How do we actually extract the wind’s energy for useful work?

**Definition:**

**Tip speed ratio** $\lambda$ is the ratio of the tangential blade tip speed to the undisturbed wind speed. Each turbine has an optimal value. $\lambda$ too high, each blade interferes with following blade’s air flow, lowering the efficiency of energy extraction. $\lambda$ too low, wind passes undisturbed between blades with no extraction of energy.
Number of blades

• More blades (high solidity) low \( \lambda \), high torque at low speed. (Suits pumping water)
• Few blades, high \( \lambda \), lower torque at high speeds (Suits generating electricity)
• We previously noted that the (theoretical) Betz limit is 59%.
• A practical high efficiency turbine might be 40% efficient at converting wind energy to mechanical rotational energy.
• For electricity generation, three blades is practically most efficient.
Wind Turbines: How many blades?

- Why Not an Even Number of Blades?
- Modern wind turbine engineers avoid building large machines with an even number of rotor blades. The most important reason is the stability of the turbine. A rotor with an odd number of rotor blades (and at least three blades) can be considered to be similar to a disc when calculating the dynamic properties of the machine.
- A rotor with an even number of blades will give stability problems for a machine with a stiff structure. The reason is that at the very moment when the uppermost blade bends backwards, because it gets the maximum power from the wind, the lowermost blade passes into the wind shade in front of the tower.
One-Bladed Concept

Yes, one-bladed wind turbines do exist, and indeed, they save the cost of another rotor blade! If anything can be built, engineers will do it. One-bladed wind turbines are not very widespread commercially, however, because the same problems that are mentioned under the two-bladed design apply to an even larger extent to one-bladed machines.

In addition to higher rotational speed, and the noise and visual intrusion problems, they require a counterweight to be placed on the other side of the hub from the rotor blade in order to balance the rotor. This obviously negates the savings on weight compared to a two-bladed design.
Two- and one-bladed machines require a more complex design with a hinged (teetering hub) rotor as shown in the picture, i.e. the rotor has to be able to tilt in order to avoid too heavy shocks to the turbine when a rotor blade passes the tower. The rotor is therefore fitted onto a shaft which is perpendicular to the main shaft, and which rotates along with the main shaft. This arrangement may require additional shock absorbers to prevent the rotor blade from hitting the tower.
Two-Bladed (Teetering) Concept

Two-bladed wind turbine designs have the advantage of saving the cost of one rotor blade and its weight, of course. However, they tend to have difficulty in penetrating the market, particularly because they require higher rotational speed to yield the same energy output. This is a disadvantage both in regard to noise and visual intrusion. Lately, several traditional manufacturers of two-bladed machines have switched to three-bladed designs.
The Danish Three-Bladed Concept

Most modern wind turbines are three-bladed designs with the rotor position maintained upwind (on the windy side of the tower) using electrical motors in their yaw mechanism. This design is usually called the classical Danish concept, and tends to be a standard against which other concepts are evaluated. The vast majority of the turbines sold in world markets have this design. The basic design was first introduced with the renowned Gedser wind turbine. Another characteristic is the use of an asynchronous generator. You may read more about the Danish concept in the articles section of this web site.
The Wind Turbine Yaw Mechanism

The wind turbine yaw mechanism is used to turn the wind turbine rotor against the wind.

**Yaw Error**

The wind turbine is said to have a yaw error, if the rotor is not perpendicular to the wind. A yaw error implies that a lower share of the energy in the wind will be running through the rotor area. (The share will drop to the cosine of the yaw error, for those of you who know math).

If this were the only thing that happened, then yaw control would be an excellent way of controlling the power input to the wind turbine rotor. That part of the rotor which is closest to the source direction of the wind, however, will be subject to a larger force (bending torque) than the rest of the rotor. On the one hand, this means that the rotor will have a tendency to yaw against the wind automatically, regardless of whether we are dealing with an upwind or a downwind turbine. On the other hand, it means that the blades will be bending back and forth in a flapwise direction for each turn of the rotor. Wind turbines which are running with a yaw error are therefore subject to larger fatigue loads than wind turbines which are yawed in a perpendicular direction against the wind.
Almost all horizontal axis wind turbines use forced yawing, i.e. they use a mechanism which uses electric motors and gearboxes to keep the turbine yawed against the wind.

The image shows the yaw mechanism of a typical 750 kW machine seen from below, looking into the nacelle. We can see the yaw bearing around the outer edge, and the wheels from the yaw motors and the yaw brakes inside. Almost all manufacturers of upwind machines prefer to brake the yaw mechanism whenever it is unused. The yaw mechanism is activated by the electronic controller which several times per second checks the position of the wind vane on the turbine, whenever the turbine is running.
Cable Twist Counter

Cables carry the current from the wind turbine generator down through the tower. The cables, however, will become more and more twisted if the turbine by accident keeps yawing in the same direction for a long time. The wind turbine is therefore equipped with a cable twist counter which tells the controller that it is time to untwist the cables. Occasionally you may therefore see a wind turbine which looks like it has gone berserk, yawing continuously in one direction for five revolutions. Like other safety equipment in the turbine there is redundancy in the system. In this case the turbine is also equipped with a pull switch which is activated if the cables become too twisted.
Optimizing Wind Turbines

The water pumping windmills look very different from modern, large wind turbines. But they are quite sensibly designed for the purpose they serve: The very solid rotor with many blades means that they will be running even at very low wind speeds, and thus pumping a fair amount of water all year round. Clearly, they will be very inefficient at high wind speeds, and they will have to shut themselves down, and yaw out of the wind in order to avoid damage to the turbine, due to the very solid rotor. But that does not really matter: We do not want them to empty the wells and flood the water tank during a gale.

The ideal wind turbine design is not dictated by technology alone, but by a combination of technology and economics: Wind turbine manufacturers wish to optimise their machines, so that they deliver electricity at the lowest possible cost per kilowatt hour (kWh) of energy. But manufacturers are not very concerned about how efficiently they use the wind resource: The fuel is free, after all.

It is not necessarily a good idea to maximise annual energy production, if that means that one has to build a very expensive wind turbine.
Victoria in Southern Australia would never have been populated in the late 19th century, were it not for the water pumping windmills - and these windmills are really optimised for their purpose.
Relative Generator and Rotor Size

A small generator, (i.e. a generator with low rated power output in kW) requires less force to turn than a large one. If you fit a large wind turbine rotor with a small generator it will be producing electricity during many hours of the year, but it will capture only a small part of the energy content of the wind at high wind speeds. A large generator, on the other hand, will be very efficient at high wind speeds, but unable to turn at low wind speeds. Clearly, manufacturers will look at the distribution of wind speeds and the energy content of the wind at different wind speeds to determine the ideal combination of the size of the rotor and the size of the generator at different wind turbine sites. Fitting a wind turbine with two (or more) generators can sometimes be an advantage, but whether it really pays to do it depends on the electricity price.
Testing Wind Turbine Rotor Blades

Fatigue Testing of Rotor Blades

The video to the left (122 K) shows how a 32 m rotor blade is fatigue tested by being bent cyclically in a flapwise direction for 5 million full cycles. A full flapwise test thus takes about three months. If you look closely to the left you can see another (shorter) rotor blade being bent cyclically in an edgewise (chordwise) direction. In both cases the blades are bent using a cycle close to the natural frequency of the blade. The natural frequency is the frequency with which the blade will oscillate back and forth, if you push it once in a certain direction and let go. The natural frequencies are different in the flapwise and edgewise direction: The blade tends to be much stiffer in the edgewise direction, thus it has a higher natural frequency for edgewise bending.
Each blade is set in motion by an electric motor mounted on the blade which swings a weight up and down. The foundations which carry the blade socket have to be very solid: The foundation for the large blade socket consists of 2,000 tonnes of concrete. This video was shot at the rotor blade test facility of the Risoe National Laboratory Sparkær Test Centre in Jutland, Denmark. (Type approval requirements for rotor blades are very strict in Denmark, requiring physical testing of rotor blades for both fatigue properties (fatigue testing) and strength properties (static testing). Other countries usually have less stringent requirements for type approval of rotor blades).
Rotor Blade Materials

Rotor blades are usually made using a matrix of fibre glass mats which are impregnated with a material such as polyester (GRP = Glass fibre reinforced polyester). The polyester is hardened after it has impregnated the fibre glass. Epoxy may be used instead of polyester. Likewise the basic matrix may be made wholly or partially from carbon fibre, which is a lighter, but costlier material with high strength. Wood-epoxy laminates are also being used for large rotor blades.

The Purpose of Testing Rotor Blades

The purpose of rotor blade testing is to verify that laminations in the blade are, safe, i.e. that the layers of the rotor blade do not separate (delamination). Also, the test verifies that the fibres do not break under repeated stress.
In the section on wind shear, you have learned that taller towers generally increase a wind turbine's energy production. Once again, whether a taller tower is worth the extra cost depends both on the roughness class, and the cost of electricity.
Wind turbine towers, Navarra, Spain

The tower of the wind turbine carries the nacelle and the rotor. Towers for large wind turbines may be either tubular steel towers, lattice towers, or concrete towers. Guyed tubular towers are only used for small wind turbines (battery chargers etc.)
Most large wind turbines are delivered with tubular steel towers, which are manufactured in sections of 20-30 metres with flanges at either end, and bolted together on the site. The towers are conical (i.e. with their diameter increasing towards the base) in order to increase their strength and to save materials at the same time.
Lattice towers are manufactured using welded steel profiles. The basic advantage of lattice towers is cost, since a lattice tower requires only half as much material as a freely standing tubular tower with a similar stiffness. The basic disadvantage of lattice towers is their visual appearance, (although that issue is clearly debatable). Be that as it may, for aesthetic reasons lattice towers have almost disappeared from use for large, modern wind turbines.
Guyed Pole Towers

Many small wind turbines are built with narrow pole towers supported by guy wires. The advantage is weight savings, and thus cost. The disadvantages are difficult access around the towers which make them less suitable in farm areas. Finally, this type of tower is more prone to vandalism, thus compromising overall safety.
Hybrid Tower Solutions

Some towers are made in different combinations of the techniques mentioned above. One example is the three-legged Bonus 95 kW tower which you see in the photograph, which may be said to be a hybrid between a lattice tower and a guyed tower.
**Cost Considerations**
The price of a tower for a wind turbine is generally around 20 per cent of the total price of the turbine. For a tower around 50 metres' height, the additional cost of another 10 metres of tower is about 15,000 USD. It is therefore quite important for the final cost of energy to build towers as optimally as possible. Lattice towers are the cheapest to manufacture, since they typically require about half the amount of steel used for a tubular steel tower.

**Aerodynamic Considerations**
Generally, it is an advantage to have a tall tower in areas with high terrain roughness, since the wind speeds increases farther away from the ground, as we learned on the page about wind shear. Lattice towers and guyed pole towers have the advantage of giving less wind shade than a massive tower.
Structural Dynamic Considerations
The rotor blades on turbines with relatively short towers will be subject to very different wind speeds (and thus different bending) when a rotor blade is in its top and in its bottom position, which will increase the fatigue loads on the turbine.

Choosing Between Low and Tall Towers
Obviously, you get more energy from a larger wind turbine than a small one, but if you take a look at the three wind turbines below, which are 225 kW, 600 kW, and 1,500 kW respectively, and with rotor diameters of 27, 43, and 60 metres, you will notice that the tower heights are different as well.
Clearly, we cannot sensibly fit a 60 metre rotor to a tower of less than 30 metres. But if we consider the cost of a large rotor and a large generator and gearbox, it would surely be a waste to put it on a small tower, because we get much higher wind speeds and thus more energy with a tall tower. (See the section on wind resources). Each metre of tower height costs money, of course, so the optimum height of the tower is a function of tower costs per metre (10 metre extra tower will presently cost you about 15,000 USD) how much the wind locally varies with the height above ground level, i.e. the average local terrain roughness (large roughness makes it more useful with a taller tower), the price the turbine owner gets for an additional kilowatt hour of electricity. Manufacturers often deliver machines where the tower height is equal to the rotor diameter. Aesthetically, many people find that turbines are more pleasant to look at, if the tower height is roughly equal to the rotor diameter
Power Output Increases with the Swept Rotor Area

When a farmer tells you how much land he is farming, he will usually state an area in terms of hectares or acres. With a wind turbine it is much the same story, though doing wind farming we farm a vertical area instead of a horizontal one.

The area of the disc covered by the rotor, (and wind speeds, of course), determines how much energy we can harvest in a year. The picture gives you an idea of the normal rotor sizes of wind turbines: A typical turbine with a 600 kW electrical generator will typically have a rotor diameter of some 44 metres (144 ft.). If you double the rotor diameter, you get an area which is four times larger (two squared). This means that you also get four times as much power output from the rotor.
Rotor diameters may vary somewhat from the figures given above, because many manufacturers optimise their machines to local wind conditions: A larger generator, of course, requires more power (i.e. strong winds) to turn at all. So if you install a wind turbine in a low wind area you will actually maximise annual output by using a fairly small generator for a given rotor size (or a larger rotor size for a given generator) For a 600 kW machine rotor diameters may vary from 39 to 48 m (128 to 157 ft.) The reason why you may get more output from a relatively smaller generator in a low wind area is that the turbine will be running more hours during the year.
Reasons for Choosing Large Turbines

1. There are economies of scale in wind turbines, i.e. larger machines are usually able to deliver electricity at a lower cost than smaller machines. The reason is that the cost of foundations, road building, electrical grid connection, plus a number of components in the turbine (the electronic control system etc.), are somewhat independent of the size of the machine.

2. Larger machines are particularly well suited for offshore wind power. The cost of foundations does not rise in proportion to the size of the machine, and maintenance costs are largely independent of the size of the machine.

3. In areas where it is difficult to find sites for more than a single turbine, a large turbine with a tall tower uses the existing wind resource more efficiently.
Reasons for Choosing Smaller Turbines

1. The local electrical grid may be too weak to handle the electricity output from a large machine. This may be the case in remote parts of the electrical grid with low population density and little electricity consumption in the area.

2. There is less fluctuation in the electricity output from a wind park consisting of a number of smaller machines, since wind fluctuations occur randomly, and therefore tend to cancel out. Again, smaller machines may be an advantage in a weak electrical grid.

3. The cost of using large cranes, and building a road strong enough to carry the turbine components may make smaller machines more economic in some areas.

4. Several smaller machines spread the risk in case of temporary machine failure, e.g. due to lightning strikes.

5. Aesthetical landscape considerations may sometimes dictate the use of smaller machines. Large machines, however, will usually have a much lower rotational speed, which means that one large machine really does not attract as much attention as many small, fast moving rotors.
Designing for Low Mechanical Noise from Wind Turbines

Sound emissions from wind turbines may have two different origins: Mechanical noise, and aerodynamic noise.

**Mechanical Sources of Sound Emission**
Mechanical noise, i.e. metal components moving or knocking against each other may originate in the gearbox, in the drive train (the shafts), and in the generator of a wind turbine. Machines from the early 1980s or before do emit some mechanical noise, which may be heard in the immediate surroundings of the turbine, in the worst cases even up to a distance of 200 m (600 ft.)

A survey on research and development priorities of Danish wind turbine manufacturers conducted in 1995, however, showed that no manufacturer considered mechanical noise as a problem any longer, and therefore no further research in the area was considered necessary. The reason was, that within three years noise emissions had dropped to half their previous level due to better engineering practices.
Designing for Low Aerodynamic Noise from Wind Turbines

Aerodynamic Sources of Sound Emission

When the wind hits different objects at a certain speed, it will generally start making a sound. If it hits the leaves of trees and bushes, or a water surface it will create a random mixture of high frequencies, often called white noise.

The wind may also set surfaces in vibration, as sometimes happens with parts of a building, a car or even an (engineless) glider aeroplane. These surfaces in turn emit their own sound. If the wind hits a sharp edge, it may produce a pure tone, as you can hear it from musical wind instruments.
Quieting Wind Turbine Gearboxes

Gearboxes for wind turbines are no longer standard industrial gearboxes, but they have been adapted specifically for quiet operation of wind turbines. One way of doing this is to ensure that the steel wheels of the gearbox have a semi-soft, flexible core, but a hard surface to ensure strength and long time wear. The way this is done is basically to heat the gear wheels after their teeth have been ground, and then let them cool off slowly while they are packed in a special high carbon-content powder. The carbon will then migrate into the surface of the metal. This ensures a high carbon content and high durability in the surface of the metal, while the steel alloy in the interior remains softer and more flexible.
Structural Dynamics Analysis

When going by car, plane, or train, you may have experienced how resonance of different components, e.g. in the dashboard of a car or a window of a train may amplify noise. An important consideration, which enters into the turbine design process today, is the fact that the rotor blades may act as membranes that may retransmit noise vibrations from the nacelle and tower. The turbine manufacturers nowadays make computer models of their machines before building them, to ensure that the vibrations of different components do not interact to amplify noise. If you look at the chassis frame of the nacelle on some of the large wind turbines on the market today, you may discover some odd holes which were drilled into the chassis frame for no apparent reason. These holes were precisely made to ensure that the frame will not vibrate in step with the other components in the turbine.
Sound Insulation

Sound insulation plays a minor role in most modern wind turbines on the market today, although it can be useful to minimize some medium- and high-frequency noise. In general, however, it seems to be more efficient to attack noise problems at the source, in the structure of the machine itself.
Rotor Blade Sound Emission and the Fifth Power Law

Rotor blades make a slight swishing sound which you may hear if you are close to a wind turbine at relatively low wind speeds. Rotor blades must brake the wind to transfer energy to the rotor. In the process they cause some emission of white noise. If the surfaces of the rotor blades are very smooth (which indeed they must be for aerodynamic reasons), the surfaces will emit a minor part of the noise. Most of the noise will originate from the trailing (back) edge of the blades. Careful design of trailing edges and very careful handling of rotor blades while they are mounted, have become routine practice in the industry.

Other things being equal, sound pressure will increase with the fifth power of the speed of the blade relative to the surrounding air. You will therefore notice that modern wind turbines with large rotor diameters have very low rotational speed.
Rotor Blade Tip Design

Since the tip of the blade moves substantially faster than the root of the blade, great care is taken about the design of the rotor tip. If you look closely at different rotor blades you will discover subtle changes in their geometry over time, as more and more research in the area is being done. The research is also done for performance reasons, since most of the torque (rotational moment) of the rotor comes from the outer part of the blades. In addition, the airflows around the tip of rotor blades is extremely complex, compared to the airflow over the rest of the rotor blade.
Research on Quieter Blades

Research on quieter rotor blades continues, but as mentioned in the section Noise is a Minor Problem, most of the benefits of that research will be turned into increased rotational speed and increased energy output, since noise is generally not a problem per se, given the distances to neighbouring houses etc.
What does a Wind Turbine Cost?
The Price Banana

The graph above gives an impression of the price range of modern, Danish grid connected wind turbines as of February 1998. As you can see prices vary for each generator size. The reasons are e.g. different tower heights, and different rotor diameters. One extra metre of tower will cost you roughly 1,500 USD. A special low wind machine with a relatively large rotor diameter will be more expensive than a high wind machine with a small rotor diameter.
Economies of Scale

As you move from a 150 kW machine to a 600 kW machine, prices will roughly triple, rather than quadruple. The reason is, that there are economies of scale up to a certain point, e.g. the amount of manpower involved in building a 150 kW machine is not very different from what is required to build a 600 kW machine. E.g. the safety features, and the amount of electronics required to run a small or a large machine is roughly the same. There may also be (some) economies of scale in operating wind parks rather than individual turbines, although such economies tend to be rather limited.

Price Competition and Product Range
Price competition is currently particularly tough, and the product range particularly large around 1000 kW. This is where you are likely to find a machine which is optimised for any particular wind climate.
**Typical 1000 kW Machines on the Market Today**

Even if prices are very similar in the range from 600 to 750 kW, you would not necessarily want to pick a machine with as large a generator as possible. A machine with a large 750 kW generator (and a relatively small rotor diameter) may generate less electricity than, say a 600 kW machine, if it is located in a low wind area. The working horse today is typically a 1000 kilowatt machine with a tower height of some 60 to 80 metres and a rotor diameter of around 54 metres.

**1 000 Dollars per Kilowatt Average**

The average price for large, modern wind farms is around 1 000 USD per kilowatt electrical power installed. (Note, that we are not talking about annual energy production.) Energy production is measured in kilowatt hours. For single turbines or small clusters of turbines the costs will usually be somewhat higher.
Installation Costs for Wind Turbines

Installation costs include foundations, normally made of reinforced concrete, road construction (necessary to move the turbine and the sections of the tower to the building site), a transformer (necessary to convert the low voltage (690 V) current from the turbine to 10-30 kV current for the local electrical grid, telephone connection for remote control and surveillance of the turbine, and cabling costs, i.e. the cable from the turbine to the local 10-30 kV power line.

Novar Wind Farm, Scotland, under construction in a moor, July 1997
Installation Costs Vary

Obviously, the costs of roads and foundations depend on soil conditions, i.e. how cheap and easy it is to build a road capable of carrying 30 tonne trucks. Another variable factor is the distance to the nearest ordinary road, the cost of getting a mobile crane to the site, and the distance to a power line capable of handling the maximum energy output from the turbine.

A telephone connection and remote control is not a necessity, but is often fairly cheap, and thus economic to include in a turbine installation. Transportation costs for the turbine may enter the calculation, if the site is very remote, though usually they will not exceed some 15 000 USD.
Economies of Scale

It is obviously cheaper to connect many turbines in the same location, rather than just one. On the other hand, there are limits to the amount of electrical energy the local electrical grid can handle. If the local grid is too weak to handle the output from the turbine, there may be need for grid reinforcement, i.e. extending the high voltage electrical grid. It varies from country to country who pays for grid reinforcement - the power company or the owner of the turbine.
Operation and Maintenance Costs for Wind Turbines

Modern wind turbines are designed to work for some 120,000 hours of operation throughout their design lifetime of 20 years. That is far more than an automobile engine which will generally last for some 4,000 to 6,000 hours.

Operation and Maintenance Costs

Experience shows that maintenance cost are generally very low while the turbines are brand new, but they increase somewhat as the turbine ages. Studies done on the 5,000 Danish wind turbines installed in Denmark since 1975 show that newer generations of turbines have relatively lower repair and maintenance costs than the older generations. (The studies compare turbines which are the same age, but which belong to different generations).

Older Danish wind turbines (25-150 kW) have annual maintenance costs with an average of around 3 per cent of the original turbine investment. Newer turbines are on average substantially larger, which would tend to lower maintenance costs per kW installed power (you do not need to service a large, modern machine more often than a small one). For newer machines the estimates range around 1.5 to 2 per cent per year of the original turbine investment.

Most of maintenance cost is a fixed amount per year for the regular service of the turbines, but some people prefer to use a fixed amount per kWh of output in their calculations, usually around 0.01 USD/kWh. The reasoning behind this method is that tear and wear on the turbine generally increases with increasing production.
Economies of Scale

Other than the economies of scale which vary with the size of the turbine, mentioned above, there may be economies of scale in the operation of wind parks rather than individual turbines. These economies are related to the semi-annual maintenance visits, surveillance and administration, etc.

Turbine Reinvestment (Refurbishment, Major Overhauls)

Some wind turbine components are more subject to tear and wear than others. This is particularly true for rotor blades and gearboxes. Wind turbine owners who see that their turbine is close to the end of their technical design lifetime may find it advantageous to increase the lifetime of the turbine by doing a major overhaul of the turbine, e.g. by replacing the rotor blades. The price of a new set of rotor blades, a gearbox, or a generator is usually in the order of magnitude of 15-20 per cent of the price of the turbine.
The components of Danish wind turbines are designed to last 20 years. It would, of course, be possible to design certain components to last much longer, but it would really be a waste, if other major components were to fail earlier.

The 20 year design lifetime is a useful economic compromise which is used to guide engineers who develop components for the turbines. Their calculations have to prove that their components have a very small probability of failure before 20 years have elapsed.

The actual lifetime of a wind turbine depends both on the quality of the turbine and the local climatic conditions, e.g. the amount of turbulence at the site. Offshore turbines may e.g. last longer, due to low turbulence at sea. This may in turn lower costs.
The graph shows how annual energy production in million kilowatt hours varies with the windiness of the site. With a mean wind speed of, say 6.75 metres per second at hub height you get about 1.5 million kilowatt hours of energy per year.

As you can see, annual energy output varies roughly with the cube of the wind speed at turbine hub height. Just how sensitive energy production is to wind speed varies with the probability distribution for the wind, as explained in the page on the Weibull distribution. In this graph we have three examples with different k-values (shape factors).
The Availability Factor

The figures for annual energy output assume that wind turbines are operational and ready to run all the time. In practice, however, wind turbines need servicing and inspection once every six months to ensure that they remain safe. In addition, component failures and accidents (such as lightning strikes) may disable wind turbines. Very extensive statistics show that the best turbine manufacturers consistently achieve availability factors above 98 per cent, i.e. the machines are ready to run more than 98 per cent of the time. Total energy output is generally affected less than 2 per cent, since wind turbines are never serviced during high winds. Such a high degree of reliability is remarkable, compared to other types of machinery, including other electricity generating technologies. The availability factor is therefore usually ignored when doing economic calculations, since other uncertainties (e.g. wind variability) are far larger. Not all wind turbine manufacturers around the world have a good, long reliability record, however, so it is always a good idea to check the manufacturers' track record and servicing ability before you go out and buy a new wind turbine.
General cost comments

- Costs are roughly proportional to mass, that is to blade size for ‘small’ machines.
- Power extractable goes up as swept area and thus as the square of blade length.
- Thus increasing blade size is attractive.
- This is the case for $R < 60m, Cost_{Cap} \sim R, Cost_{Elec} \sim 1 \ R$
- When $R > 60m$ the gearbox cost dominates.
  Then $Cost_{Cap} \sim R^3$ and $Cost_{Elec} \sim R^2$
## 50 MW Wind Farm Cost

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Project total $76,455,000 U.S. Dollars
References

• www.windpower.org  Danish site, contains lots of background including nice animations

• Manwell J.F. et al “Wind Energy Explained”  
  ISBN 0 471 49972 2 (covers everything in lecture and lots more)

  ISBN 0 471 48997 2, more advanced (expensive)

• web sites of manufacturers e.g. www.vestas.com / www.enercon.de