Guided Tour on Wind Energy

Welcome to your own guided tour on wind energy.
Each of the nine tours is a self-contained unit, so you may take the tours in any order.
We suggest, however, that after the introduction you start with the first section on Wind Energy Resources, since it makes it much easier to understand the other sections.

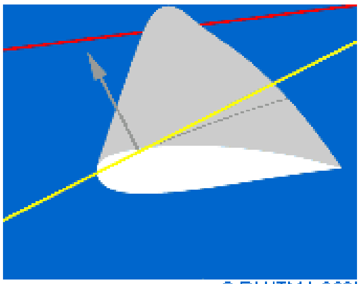
6. Modern Wind Turbines
7. Offshore Wind Turbines
8. Megawatt-Sized Wind Turbines
9. Multi-Megawatt Wind Turbines

We keep adding pages to this guided tour. We'll e-mail you when they are ready, if you register with our Mailing List.

Guided Tour

Updated 4 January 2001
http://www.windpower.dk/tour/index.htm

Quiz
Home



Read about Wind Energy
More than 100 animated pages and calculators on wind resources, wind turbine technology, economics, and environmental aspects of wind energy in the Guided Tour section.

NEW Annual Report The Danish Wind Turbine Manufacturers Association Annual Report 2000-2001 is now available. Click here to download.

Go Get It! You may download this web site (about 7 MB) in about 20 minutes with a 56 kB modem, so that you can read it at your own pace, without worrying about phone bills or slow Internet connections.

Try our search engine page, or type your query here, and click

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The calculators and plotter programmes in this web site require a Netscape 4.x, or Internet Explorer 4.x, or later browser to work, but you may read the text and the examples in any case. If you are using Navigator 3 or later or Internet Explorer 4 or later, and you see this message, you need to enable JavaScript. In Netscape, choose Options | Network Preferences, choose the Languages tab, and click Enable JavaScript. Then click reload on your browser. In Internet Explorer, choose Edit | Preferences | Java, and enable Java, select the Microsoft virtual machine, and enable the "Just in time compiler". Then click reload on your browser.

Updated 4 May 2001
http://www.windpower.org/core.htm

Introduction to the Guided Tours on Wind Energy

If You Want to Know a Lot

These guided tours are written for people who want to know a lot about wind energy, short of becoming wind engineers. They also answer most of the questions which students ask us - without going into difficult details of math and physics.

Even so, we also explore some of the challenging frontiers of wind energy technology. We are mostly concerned with commercial, large, grid connected turbines 100 kW and up.

If You Want to Know a Little

Take a look at the Frequently Asked Questions about wind energy and the Wind Energy Pictures.

If You just Want a Wind Turbine

You do not have to be an expert on thermodynamics to start a car engine and drive a car.

With a wind turbine it is even simpler: You don't have to buy fuel. It's there for free. If you want to know about the practical issues, like where do you place it, and what does it cost, then look at the following pages:

Frequently Asked Questions
Selecting a Wind Turbine Site
Wind Energy Economics
Wind Energy Pictures
Manufacturers

Offshore Tour

If you already know a lot about wind energy, you may wish to get acquainted with the new territory of offshore wind energy. In that case, follow the signposts: Offshore Tour to visit these eleven pages:

Offshore Wind Conditions
Offshore Wind Power Research
Wind Turbine Offshore Foundations
Offshore Foundations: Traditional Concrete
Offshore Foundations: Gravitation + Steel
Offshore Foundations: Mono Pile
Offshore Foundations: Tripod
Grid Connection of Offshore Wind Parks
The Economics of Offshore Wind Energy
Birds and Offshore Wind Turbines

Offshore Wind Turbine Pictures
You will return to this point after the Offshore Tour.

Other Tour Resources

After the tour, you might like to test your skills answering the quiz on wind energy.

In case you want to see unit definitions and other hard information, you may find it in the Reference Manual. In the Manual's Glossary page you may find Danish, German, Spanish, and French translations of specialist terms used in this guided tour, and references to where they are explained. Please note that this web site also exists in Danish and German.

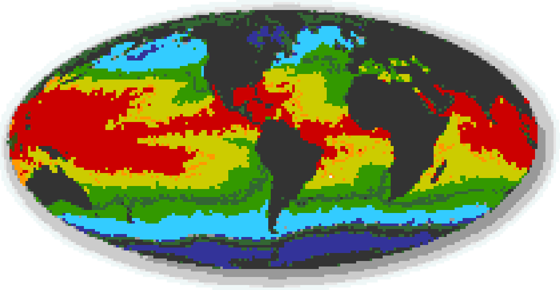
You may use the links below or on the top to navigate forward or back in the guided tour. You will return to the table of contents at the end of each one of the tours.

Where does Wind Energy come From?

All renewable energy (except tidal and geothermal power), and even the energy in fossil fuels, ultimately comes from the sun. The sun radiates 100,000,000,000,000 kilowatt hours of energy to the earth per hour. In other words, the earth receives 10 to the 18th power of watts of power.

About 1 to 2 per cent of the energy coming from the sun is converted into wind energy. That is about 50 to 100 times more than the energy converted into biomass by all plants on earth.

Temperature Differences Drive Air Circulation



The regions around equator, at 0 latitude are heated more by the sun than the rest of the globe. These hot areas are indicated in the warm colours, red, orange and yellow in this infrared picture of sea surface temperatures (taken from a NASA satellite, NOAA-7 in July 1984).

Hot air is lighter than cold air and will rise into the sky until it reaches approximately 10 km (6 miles) altitude and will spread to the North and the South. If the globe did not rotate, the air would simply arrive at the North Pole and the South Pole, sink down, and return to the equator.

The Coriolis Force

Since the globe is rotating, any movement on the Northern hemisphere is diverted to the right, if we look at it from our own position on the ground. (In the southern hemisphere it is bent to the left). This apparent bending force is known as the **Coriolis force**. (Named after the French mathematician Gustave Gaspard Coriolis 1792-1843).

It may not be obvious to you that a particle moving on the northern hemisphere will be bending towards the right.

Consider this red cone moving southward in the direction of the tip of the cone.

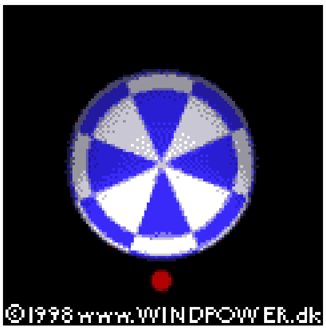
The earth is spinning, while we watch the spectacle from a camera fixed in outer space. The cone is moving straight towards the south.

Below, we show the same image with the camera locked on to the globe.

Look at the same situation as seen from a point above the North Pole. We have fixed the camera, so that it rotates with the earth.

Watch closely, and you will notice that the red cone is veering in a curve towards the right as it moves. The reason why it is not following the direction in which the cone is pointing is, of course, that we as observers are rotating along with the globe.

Below, we show the same image,with the camera fixed in outer space, while the earth rotates.



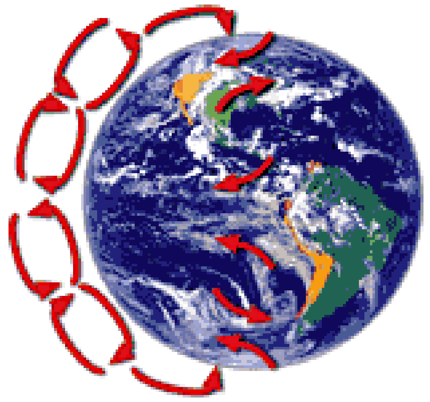
The Coriolis force is a visible phenomenon. Railroad tracks wear out faster on one side than the other. River beds are dug deeper on one side than the other. (Which side depends on which hemisphere we are in: In the Northern hemisphere moving particles are bent towards the right).

In the Northern hemisphere the wind tends to rotate counterclockwise (as seen from above) as it approaches a low pressure area. In the Southern hemisphere the wind rotates clockwise around low pressure areas.

On the next page we shall see how the Coriolis force affects the wind directions on the globe.

Wind Energy Resources: Global Winds

How the Coriolis Force Affects Global Winds



The wind rises from the equator and moves north and south in the higher layers of the atmosphere.
Around 30 latitude in both hemispheres the Coriolis force prevents the air from moving much farther. At this latitude there is a high pressure area, as the air begins sinking down again.
As the wind rises from the equator there will be a low pressure area close to ground level attracting winds from the North and South.
At the Poles, there will be high pressure due to the cooling of the air.
Keeping in mind the bending force of the Coriolis force, we thus have the following general results for the prevailing wind direction:

Prevailing Wind Directions

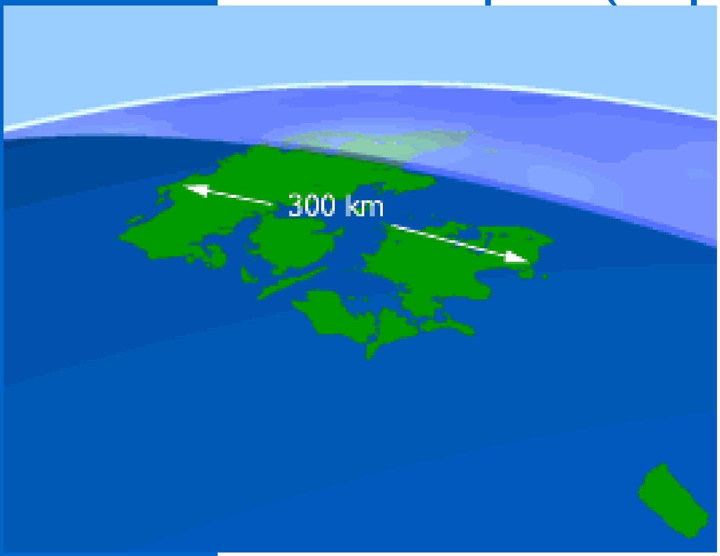
Latitude	90-60°N	60-30°N	30-0°N	0-30°S	30-60°S	60-90°S
Direction	NE	SW	NE	SE	NW	SE

The size of the atmosphere is grossly exaggerated in the picture above (which was made on a photograph from the NASA GOES-8 satellite). In reality the atmosphere is only 10 km thick, i.e. 1/1200 of the diameter of the globe. That part of the atmosphere is more accurately known as the **troposphere**. This is where all of our weather (and the greenhouse effect) occurs.

The prevailing wind directions are important when siting wind turbines, since we obviously want to place them in the areas with least obstacles from the prevailing wind directions. Local geography, however, may influence the general results in the table above, cf. the following pages.

The Geostrophic Wind

The Atmosphere (Troposphere)



The atmosphere around the globe is a very thin layer. The globe has a diameter of 12,000 km. The **troposphere,** which extends to about 11 km (36,000 ft.) altitude, is where all of our weather, and the greenhouse effect occurs. On the picture you can see at stretch of islands 300 km (200 miles) across, and the approximate height of the troposphere. To look at it at a different scale: If the globe were a ball with a diameter of 1.2 metres (4 ft.), the atmosphere would only be 1 mm (1/25") thick.

The Geostrophic Wind

The winds we have been considering on the previous pages on global winds are actually the **geostrophic winds**. The geostrophic winds are largely driven by temperature differences, and thus pressure differences, and are not very much influenced by the surface of the earth. The geostrophic wind is found at altitudes above 1000 metres (3300 ft.) above ground level.

The geostrophic wind speed may be measured using weather balloons.

Surface Winds

Winds are very much influenced by the ground surface at altitudes up to 100 metres. The wind will be slowed down by the earth's surface roughness and obstacles, as we will learn in a moment. Wind directions near the surface will be slightly different from the direction of the geostrophic wind because of the earth's rotation (cf. the Coriolis force).

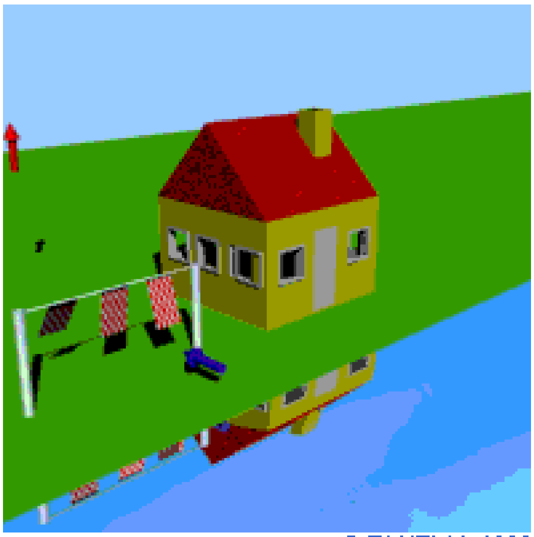
When dealing with wind energy, we are concerned with surface winds, and how to calculate the usable energy content of the wind.

Local Winds: Sea Breezes

Although global winds are important in determining the prevailing winds in a given area, local climatic conditions may wield an influence on the most common wind directions.

Local winds are always superimposed upon the larger scale wind systems, i.e. the wind direction is influenced by the sum of global and local effects. When larger scale winds are light, local winds may dominate the wind patterns.

Sea Breezes



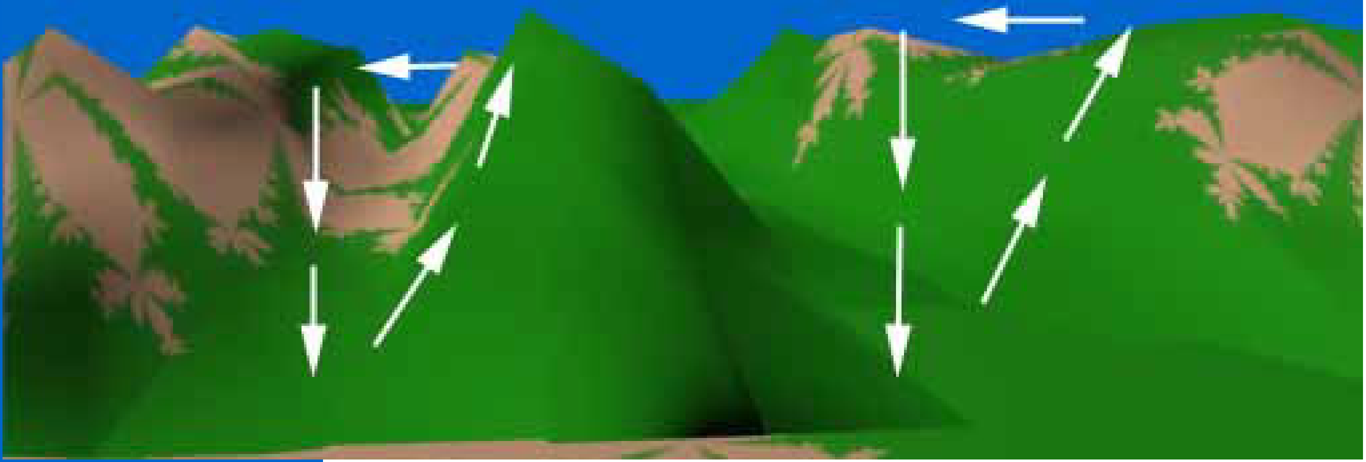
© DWTMA 1998

Land masses are heated by the sun more quickly than the sea in the daytime. The air rises, flows out to the sea, and creates a low pressure at ground level which attracts the cool air from the sea. This is called a **sea breeze**. At nightfall there is often a period of calm when land and sea temperatures are equal.

At night the wind blows in the opposite direction. The **land breeze** at night generally has lower wind speeds, because the temperature difference between land and sea is smaller at night.

The **monsoon** known from South-East Asia is in reality a large-scale form of the sea breeze and land breeze, varying in its direction between seasons, because land masses are heated or cooled more quickly than the sea.

Local Winds: Mountain Winds



Mountain regions display many interesting weather patterns.

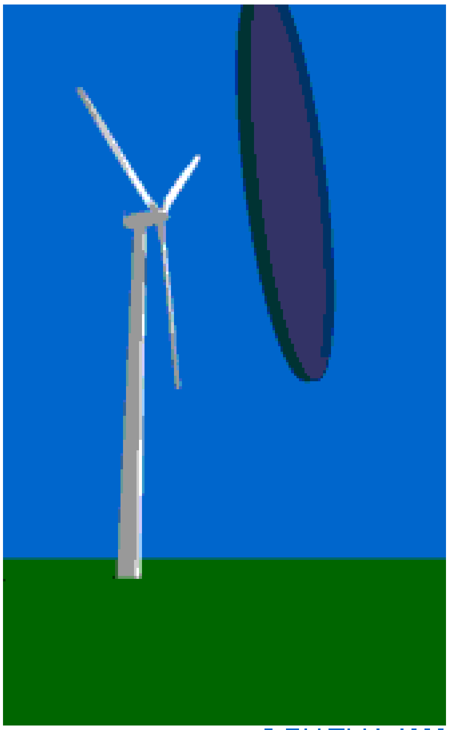
One example is the **valley wind** which originates on south-facing slopes (north-facing in the southern hemisphere). When the slopes and the neighbouring air are heated the density of the air decreases, and the air ascends towards the top following the surface of the slope. At night the wind direction is reversed, and turns into a downslope wind.

If the valley floor is sloped, the air may move down or up the valley, as a canyon wind.

Winds flowing down the leeward sides of mountains can be quite powerful: Examples are the Foehn in the Alps in Europe, the Chinook in the Rocky Mountains, and the Zonda in the Andes.

Examples of other local wind systems are the Mistral flowing down the Rhone valley into the Mediterranean Sea, the Scirocco, a southerly wind from Sahara blowing into the Mediterranean sea.

The Energy in the Wind: Air Density and Rotor Area



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A wind turbine obtains its power input by converting the force of the wind into a **torque** (turning force) acting on the rotor blades. The amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed.

The cartoon shows how a cylindrical slice of air 1 metre thick moves through the 1,500 m^2 rotor of a typical 600 kilowatt wind turbine.
With a 43 metre rotor diameter each cylinder actually weighs 1.9 tonnes, i.e. 1,500 times 1.25 kilogrammes.

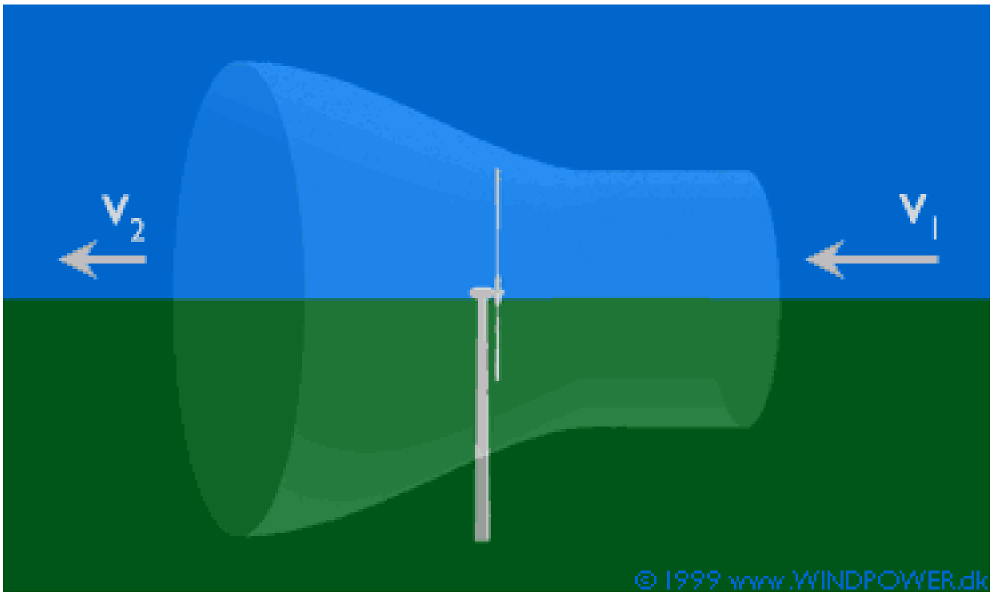
Density of Air

The kinetic energy of a moving body is proportional to its mass (or weight). The kinetic energy in the wind thus depends on the density of the air, i.e. its mass per unit of volume.
In other words, the "heavier" the air, the more energy is received by the turbine.
At normal atmospheric pressure and at 15 Celsius air weighs some 1.225 kilogrammes per cubic metre, but the density decreases slightly with increasing humidity.
Also, the air is denser when it is cold than when it is warm. At high altitudes, (in mountains) the air pressure is lower, and the air is less dense.

Rotor Area

A typical 600 kW wind turbine has a rotor diameter of 43-44 metres, i.e. a rotor area of some 1,500 square metres. The rotor area determines how much energy a wind turbine is able to harvest from the wind.
Since the rotor area increases with the **square** of the rotor diameter, a turbine which is twice as large will receive $2^2 = 2 \times 2 =$ **four** times as much energy. The page on the size of wind turbines gives you more details.

Wind Turbines Deflect the Wind



The image on the previous page on the energy in the wind is a bit simplified. In reality, a wind turbine will deflect the wind, even before the wind reaches the rotor plane. This means that we will never be able to capture all of the energy in the wind using a wind turbine. We will discuss this later, when we get to Betz' Law.

In the image above we have the wind coming from the right, and we use a device to capture part of the kinetic energy in the wind. (In this case we use a three bladed rotor, but it could be some other mechanical device).

The Stream Tube

The wind turbine rotor must obviously slow down the wind as it captures its kinetic energy and converts it into rotational energy. This means that the wind will be moving more slowly to the left of the rotor than to the right of the rotor.

Since the amount of air entering through the swept rotor area from the right (every second) must be the same as the amount of air leaving the rotor area to the left, the air will have to occupy a larger cross section (diameter) behind the rotor plane.

In the image above we have illustrated this by showing an imaginary tube, a so called **stream tube** around the wind turbine rotor. The stream tube shows how the slow moving wind to the left in the picture will occupy a large volume behind the rotor.

The wind will not be slowed down to its final speed immediately behind the rotor plane. The slowdown will happen gradually behind the rotor, until the speed becomes almost constant.

The Air Pressure Distribution in Front of and Behind the Rotor

The graph to the left shows the air pressure plotted vertically, while the horizontal axis indicates the distance from the rotor plane. The wind is coming from the right, and the rotor is in the middle of the graph.

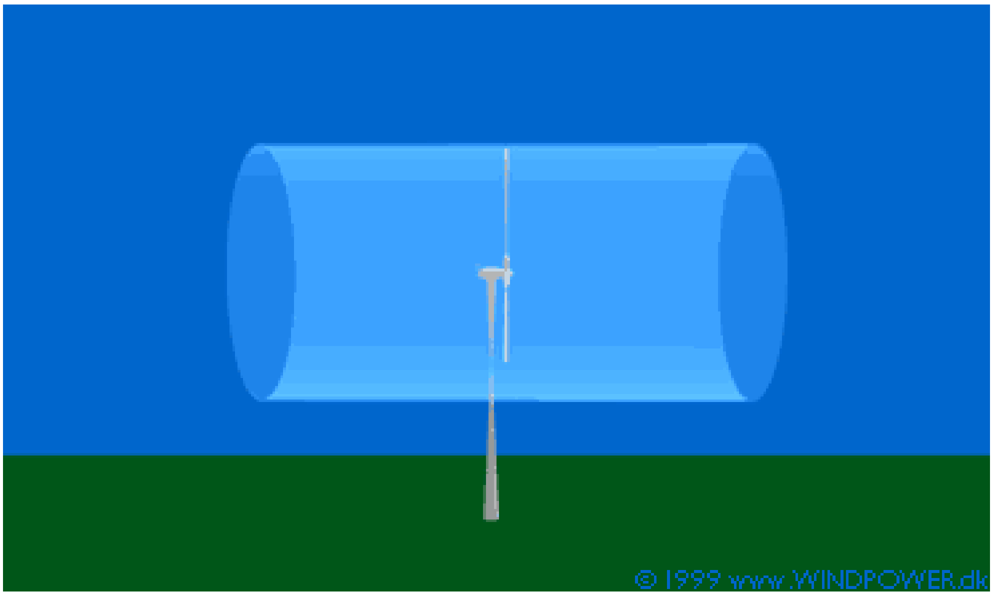
As the wind approaches the rotor from the right, the air pressure increases gradually, since the rotor acts as a barrier to the wind. Note, that the air pressure will drop immediately behind the rotor plane (to the left). It then gradually increases to the normal air pressure level in the area.

What Happens Farther Downstream?

If we move farther downstream the turbulence in the wind will cause the slow wind behind the rotor to mix with the faster moving wind from the surrounding area. The wind shade behind the rotor will therefore gradually diminish as we move away from the turbine. We will discus this further on the page about the park effect.

Why not a Cylindrical Stream Tube?

Now, you may object that a turbine would be rotating, even if we placed it within a normal, cylindrical tube, like the one below. Why do we insist that the stream tube is bottle-shaped?



Of course you would be right that the turbine rotor could turn if it were placed in a large glass tube like the one above, but let us consider what happens:

The wind to the left of the rotor moves with a lower speed than the wind to the right of the rotor. But at the same time we know that the volume of air entering the tube from the right each second must be the same as the volume of air leaving the tube to the left. We can therefore deduce that if we have some obstacle to the wind (in this case our rotor) within the tube, then some of the air coming from the right must be deflected from entering the tube (due to the high air pressure in the right ende of the tube).

So, the cylindrical tube is not an accurate picture of what happens to the wind when it meets a wind turbine. This picture at the top of the page is the correct picture.

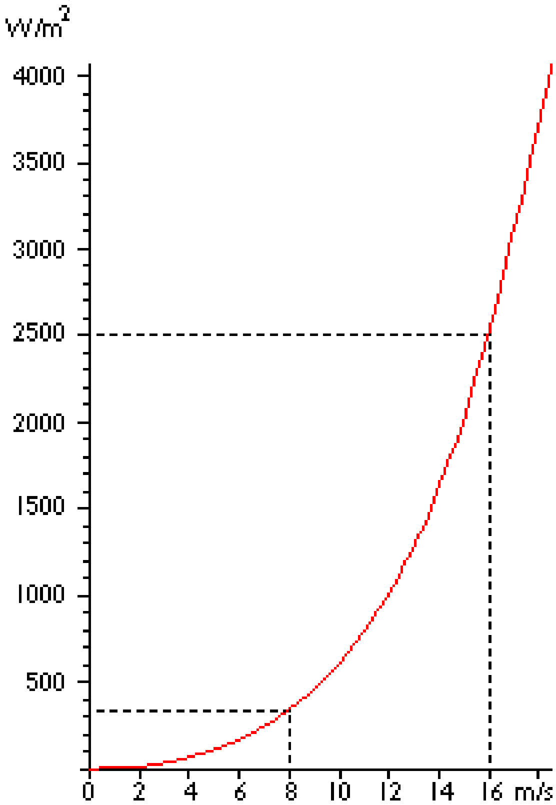
Updated 6 August 2000
http://www.windpower.org/tour/wres/tube.htm

The Power of the Wind: Cube of Wind Speed

The wind speed is extremely important for the amount of energy a wind turbine can convert to electricity: The energy content of the wind varies with the **cube** (the third power) of the average wind speed, e.g. if the wind speed is twice as high it contains $2^3 = 2 \times 2 \times 2 =$ **eight** times as much energy.

Now, why does the energy in the wind vary with the **third** power of wind speed? Well, from everyday knowledge you may be aware that if you **double** the speed of a car, it takes **four** times as much energy to brake it down to a standstill. (Essentially this is Newton's second law of motion).

In the case of the wind turbine we **use** the energy from braking the wind, and if we **double** the wind speed, we get **twice** as many slices of wind moving through the rotor every second, and each of those slices contains **four** times as much energy, as we learned from the example of braking a car.



The graph shows that at a wind speed of 8 metres per second we get a power (amount of energy per second) of 314 Watts per square metre exposed to the wind (the wind is coming from a direction perpendicular to the swept rotor area).

At 16 m/s we get eight times as much power, i.e. 2509 W/m². The table in the Reference Manual section gives you the power per square metre exposed to the wind for different wind speeds.

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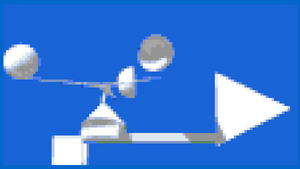

Wind Speed Measurement: Anemometers

The measurement of wind speeds is usually done using a cup anemometer, such as the one in the picture to the left. The cup anemometer has a vertical axis and three cups which capture the wind. The number of revolutions per minute is registered electronically.

Normally, the anemometer is fitted with a wind vane to detect the wind direction.

Instead of cups, anemometers may be fitted with propellers, although this is not common.

Other anemometer types include ultrasonic or laser anemometers which detect the phase shifting of sound or coherent light reflected from the air molecules. Hot wire anemometers detect the wind speed through minute temperature differences between wires placed in the wind and in the wind shade (the lee side).

The advantage of non-mechanical anemometers may be that they are less sensitive to icing. In practice, however, cup anemometers tend to be used everywhere, and special models with electrically heated shafts and cups may be used in arctic areas.

Quality Anemometers are a Necessity for Wind Energy Measurement

You often get what you pay for, when you buy something. That also applies to anemometers. You can buy surprisingly cheap anemometers from some of the major vendors in the business. They may be OK for meteorology, and they are OK to mount on a wind turbine, where a large accuracy is not really important.*) But cheap anemometers are **not** usable for wind speed measurement in the wind energy industry, since they may be very inaccurate and calibrated poorly, with measurement errors of maybe 5 per cent or even 10 per cent.

If you are planning to build a wind farm it may be an economic disaster if you have an anemometer which measures wind speeds with a 10% error. In that case, you may risk counting on an energy content of the wind which is $1.1^3 - 1 = 33\%$ higher than than it is in reality. If you have to recalculate your measurements to a different wind turbine hub height (say, from 10 to 50 m height), you may even multiply that error with a factor of 1.3, thus you end up with a 75% error on your energy calculation.

It is possible to buy a professional, well calibrated anemometer with a measurement error around 1% for about 700-900 USD. That is quite plainly peanuts compared to the risk of making a potentially disastrous economic error. Naturally, price may not always be a reliable indicator of quality, so ask someone from a well reputed wind energy research institution for advice on purchasing anemometers.

*) The anemometer on a wind turbine is really only used to determine whether there is enough wind to make it worthwhile to yaw the turbine rotor against the wind and start it.

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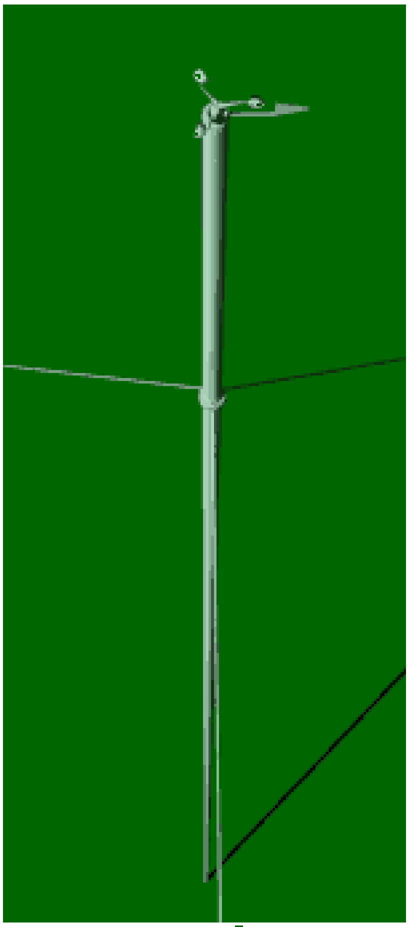
Wind Speed Measurement in Practice



The best way of measuring wind speeds at a prospective wind turbine site is to fit an anemometer to the top of a mast which has the same height as the expected hub height of the wind turbine to be used. This way one avoids the uncertainty involved in recalculating the wind speeds to a different height.

By fitting the anemometer to the **top** of the mast one minimises the disturbances of airflows from the mast itself. If anemometers are placed on the side of the mast it is essential to place them in the prevailing wind direction in order to minimise the wind shade from the tower.

Which Tower?

Guyed, thin cylindrical poles are normally preferred over lattice towers for fitting wind measurement devices in order to limit the wind shade from the tower.

The poles come as kits which are easily assembled, and you can install such a mast for wind measurements at (future) turbine hub height without a crane.

Anemometer, pole and data logger (mentioned below) will usually cost somewhere around 5,000 USD.

Data Logging

The data on both wind speeds and wind directions from the anemometer(s) are collected on electronic chips on a small computer, a **data logger**, which may be battery operated for a long period.

An example of such a data logger is shown to the left. Once a month or so you may need to go to the logger to collect the chips and replace them with blank chips for the next month's data. (Be warned: The most common mistake by people doing wind measurements is to mix up the chips and bring the blank ones back!)

Arctic Conditions

If there is much freezing rain in the area, or frost from clouds in mountains, you may need a heated anemometer, which requires an electrical grid connection to run the heater.

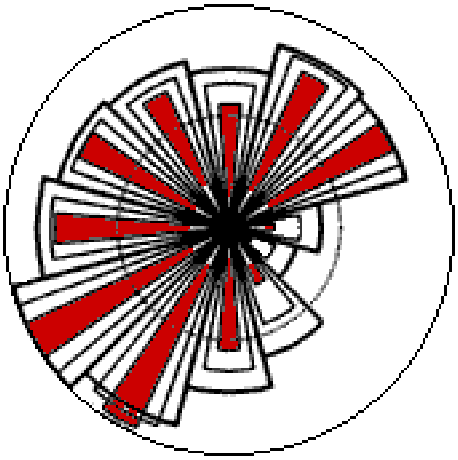
10 Minute Averages

Wind speeds are usually measured as **10 minute averages**, in order to be compatible with most standard software (and literature on the subject). The result for wind speeds are different, if you use different periods for averaging, as we'll see later.

NRG data logger
Photograph © 1998
by Soren Krohn

Updated 6 August 2000
http://www.windpower.org/tour/wres/wndsprac.htm

The Wind Rose



Wind rose from Brest France, taken from the European Wind Atlas, Ris National Laboratory Denmark

You will notice that strong winds usually come from a particular direction, as discussed in the Wind Energy Resource section.

To show the information about the distributions of wind speeds, and the frequency of the varying wind directions, one may draw a so-called **wind rose** on the basis of meteorological observations of wind speeds and wind directions.

The picture shows the wind rose for Brest, on the Atlantic coast of France.

We have divided the compass into 12 sectors, one for each 30 degrees of the horizon. (A wind rose may also be drawn for 8 or 16 sectors, but 12 sectors tend to be the standard set by the European Wind Atlas, from which this image was taken).

The radius of the 12 outermost, wide wedges gives the relative frequency of each of the 12 wind directions, i.e. how many per cent of the time is the wind blowing from that direction.

The second wedge gives the same information, but multiplied by the average wind speed in each particular direction. The result is then normalised to add up to 100 per cent. This tells you how much each sector contributes to the average wind speed at our particular location.

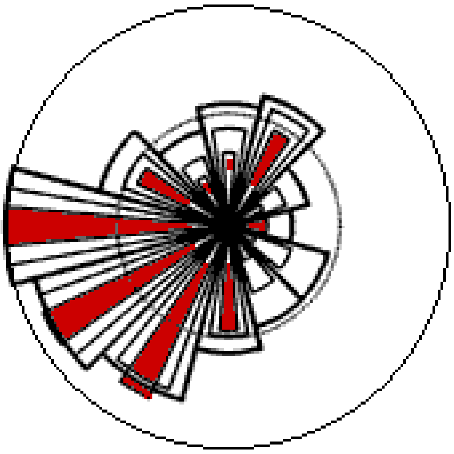
The innermost (red) wedge gives the same information as the first, but multiplied by the cube of the wind speed in each particular location. The result is then normalised to add up to 100 per cent. This tells you how much each sector contributes to the energy content of the wind at our particular location.

Remember, that the energy content of the wind varies with the cube of the wind speed, as we discussed in the page on The Energy in the Wind. So the red wedges are really the most interesting ones. They tell us where to find the most power to drive our wind turbines.

In this case we can see that the prevailing wind direction is Southwest, just as we would have predicted from the page on Global Winds.

A wind rose gives you information on the **relative** wind speeds in different directions, i.e.each of the three sets of data (frequency, mean wind speed, and mean cube of wind speed) has been multiplied by a number which ensures that the largest wedge in the set exactly matches the radius of the outermost circle in the diagram.

Wind Roses Vary



Wind roses vary from one location to the next. They actually are a form of meteorological fingerprint.

As an example, take a look at this wind rose from Caen, France, only about 150 km (100 miles) North of Brest. Although the primary wind direction is the same, Southwest, you will notice that practically all of the wind energy comes from West and Southwest, so on this site we need not concern ourselves very much about other wind directions.

Wind roses from neighbouring areas are often fairly similar, so in practice it may sometimes be safe to interpolate (take an average) of the wind roses from surrounding observations. If you have complex terrain, i.e. mountains and valleys running in different directions, or coastlines facing in different directions, it is generally **not** safe to make simple assumptions like these.

The wind rose, once again, only tells you the **relative** distribution of wind directions, not the actual level of the mean wind speed.

How to Use the Wind Rose

A look at the wind rose is extremely useful for siting wind turbines. If a large share of the energy in the wind comes from a particular direction, then you will want to have as few obstacles as possible, and as smooth a terrain as possible in that direction, when you place wind turbines in the landscape.

In these examples most of the energy comes from the Southwest. We therefore need not be very concerned about obstacles to the East or Southeast of wind turbines, since practically no wind energy would come from those directions.

You should note, however, that wind patterns may vary from year to year, and the energy content may vary (typically by some ten per cent) from year to year, so it is best to have observations from several years to make a credible average. Planners of large wind parks will usually rely on one year of local measurements, and then use long-term meteorological observations from nearby weather stations to adjust their measurements to obtain a reliable long term average.

Since this wind rose comes from the European Wind Atlas we are reasonably confident that we can rely on it. The European Wind Atlas contains a description of each of the measurement stations, so we may be warned about possible local disturbances to the airflow. On the page on selecting a wind turbine site, we return to the pitfalls in using meteorology data.

Wind Rose Plotter Programme

Calculator

Plot your own wind rose

Wind frequency	Mean wind speed
6.7	5.85
5.0	5.67
8.5	6.75
7.5	7.19
7.7	6.84
7.7	5.93
7.9	5.76
9.2	5.85
14.5	7.35
14.5	6.47
6.7	6.38
4.1	5.76
0	0
0	0
0	0
0	0

This calculator requires a Netscape 4 or IE 4 or later browser to work. If you are using Navigator 4 or later or Internet Explorer 4 or later, and you see this message, you need to enable JavaScript. In Netscape, choose Options | Network Preferences, choose the Languages tab, and click Enable JavaScript. Then click reload on your browser. In Internet Explorer, choose Edit | Preferences | Java, and enable Java, select the Microsoft virtual machine, and enable the "Just in time compiler". Then click reload on your browser. Do not operate the form until this page and its programme have loaded completely.

The explanation of the wind rose may be found on the previous page. The Wind Frequency is the percentage of the time the wind is coming from a particular direction. The first row in the table to the left corresponds to North (the top wedge). The subsequent rows correspond to the sectors of the wind rose in a clockwise direction.

Use 12 Sectors. Fill wedges. Reset to Copenhagen data.

☑ Show wind frequency.

☑ Show wind speed.

☑ Show wind energy.

For each of the sectors the outermost (blue) wedges show the wind frequency distribution.

The middle (black) wedges show the distribution of the product of the two columns, i.e. the wind speeds times their frequency.

The innermost (red) wedges show the distribution of the wind speeds cubed (i.e. the energies) multiplied by their frequencies.

Updated 9 September 2000
http://www.windpower.org/tour/wres/roseplot.htm

Roughness and Wind Shear

High above ground level, at a height of about 1 kilometre, the wind is hardly influenced by the surface of the earth at all. In the lower layers of the atmosphere, however, wind speeds are affected by the friction against the surface of the earth. In the wind industry one distinguishes between the **roughness** of the terrain, the influence from obstacles, and the influence from the terrain contours, which is also called the **orography** of the area. We shall be dealing with orography, when we investigate so called **speed up effects**, i.e. tunnel effects and hill effects, later.

Roughness

In general, the more pronounced the roughness of the earth's surface, the more the wind will be slowed down.

Forests and large cities obviously slow the wind down considerably, while concrete runways in airports will only slow the wind down a little. Water surfaces are even smoother than concrete runways, and will have even less influence on the wind, while long grass and shrubs and bushes will slow the wind down considerably.

Roughness Classes and Roughness Lengths

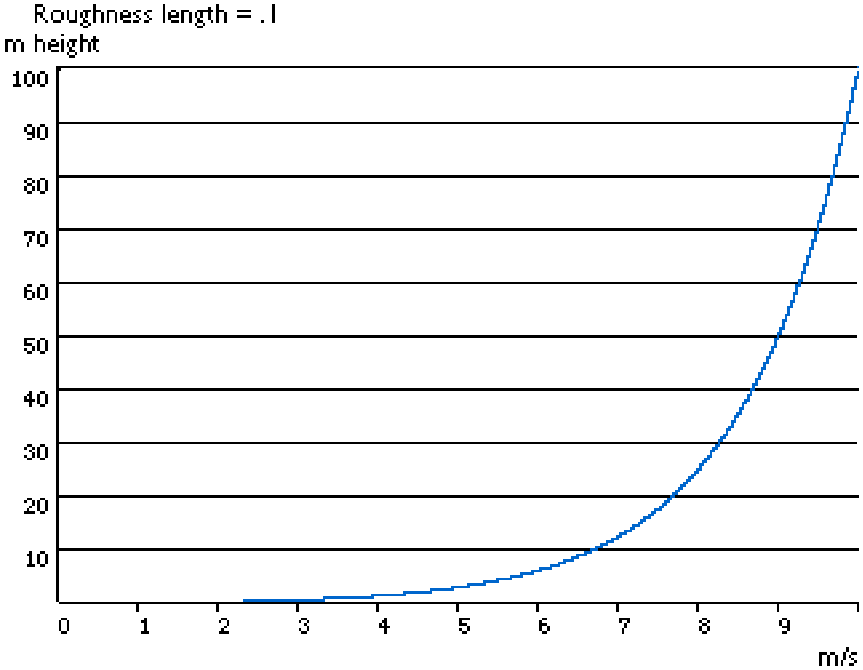
In the wind industry, people usually refer to **roughness classes** or **roughness lengths**, when they evaluate wind conditions in a landscape. A high roughness class of 3 to 4 refers to landscapes with many trees and buildings, while a sea surface is in roughness class 0.

Concrete runways in airports are in roughness class 0.5. The same applies to the flat, open landscape to the left which has been grazed by sheep.

The proper definition of roughness classes and roughness lengths may be found in the Reference Manual. The term roughness length is really the distance above ground level where the wind speed theoretically should be zero.

Sheep are a wind turbine's best friend. In this picture from Akaroa Spit, New Zealand, the sheep keep the roughness of the landscape down through their grazing. Photograph © 1998 Soren Krohn

Wind Shear



This graph was plotted with the wind speed calculator on the next page. It shows you how wind speeds vary in roughness class 2 (agricultural land with some houses and sheltering hedgerows with some 500 m intervals), if we assume that the wind is blowing at 10 m/s at a height of 100 metres.

The fact that the wind profile is twisted towards a lower speed as we move closer to ground level, is usually called **wind shear**. Wind shear may also be important when designing wind turbines. If you consider a wind turbine with a hub height of 40 metres and a rotor diameter of 40 metres, you will notice that the wind is blowing at 9.3 m/s when the tip of the blade is in its uppermost position, and only 7.7 m/s when the tip is in the bottom position. This means that the forces acting on the rotor blade when it is in its top position are far larger than when it is in its bottom position.

Updated 6 August 2000
http://www.windpower.org/tour/wres/shear.htm

www.WINDPOWER.org
Danish Wind Turbine Manufacturers Association

Guided Tour

Wind Speed Calculator

Calculator

This calculator requires a Netscape 3, IE 4, or later browser to work, but you may read the text and the examples in any case. If you are using Navigator 3, IE 4, or later and you see this message, you need to enable JavaScript. Choose Options | Network Preferences, choose the Languages tab, and click Enable JavaScript. Then click reload on your browser. Do not operate the form until this page and its programme have loaded completely.

Enter your wind speed measurement in any column at the appropriate height, e.g. 10 metres. Then click outside the field, click Submit, or use the tab key. The programme will then calculate wind speeds for other heights. You may plot your results in a separate window by clicking on **Plot** in the appropriate column. (If the plot window disappears, it is probably hidden behind this window).

Roughness							
- class	0.0	0.5	1.0	1.5	2.0	3.0	4.0
- length m	0.0002	0.0024	0.03	0.055	0.1	0.4	1.6
100 m	10	10	10	10	10	10	10
90 m	9.92	9.9	9.87	9.86	9.85	9.81	9.75
80 m	9.83	9.79	9.72	9.7	9.68	9.6	9.46
70 m	9.73	9.66	9.56	9.52	9.48	9.35	9.14
60 m	9.61	9.52	9.37	9.32	9.26	9.07	8.76
50 m	9.47	9.35	9.15	9.08	9	8.74	8.32
40 m	9.3	9.14	8.87	8.78	8.67	8.34	7.78
30 m	9.08	8.87	8.52	8.4	8.26	7.82	7.09
20 m	8.77	8.49	8.02	7.86	7.67	7.09	6.11
10 m	8.25	7.84	7.16	6.93	6.67	5.83	4.43
	Plot	Plot	Plot	Plot	Plot	Plot	Plot

Reset to Example

Average wind speeds are often available from meteorological observations measured at a height of 10 metres. Hub heights of modern 600 to 1,500 kW wind turbines are usually 40 to 80 metres, however. The spreadsheet will calculate average wind speeds at different heights and roughness classes. Just enter a wind speed measured at a certain height for a given roughness class and click the **Submit** button.

Please note, that the results are not strictly valid if there are obstacles close to the wind turbine (or the point of meteorological measurement) at or above the specified hub height. ["close" means anything up to one kilometre]. Take a look at the example below the table to make sure you understand how it works, before you start entering your data. More accurate and extensive roughness definitions may be found in the units section.

An Example

As an example, have a look at the spreadsheet above. We have already entered 10 m/s at 100 metre height. You will notice that the wind speed declines as you approach ground level. You will also notice that it declines more rapidly in rough terrain.

Remember, that the energy content of the wind varies with the **third** power of the wind speed. If you look at the column with roughness class 2, you will see that wind speeds declines 10 per cent going from 100 metres to 50 metres. But the power of the wind declines to $0.9^3 = 0.73$, i.e. by 27 per cent. (From 613 to 447 W/m^2).

If you compare the wind speeds below 100 m in roughness class 2 with roughness class 1, you will notice that for a given height the wind speeds are lower everywhere in roughness class 2.

If you have a wind turbine in roughness class 2, you may consider whether it is worthwhile to invest 15,000 USD extra to get a 60 metre tower instead of a 50 metre tower. In the table you can see that it will give you 2.9 per cent more wind, and you can calculate, that it will give you 9 per cent more wind energy.

You can solve this problem once you have learned how the turbine electricity production varies with the available wind energy. We will return to that question when you have learned to use the power density calculator and the wind energy economics calculator.

Now, try the calculator for yourself.

Updated 9 September 2000
http://www.windpower.org/tour/wres/calculat.htm

Wind Shear and Escarpments

Aerial photograph
© 1999 Soren Krohn

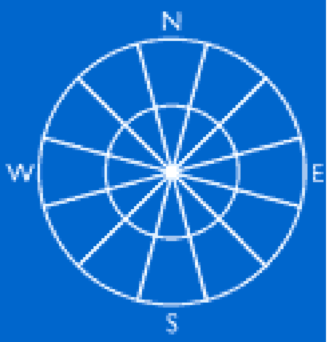
Do not Include the Altitude of Your Terrain in Wind Shear Calculations

The aerial photograph above shows a good site for wind turbines along a shoreline with the turbines standing on a cliff which is about 10 m (30 ft.) tall. It is a common mistake to believe that in this case one may add the height of the cliff to the height of the wind turbine tower to obtain the effective height of the wind turbine, when one is doing wind speed calculations, at least when the wind is coming from the sea.

This is patently wrong. The cliff in the front of the picture will create turbulence, and brake the wind even before it reaches the cliff. It is therefore not a good idea to move the turbines closer to the cliff. That would most likely lower energy output, and cause a lower lifetime for the turbines, due to more tear and wear from the turbulence.

If we had the choice, we would much rather have a nicely rounded hill in the direction facing the sea, rather than the escarpment you see in the picture. In case of a rounded hill, we might even experience a speed up effect, as we explain later when we get to the page on the hill effect.

The Roughness Rose



If we have measured the wind speed exactly at hub height over a long period at the exact spot where a wind turbine will be standing we can make very exact predictions of energy production. Usually, however, we have to recalculate wind measurements made somewhere else in the area. In practice, that can be done with great accuracy, except in cases with very complex terrain (i.e. very hilly, uneven terrain).

Just like we use a wind rose to map the amount of wind energy coming from different directions, we use a **roughness rose** to describe the roughness of the terrain in different directions from a prospective wind turbine site.

Normally, the compass is divided into 12 sectors of 30 degrees each, like in the picture to the left, but other divisions are possible. In any case, they should match our wind rose, of course.

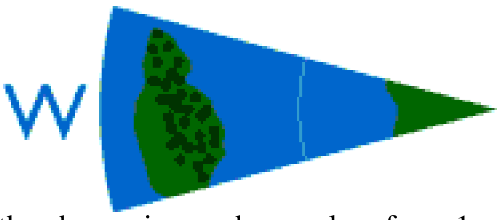
For each sector we make an estimate of the roughness of the terrain, using the definitions from the Reference Manual section. In principle, we could then use the wind speed calculator on the previous page to estimate for each sector how the average wind speed is changed by the different roughness of the terrain.

Averaging Roughness in Each Sector

In most cases, however, the roughness will not fall neatly into any of the roughness classes, so we'll have to do a bit of averaging. We have to be very concerned with the roughness in the prevailing wind directions. In those directions we look at a map to measure how far away we have unchanged roughness.

Accounting for Roughness Changes Within Each Sector

Let us imagine that we have a sea or lake surface in the western sector (i.e. roughness class 0) some 400 m from the turbine site, and 2 kilometres away we have a forested island. If west is an important wind direction, we will definitely have to account for the change in roughness class from 1 to 0 to 3.



This requires more advanced models and software than what we have shown on this web site. It is also useful to be able to use the software to manage all our wind and turbine data, so at a future update of this site we'll explain how professional wind calculation software works.

Meanwhile, you may look at the Links page to find the link to Risoe's WAsP model and Energy & Environmental Data's WindPro Windows-based software.

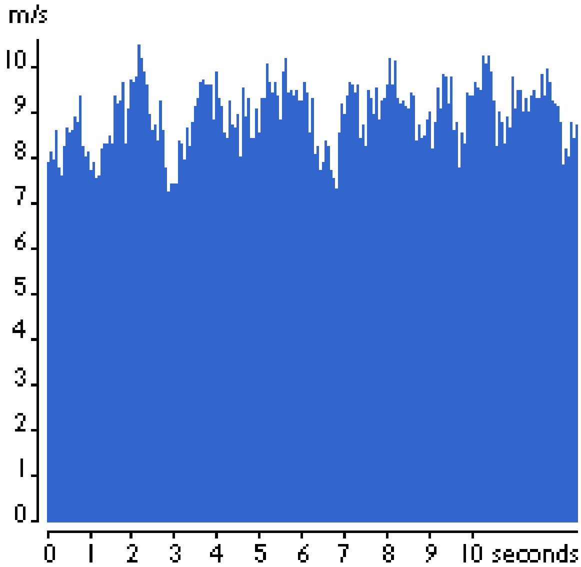
Accounting for Wind Obstacles

It is extremely important to account for local wind obstacles in the prevailing wind direction near the turbine (closer than 700 m or so), if one wants to make accurate predictions about energy output. We return to that subject after a couple of pages.

Updated 9 September 2000
http://www.windpower.org/tour/wres/rrose.htm

Wind Speed Variability

Short Term Variability of the Wind

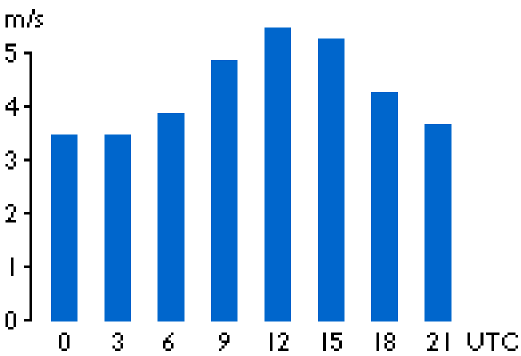


The wind speed is always fluctuating, and thus the energy content of the wind is always changing.

Exactly how large the variation is depends both on the weather and on local surface conditions and obstacles.

Energy output from a wind turbine will vary as the wind varies, although the most rapid variations will to some extent be compensated for by the inertia of the wind turbine rotor.

Diurnal (Night and Day) Variations of the Wind



In most locations around the globe it is more windy during the daytime than at night. The graph to the left shows how the wind speed at Beldringe, Denmark varies by 3 hour intervals round the clock. (Information from the European Wind Atlas).

This variation is largely due to the fact that temperature differences e.g. between the sea surface and the land surface tend to be larger during the day than at night. The wind is also more turbulent and tends to change direction more frequently during the day than at night.

From the point of view of wind turbine owners, it is an advantage that most of the wind energy is produced during the daytime, since electricity consumption is higher than at night. Many power companies pay more for the electricity produced during the peak load hours of the day (when there is a shortage of cheap generating capacity). We will return to this subject in the section on Wind Turbines in the Electrical grid.

Seasonal Variations of the Wind

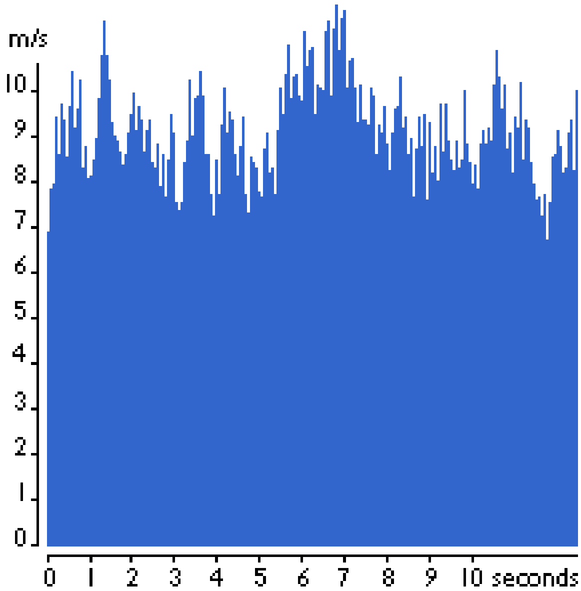
We treat this subject in the section on Wind Turbines in the Electrical grid.

Home

Guided Tour

Updated 6 August 2000
http://www.windpower.org/tour/wres/variab.htm

Turbulence



You have probably experienced how hailstorms or thunderstorms in particular, are associated with frequent **gusts** of wind which both change speed and direction.

In areas with a very uneven terrain surface, and behind obstacles such as buildings there is similarly created a lot of **turbulence**, with very irregular wind flows, often in whirls or vortexes in the neighbourhood.

You can see an example of how turbulence increases the fluctuations in the wind speed in the image, which you may compare with the image on the previous page.

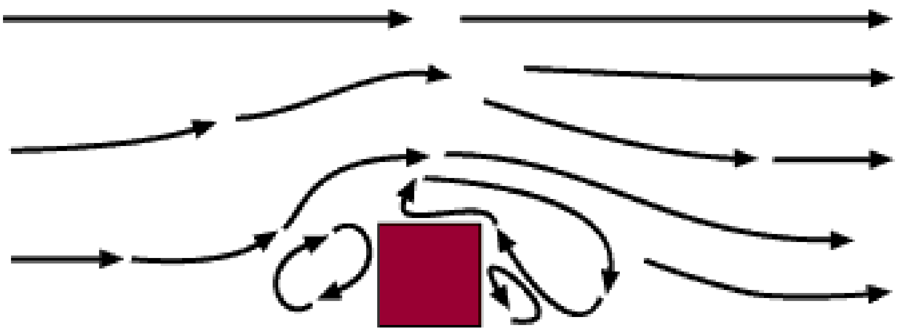
Turbulence decreases the possibility of using the energy in the wind effectively for a wind turbine. It also imposes more tear and wear on the wind turbine, as explained in the section on fatigue loads. Towers for wind turbines are usually made tall enough to avoid turbulence from the wind close to ground level.

Wind Obstacles

This movie was shot at a coastal wind site with the wind coming from the right side of the picture. It shows an interesting phenomenon:

We would really expect the wind turbine to the right (which is facing the wind directly) to be the one to start first when the wind starts blowing. But you can see, that the wind turbine to the right will not start at the low wind speeds which are sufficient to drive the other two wind turbines. The reason is the small wood in front of the wind turbines which shelters the rightmost turbine in particular. In this case, the annual production of these wind turbines is probably reduced by some 15 per cent on average, and even more in case of the rightmost turbine.

(The turbines are located some five rotor diameters apart, and the wood is located at a similar distance from the first wind turbine. The reason why the turbines look like they are standing very close together, is that the movie was shot from about a mile away with the equivalent of a 1200 mm lens for a 35 mm camera).



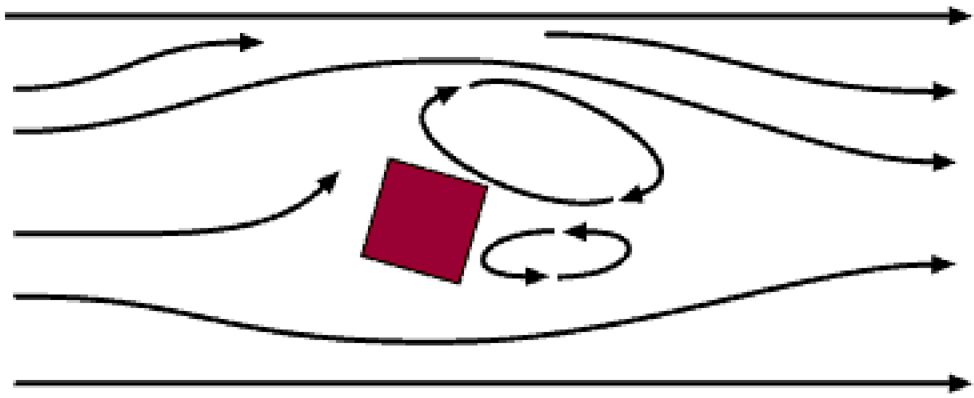
Side view of wind flow around an obstacle. Note the pronounced turbulent airflow downstream

Obstacles to the wind such as buildings, trees, rock formations etc. can decrease wind speeds significantly, and they often create turbulence in their neighbourhood.

As you can see from this drawing of typical wind flows around an obstacle, the turbulent zone may extend to some three time the height of the obstacle. The turbulence is more pronounced behind the obstacle than in front of it.

Therefore, it is best to avoid major obstacles close to wind turbines, particularly if they are upwind in the prevailing wind direction, i.e. "in front of" the turbine.

Top view of wind flow around an obstacle.



Shelter Behind Obstacles

Obstacles will decrease the wind speed downstream from the obstacle. The decrease in wind speed depends on the **porosity** of the obstacle, i.e. how "open" the obstacle is. (Porosity is defined as the open area divided by the total area of the object facing the wind).

A building is obviously solid, and has no porosity, whereas a fairly open tree in winter (with no leaves) may let more than half of the wind through. In summer, however, the foliage may be very dense, so as to make the porosity less than, say one third.

The slowdown effect on the wind from an obstacle increases with the height and length of the obstacle. The effect is obviously more pronounced close to the obstacle, and close to the ground.

When manufacturers or developers calculate the energy production for wind turbines, they always take obstacles into account if they are close to the turbine - say, less than 1 kilometre away in one of the more important wind directions.

Updated 23 January 2001
http://www.windpower.org/tour/wres/obst.htm

Wind Shade

Wind Speed in per cent of Wind Speed Without Obstacle

m height	21	43	64	86	107	129	150	171	193	214	236	257	279	300	321	343	364	386	407	429	450 m
75	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	99	99	99	99
73	100	100	100	100	100	100	100	100	100	100	100	100	100	100	99	99	99	99	99	99	99
70	100	100	100	100	100	100	100	100	100	100	100	99	99	99	99	99	99	99	99	99	99
68	100	100	100	100	100	100	100	100	100	99	99	99	99	99	99	99	99	99	99	99	99
65	100	100	100	100	100	100	100	100	99	99	99	99	99	99	99	99	99	99	99	99	99
63	100	100	100	100	100	100	100	99	99	99	99	99	99	99	99	99	99	99	99	99	99
60	100	100	100	100	100	100	99	99	99	99	99	99	99	98	98	98	98	98	98	98	98
58	100	100	100	100	100	99	99	99	99	98	98	98	98	98	98	98	98	98	98	98	98
55	100	100	100	100	100	99	99	98	98	98	98	98	98	98	98	98	98	98	98	98	98
53	100	100	100	100	99	99	98	98	98	97	97	97	97	97	97	97	97	97	98	98	98
50	100	100	100	99	99	98	98	97	97	97	97	97	97	97	97	97	97	97	97	97	97
48	100	100	100	99	98	98	97	96	96	96	96	96	96	96	96	96	96	97	97	97	97
45	100	100	99	99	98	97	96	95	95	95	95	95	95	95	95	96	96	96	96	97	97
43	100	100	99	98	96	95	94	94	93	93	94	94	94	94	95	95	95	96	96	96	96
40	100	100	98	96	95	93	93	92	92	92	92	93	93	94	94	94	95	95	95	96	96
38	100	99	97	95	93	91	90	90	90	90	91	91	92	93	93	94	94	95	95	95	96
35	100	98	95	92	90	88	88	87	87	88	89	90	91	92	92	93	94	94	94	95	95
33	100	97	92	88	86	85	84	84	85	86	87	89	90	91	91	92	93	93	94	94	95
30	99	94	87	83	81	80	81	81	82	84	86	87	88	90	91	92	92	93	94	94	95
28	99	89	81	76	75	75	76	78	79	81	84	86	87	89	90	91	92	93	93	94	94
25	96	81	71	68	68	70	72	74	76	79	82	84	86	88	89	90	91	92	93	94	94
23	90	68	59	58	60	63	67	70	73	77	80	83	85	87	89	90	91	92	93	93	94
20	78	48	43	46	52	57	63	67	71	75	79	82	85	87	88	90	91	92	93	94	94
18	52	21	24	34	43	52	59	65	69	74	79	82	85	87	88	90	91	92	93	94	94
15	4		4	22	36	48	56	63	69	74	79	82	85	87	89	90	91	92	93	94	95
13				13	32	46	56	63	69	75	79	83	86	88	90	91	92	93	94	94	95
10				9	32	47	58	65	71	77	81	85	87	89	91	92	93	94	95	95	96
8				14	38	53	63	70	75	80	84	87	89	91	92	93	94	95	96	96	97
5				31	51	63	72	78	82	85	88	91	92	94	94	95	96	96	97	97	98
3			36	60	72	80	84	88	90	92	94	95	96	97	97	98	98	98	98	99	99

= Obstacle 20 m tall

= Turbine Tower 50 m tall

Roughness length = 0.055, Porosity = 0; Obstacle length = 60 m

Note: Vertical and horizontal scales are different. Horizontal scale shows distance from obstacle

This graph gives you an estimate of how wind speeds decrease behind a blunt obstacle, i.e. an obstacle which is not nicely streamlined. In this case we use a seven story office building, 20 metres tall and 60 metres wide placed at a distance of 300 m from a wind turbine with a 50 m hub height. You can quite literally see the wind shade as different shades of grey. The blue numbers indicate the wind speed in per cent of the wind speed without the obstacle.

At the top of the yellow wind turbine tower the wind speed has decreased by some 3 per cent to 97 per cent of the speed without the obstacle. You should note that this means a loss of wind energy of some 10 per cent, i.e. $1.03^3 - 1$, as you may see in the graph at the bottom of this page.

If you have a reasonably fast computer (or a bit of patience with a slower one) you can plot tables and graphs like this one using the wind shade calculator in a couple of pages.

Wind Energy in per cent of Wind Energy Without Obstacle

m height	21	43	64	86	107	129	150	171	193	214	236	257	279	300	321	343	364	386	407	429	450 m
75	100	100	100	100	100	100	100	100	100	99	99	99	99	99	99	99	99	98	98	98	98
73	100	100	100	100	100	100	100	100	99	99	99	99	99	99	98	98	98	98	98	98	98
70	100	100	100	100	100	100	100	99	99	99	99	98	98	98	98	98	98	98	98	98	98
68	100	100	100	100	100	100	99	99	99	98	98	98	98	98	97	97	97	97	97	97	97
65	100	100	100	100	100	100	99	99	98	98	98	97	97	97	97	97	97	97	97	97	97
63	100	100	100	100	100	99	99	98	98	97	97	97	96	96	96	96	96	96	96	96	96
60	100	100	100	100	99	99	98	98	97	96	96	96	96	95	95	95	95	95	95	95	95
58	100	100	100	100	99	98	98	97	96	95	95	95	95	94	94	94	94	94	95	95	95
55	100	100	100	99	99	98	97	96	95	94	94	93	93	93	93	93	93	94	94	94	94
53	100	100	100	99	98	97	95	94	93	92	92	92	92	92	92	92	92	93	93	93	93
50	100	100	100	98	97	95	93	92	91	90	90	90	90	90	91	91	91	91	92	92	92
48	100	100	99	97	95	93	91	89	88	88	88	88	88	88	89	89	90	90	91	91	91
45	100	100	98	96	93	90	88	86	85	85	85	85	86	87	87	88	88	89	89	90	90
43	100	99	97	93	90	86	84	82	81	81	82	83	84	84	85	86	87	87	88	89	89
40	100	99	95	90	85	82	79	78	77	77	79	80	81	82	83	84	85	86	87	88	88
38	100	98	91	85	79	76	74	72	72	73	75	76	78	80	81	82	83	85	86	86	87
35	100	95	86	78	72	69	67	67	67	68	71	73	75	77	79	80	82	83	84	85	86
33	99	91	78	69	63	61	60	60	61	64	67	70	72	74	77	78	80	82	83	84	85
30	98	83	67	57	53	52	52	53	55	59	63	66	69	72	75	77	79	80	82	83	85
28	96	71	53	45	42	43	44	47	50	54	59	63	67	70	73	75	77	79	81	83	84
25	89	53	36	31	31	34	37	40	44	50	55	60	64	68	71	74	76	78	80	82	84
23	74	31	20	19	22	26	30	35	40	46	52	58	62	66	70	73	76	78	80	82	83
20	47	11	8	10	14	19	25	30	36	43	50	56	61	65	69	72	75	78	80	82	83
18	14	1	1	4	8	14	20	27	33	41	48	55	60	65	69	73	76	78	80	82	84
15				1	5	11	18	25	32	40	48	55	61	66	70	73	76	79	81	83	85
13					3	10	17	25	33	42	50	57	63	68	72	75	78	80	83	84	86
10					3	10	19	28	36	45	54	60	66	71	75	78	80	83	85	86	88
8					5	15	25	34	43	52	60	66	71	75	79	82	84	86	87	89	90
5				3	13	26	37	47	55	62	69	74	78	82	84	87	88	90	91	92	93
3			5	21	37	50	60	67	73	78	82	86	88	90	91	93	94	94	95	96	96

= Obstacle 20 m tall   = Turbine Tower 50 m tall

Roughness length = 0.055, Porosity = 0; Obstacle length = 60 m

Note: Vertical and horizontal scales are different. Horizontal scale shows distance from obstacle

Updated 9 September 2000

http://www.windpower.org/tour/wres/shade.htm

Guide to the Wind Shade Calculator

Even if you do not have a Netscape 3 or Internet Explorer 4 browser, this page will give you a lot of useful knowledge on how obstacles affect the energy in the wind.

The calculator will quickly give you the result at hub height at the distance from the obstacle you specify. If you use the plot facility, your computer will also calculate 620 different measurement points at different heights and distances from your obstacle.

Turbine Hub Height

The higher you are above the top of the obstacle, the less wind shade. The wind shade, however, may extend to up to five times the height of the obstacle at a certain distance.

If the obstacle is taller than half the hub height, the results are more uncertain, because the detailed geometry of the obstacle, (e.g. differing slopes of the roof on buildings) will affect the result. In that case the programme will put a warning in the text box below the results.

Distance Between Obstacle and Turbine

The distance between the obstacle and the turbine is very important for the shelter effect. In general, the shelter effect will decrease as you move away from the obstacle, just like a smoke plume becomes diluted as you move away from a smokestack. In terrain with very low roughness (e.g. water surfaces) the effect of obstacles (e.g. an island) may be measurable up to 20 km away from the obstacle.

If the turbine is closer to the obstacle than five times the obstacle height, the results will be more uncertain, because they will depend on the exact geometry of the obstacle. In that case the programme will put a warning in the text box below the results.

Roughness Length or Roughness Class

The roughness of the terrain between the obstacle and the wind turbine has an important influence on how much the shelter effect is felt. Terrain with low roughness will allow the wind passing outside the obstacle to mix more easily in the wake behind the obstacle, so that it makes the wind shade relatively less important.

It may be a bit confusing at first, that we both deal with the roughness of the terrain, and with individual obstacles. A good rule of thumb is that we deal with individual obstacles which are closer than about 1000 metres from the wind turbine in the prevailing wind directions. The rest we deal with as changes in roughness classes.

Obstacle Height

The taller the obstacle, the larger the wind shade.

As we have mentioned above, if the turbine is closer to the obstacle than five times the obstacle height, or if the obstacle is taller than half the hub height, the results will be more uncertain, because they will depend on the exact geometry of the obstacle. In that case the programme will put a warning in the text box below the results.

Obstacle Width

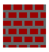
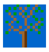
The obstacle calculation model works on the basis of the assumption that obstacles are infinitely long, and that they are placed at a right angle (perpendicular) to the wind direction.

A very narrow object will of course cast a far smaller wind shade than a large one. For practical reasons we assume that we investigate the horizon around the wind turbine in twelve 30 degree sections.

At the bottom of the drawing on the right side of the wind shade calculator we illustrate (in 10 per cent steps) how much space the obstacle take up in such a 30 degree section. You may adjust the width of the obstacle in 10 per cent steps by clicking on the squares at the bottom of the graph.

You may also type the exact length of the obstacle (as seen from the wind turbine) directly, or you may enter the percentage of the sector width that the object fills up.

Porosity

 = 0%  = 30%  = 50%  = 70%

A tree without leaves will brake the wind far less than a building. Trees with dense foliage will have a braking effect somewhere in between. In general, the wind shade will be proportional to (one minus the porosity of the obstacle).

The porosity of an obstacle is a percentage indication of how open an obstacle is, i.e. how easily the wind can pass through it. A building obviously has a zero porosity. A group of buildings with some space between them with have a porosity equal to (the area of the open space) divided by (the total area of both buildings and the open space in between, as seen from the wind turbine).

You may either specify the porosity directly in the calculator, click on one of the buttons with the symbols shown above, or use the pop up menu for suggested settings for different objects.

Control Buttons

Submit calculates your latest input. You may use the tab key or just click outside the field you change instead.

Plot Wind Speed gives you a graph and a table of the percentage of the remaining wind speed at a number of heights and distances up to 1.5 times the height and distance of your wind turbine hub. The turbine tower is shown in yellow. The calculations are quite complex, so be patient if your computer is slow.

Plot Wind Energy gives you a graph and a table of the percentage of the remaining wind energy at a number of heights and distances up to 1.5 times the height and distance of your wind turbine hub. The turbine tower is shown in yellow. The calculations are quite complex, so be patient if your computer is slow.

Plot Speed Profile gives you a plot of the wind speed profile at different heights up to 100 m at the distance where you have placed your turbine. You can see directly on the red curve how the obstacle makes the wind speed drop. You can enter any wind speed you like for the hub height. (The **shape** of the curve remains the same, which is should, since obstacles cause a **relative** change in wind speed). The curve corresponds to the curves drawn by the wind speed calculator.

Results

The result line in the calculator tells you how many per cent the wind speed will decline due to the presence of the obstacle. You may plot the change in wind speeds for a number of distances and heights up to 1.5 times your present distance and height by clicking the Plot Wind Speed button.

(If you are working with a specific Weibull distribution describing the wind in this particular sector, the change in wind speed corresponds to a change in the scale factor A. If you use the results of these calculations to find a Weibull distribution, you can just adjust the scale factor, A, with this change. The shape factor, k, remains unchanged. You will get to the Weibull distribution later in this Guided Tour, when we explore how to compute the energy output from a wind turbine).

The result line also tells you the loss of wind energy due to the presence of the obstacle. You may plot the change in wind energy for a number of distances and heights up to 1.5 times your present distance and height by clicking the Plot Wind Speed button.

More Complex Obstacle Calculations

Obstacles may not be perpendicular to the centreline in the sector, and there may be several rows of obstacles. Although you can still use the basic methods in the calculator, you would probably want to use a professional wind assessment programme such as WindPro or WAsP to manage your data in such cases.

The methods used in the wind calculator are based on the European Wind Atlas. If you read chapter 8, however, you should note that there is a misprint in formula 8.25.

Wind Shade Calculator

Calculator

This calculator requires a Netscape 3.01 or IE 4 or later browser to work. If you are using Navigator 3.01 or later or Internet Explorer 4 or later, and you see this message, you need to enable JavaScript. In Netscape, choose Options | Network Preferences, choose the Languages tab, and click Enable JavaScript. Then click reload on your browser. In Internet Explorer, choose Edit | Preferences | Java, and enable Java, select the Microsoft virtual machine, and enable the "Just in time compiler". Then click reload on your browser.Do not operate the form until this page and its programme have loaded completely. If you are too fast, the programme will complain about missing data, and you will have to click reload.

This calculator shows the shelter effect (wind shade) of blunt obstacles (buildings, trees) in any 30 degree sector near a wind turbine. You can change any number, except the results which are labelled with *. If the obstacle is too tall (more than half the hub height of your turbine) - or too close (less than five times the height of the obstacle) the programme will warn you that the results are uncertain, because the detailed geometry of the obstacle and the angle of the wind will have an important influence on the resulting effect.

Please note that you only have to consider the percentage of wind energy coming from this direction cf. the wind rose, because the obstacle obviously only affects your turbine's energy output when the wind is coming from this particular direction.

If you have a fast computer or some patience you may plot the wind speed or wind energy profile behind the obstacle. (If the plot window disappears, it is probably hidden behind another window).

You should have read about obstacles, roughness and porosity before using the calculator.

? Turbine hub height [50] m

? Distance between obstacle and turbine [300] m

? Roughness length [0.055] m

= roughness class [1.5]

? Obstacle height [20] m

? Obstacle width [60] m

= [ ] % of sector width

? Porosity [0] % [= buildings]

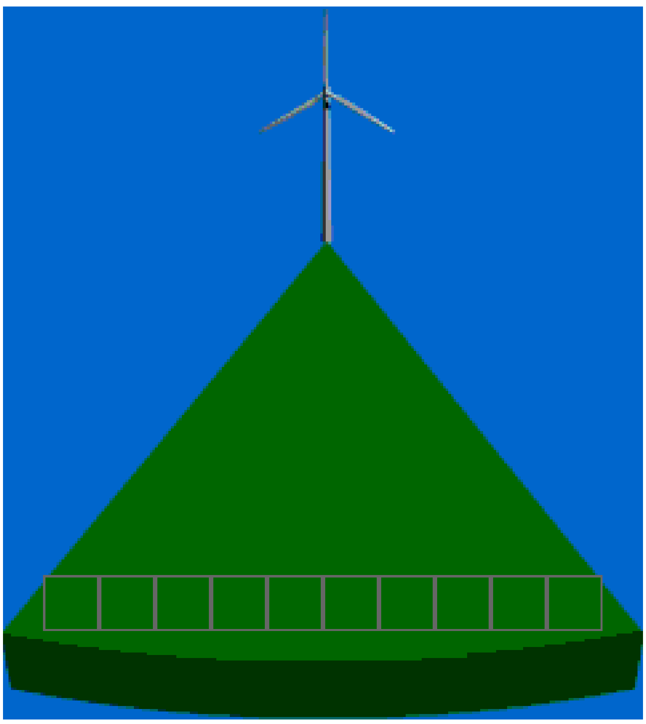
---

for [7.0] m/s hub height wind speed

[Reset to Example]

?

Click in grey squares to insert or remove obstacles



Energy in per cent of undisturbed airflow

70 75 80 85 90 95 100

Select obstacle porosity:

? Result: [ ] % wind speed decrease*

= [ ] % energy loss in this sector*

0%= 30%= 50%= 70%=

[ ] *

Guided Tour

Updated 6 August 2000
http://www.windpower.org/tour/wres/shelter/index.htm

Wake Effect

Wake effect from wind turbine
Picture © Ris National Laboratory, Denmark

Since a wind turbine generates electricity from the energy in the wind, the wind leaving the turbine must have a lower energy content than the wind arriving in front of the turbine. This follows directly from the fact that energy can neither be created nor consumed. If this sounds confusing, take a look at the definition of energy in the Reference Manual.

A wind turbine will always cast a **wind shade** in the downwind direction.

In fact, there will be a **wake** behind the turbine, i.e. a long trail of wind which is quite turbulent and slowed down, when compared to the wind arriving in front of the turbine. (The expression **wake** is obviously derived from the wake behind a ship).

You can actually see the wake trailing behind a wind turbine, if you add smoke to the air passing through the turbine, as was done in the picture. (This particular turbine was designed to rotate in a counterclockwise direction which is somewhat unusual for modern wind turbines).

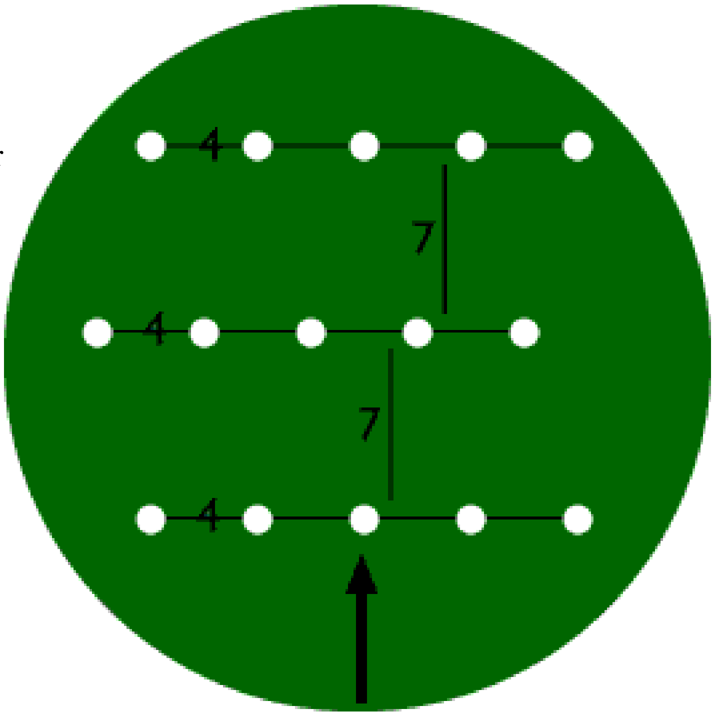
Wind turbines in parks are usually spaced at least three rotor diameters from one another in order to avoid too much turbulence around the turbines downstream. In the prevailing wind direction turbines are usually spaced even farther apart, as explained on the next page.

Park Effect

As we saw in the previous section on the wake effect, each wind turbine will slow down the wind behind it as it pulls energy out of the wind and converts it to electricity.

Ideally, we would therefore like to space turbines as far apart as possible in the prevailing wind direction. On the other hand, land use and the cost of connecting wind turbines to the electrical grid would tell us to space them closer together.

Park Layout



As a rule of thumb, turbines in wind parks are usually spaced somewhere between 5 and 9 rotor diameters apart in the prevailing wind direction, and between 3 and 5 diameters apart in the direction perpendicular to the prevailing winds.

In this picture we have placed three rows of five turbines each in a fairly typical pattern.

The turbines (the white dots) are placed 7 diameters apart in the prevailing wind direction, and 4 diameters apart in the direction perpendicular to the prevailing winds.

Energy Loss from the Park Effect

With knowledge of thewind turbine rotor, the wind rose, the Weibull distribution and the roughness in the different directions manufacturers or developers can calculate the energy loss due to wind turbines shading one another.

Typically, the energy loss will be somewhere around 5 per cent.

Speed Up Effects: Tunnel Effect

If you push an ordinary bicycle air pump, (just point to the image with a Netscape 3 or 4 Browser, do not click) you will notice that the air leaving the nozzle moves much faster than the speed with which you are pushing. The reason, of course, is that the nozzle is much narrower than the cylinder in the pump.

Tunnel Effect

If you take a walk between tall buildings, or in a narrow mountain pass, you will notice that the same effect is working:

The air becomes compressed on the windy side of the buildings or mountains, and its speed increases considerably between the obstacles to the wind. This is known as a "tunnel effect".

So, even if the general wind speed in open terrain may be, say, 6 metres per second, it can easily reach 9 metres per second in a natural "tunnel".

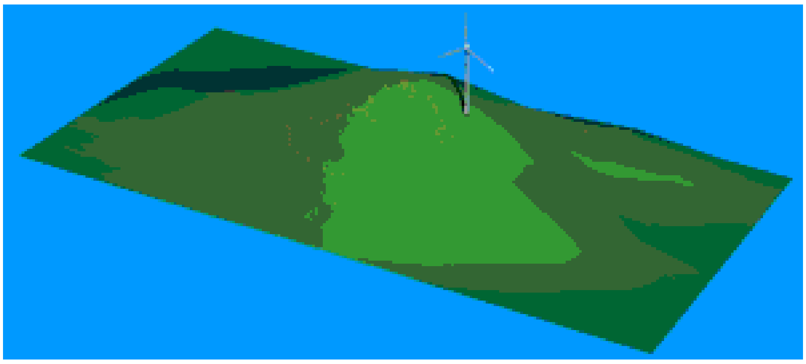
Placing a wind turbine in such a tunnel is one clever way of obtaining higher wind speeds than in the surrounding areas.

To obtain a good tunnel effect the tunnel should be "softly" embedded in the landscape. In case the hills are very rough and uneven, there may be lots of turbulence in the area, i.e. the wind will be whirling in a lot of different (and rapidly changing) directions.

If there is much turbulence it may negate the wind speed advantage completely, and the changing winds may inflict a lot of useless tear and wear on the wind turbine.

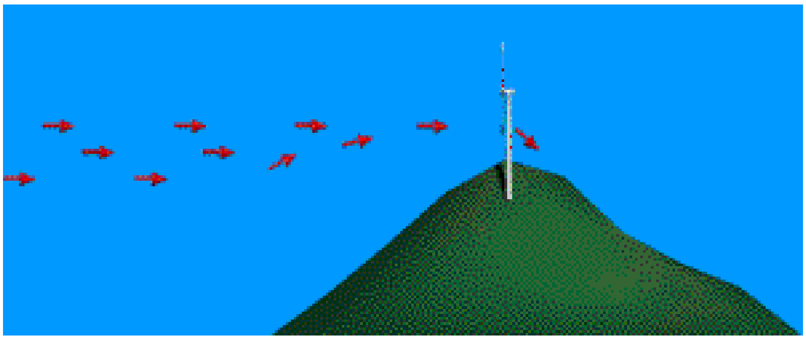
Updated 6 August 2000
http://www.windpower.org/tour/speedup.htm

Speed Up Effects: Hill Effect



A common way of siting wind turbines is to place them on hills or ridges overlooking the surrounding landscape. In particular, it is always an advantage to have as wide a view as possible in the prevailing wind direction in the area.

On hills, one may also experience that wind speeds are higher than in the surrounding area. Once again, this is due to the fact that the wind becomes compressed on the windy side of the hill, and once the air reaches the ridge it can expand again as its soars down into the low pressure area on the lee side of the hill.



You may notice that the wind in the picture starts bending some time before it reaches the hill, because the high pressure area actually extends quite some distance out in front of the hill.

Also, you may notice that the wind becomes very irregular, once it passes through the wind turbine rotor.

As before, if the hill is steep or has an uneven surface, one may get significant amounts of turbulence, which may negate the advantage of higher wind speeds.

The wind in passing the summits of mountains becomes swift and dense and as it blows beyond the mountains it becomes thin and slow, like water that issues from a narrow channel into the wide sea.

Notebooks of Leonardo da Vinci (1452-1519)

Selecting a Wind Turbine Site

Photograph

Wind Conditions

Looking at nature itself is usually an excellent guide to finding a suitable wind turbine site.

If there are trees and shrubs in the area, you may get a good clue about the prevailing wind direction, as you do in the picture to the left.

If you move along a rugged coastline, you may also notice that centuries of erosion have worked in one particular direction.

Meteorology data, ideally in terms of a wind rose calculated over 30 years is probably your best guide, but these data are rarely collected directly at your site, and here are many reasons to be careful about the use of meteorology data, as we explain in the next section.

If there are already wind turbines in the area, their production results are an excellent guide to local wind conditions. In countries like Denmark and Germany where you often find a large number of turbines scattered around the countryside, manufacturers can offer guaranteed production results on the basis of wind calculations made on the site.

Look for a view

As you have learned from the previous pages, we would like to have as wide and open a view as possible in the prevailing wind direction, and we would like to have as few obstacles and as low a roughness as possible in that same direction. If you can find a rounded hill to place the turbines, you may even get a speed up effect in the bargain.

Grid Connection

Obviously, large wind turbines have to be connected to the electrical grid.

For smaller projects, it is therefore essential to be reasonably close to a 10-30 kilovolt power line if the costs of extending the electrical grid are not to be prohibitively high. (It matters a lot who has to pay for the power line extension, of course).

The generators in large, modern wind turbines generally produce electricity at 690 volts. A transformer located next to the turbine, or inside the turbine tower, converts the electricity to high voltage (usually 10-30 kilovolts).

Grid Reinforcement

The electrical grid near the wind turbine(s) should be able to receive the electricity coming from the turbine. If there are already many turbines connected to the grid, the grid may need **reinforcement**, i.e. a larger cable, perhaps connected closer to a higher voltage transformer station. Read the section on Electrical Grid Issues for further information.

Soil Conditions

Both the feasibility of building foundations of the turbines, and road construction to reach the site with heavy trucks must be taken into account with any wind turbine project.

Pitfalls in Using Meteorology Data

Meteorologists already collect wind data for weather forecasts and aviation, and that information is often used to assess the general wind conditions for wind energy in an area.

Precision measurement of wind speeds, and thus wind energy is not nearly as important for weather forecasting as it is for wind energy planning, however.

Wind speeds are heavily influenced by the surface roughness of the surrounding area, of nearby obstacles (such as trees, lighthouses or other buildings), and by the contours of the local terrain.

Unless you make calculations which compensate for the local conditions under which the meteorology measurements were made, it is difficult to estimate wind conditions at a nearby site. In most cases using meteorology data directly will underestimate the true wind energy potential in an area.

We'll return to how the professionals do their wind speed calculations on the following pages.

Offshore Wind Conditions

500 kW offshore wind turbine at Tun Knob, Denmark. Photograph © 1996 Vestas Wind Systems A/S

Wind Conditions at Sea

The surfaces of seas and lakes are obviously very smooth, thus the roughness of a seascape is very low (at constant wind speeds). With increasing wind speeds some of the energy in the wind is used to build waves, i.e. the roughness increases. Once the waves have been built up, the roughness decreases again. We thus have a surface with varying roughness, (just as you have it in areas covered with more or less snow).

Generally speaking, however, the roughness of the water surface is very low, and obstacles to the wind are few. When doing wind calculations we have to account for islands, lighthouses etc. just like you would account for upwind obstacles or changes in roughness on land.

Low Wind Shear Means Lower Hub Height

With low roughness, wind shear at sea is very low, i.e. the wind speed does not change very much with changes in the hub height of wind turbines. It may therefore be most economic to use fairly low towers of perhaps 0.75 times the rotor diameter for wind turbines located at sea, depending upon local conditions. (Typically towers on land sites are about the size of the rotor diameter, or taller).

Low Turbulence Intensity = Longer Lifetime for Turbines

The wind at sea is generally less turbulent than on land. Wind turbines located at sea may therefore be expected to have a longer lifetime than land based turbines.

The low turbulence at sea is primarily due to the fact that temperature variations between different altitudes in the atmosphere above the sea are smaller than above land. Sunlight will penetrate several metres below the sea surface, whereas on land the radiation from the sun only heats the uppermost layer of the soil, which thus becomes much warmer.

Consequently the temperature difference between the surface and the air will be smaller above sea than above land. This is the reason for lower turbulence.

Wind Shade Conditions at Sea

The conventional WAsP model used for onshore wind modelling is in the process of being modified for offshore wind conditions, according to its developer, Ris National Laboratory.

The different production results obtained from the experience of the first major offshore wind park at Vindeby, Denmark, and the subsequently built wind park at Tun Knob, Denmark, has led to new investigations with anemometer masts being placed offshore in a number of locations in Danish waters since 1996.

The preliminary results indicate that wind shade effects from land may be more important, even at distances up to 20 kilometres, than was previously thought.

On the other hand, it appear that the offshore wind resource may be some 5 to 10 per cent higher than was previously estimated.

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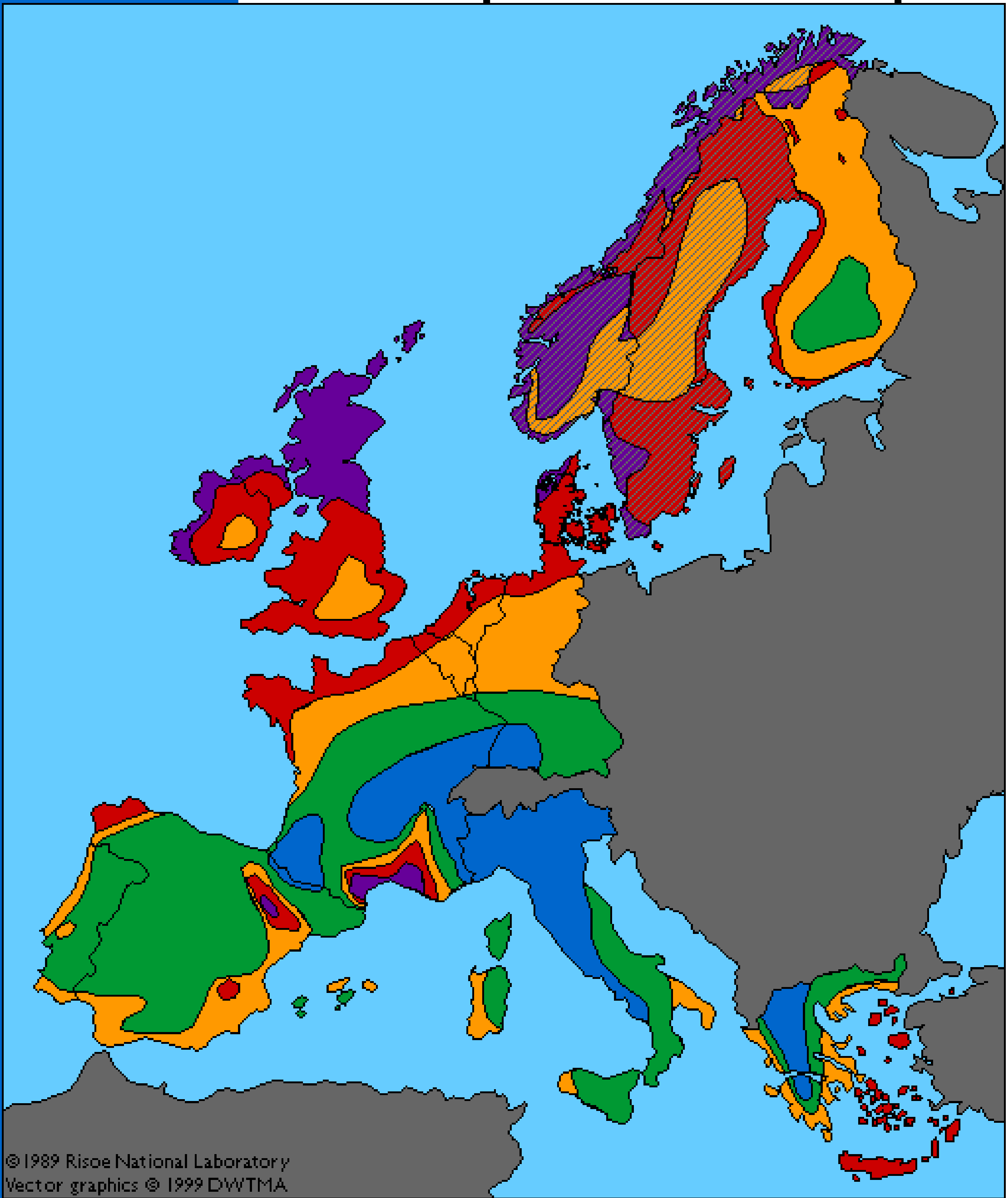
http://www.windpower.org/tour/wres/offshore.htm

www.WINDPOWER.org
Danish Wind Turbine Manufacturers Association

◀ Guided Tour ▶

Wind Map of Western Europe



Wind Resources at 50 (45) m Above Ground Level

Colour	Sheltered terrain		Open plain		At a sea coast		Open sea		Hills and ridges	
	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²	m/s	W/m²
	>6.0	>250	>7.5	>500	>8.5	>700	>9.0	>800	>11.5	>1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
	<3.5	<50	<4.5	<100	<5.0	<150	<5.5	<200	<7.0	<400
			>7.5							
			5.5-7.5							
			<5.5							

How to Read the Wind Map of Western Europe

This wind map of Western Europe was originally published as part of the European Wind Atlas. The details on how to interpret the colours are given in the legend above. Please note that the data for Norway, Sweden and Finland are from a later study, and are calculated for 45 m height above ground level, and assume an open plain.

The purple zones are the areas with the strongest winds while the blue zones have the weakest winds. The dividing lines between the different zones are not as sharp as they appear on the map. In reality, the areas tend to blend smoothly into one another.

You should note, however, that the colours on the map assume that the globe is round without obstacles to the wind, speed up effects, or varying roughness of the terrain. You may therefore easily find good, windy sites for wind turbines on hills and ridges in, say the yellow or green areas of the map, while you have little wind in sheltered terrain in the purple areas.

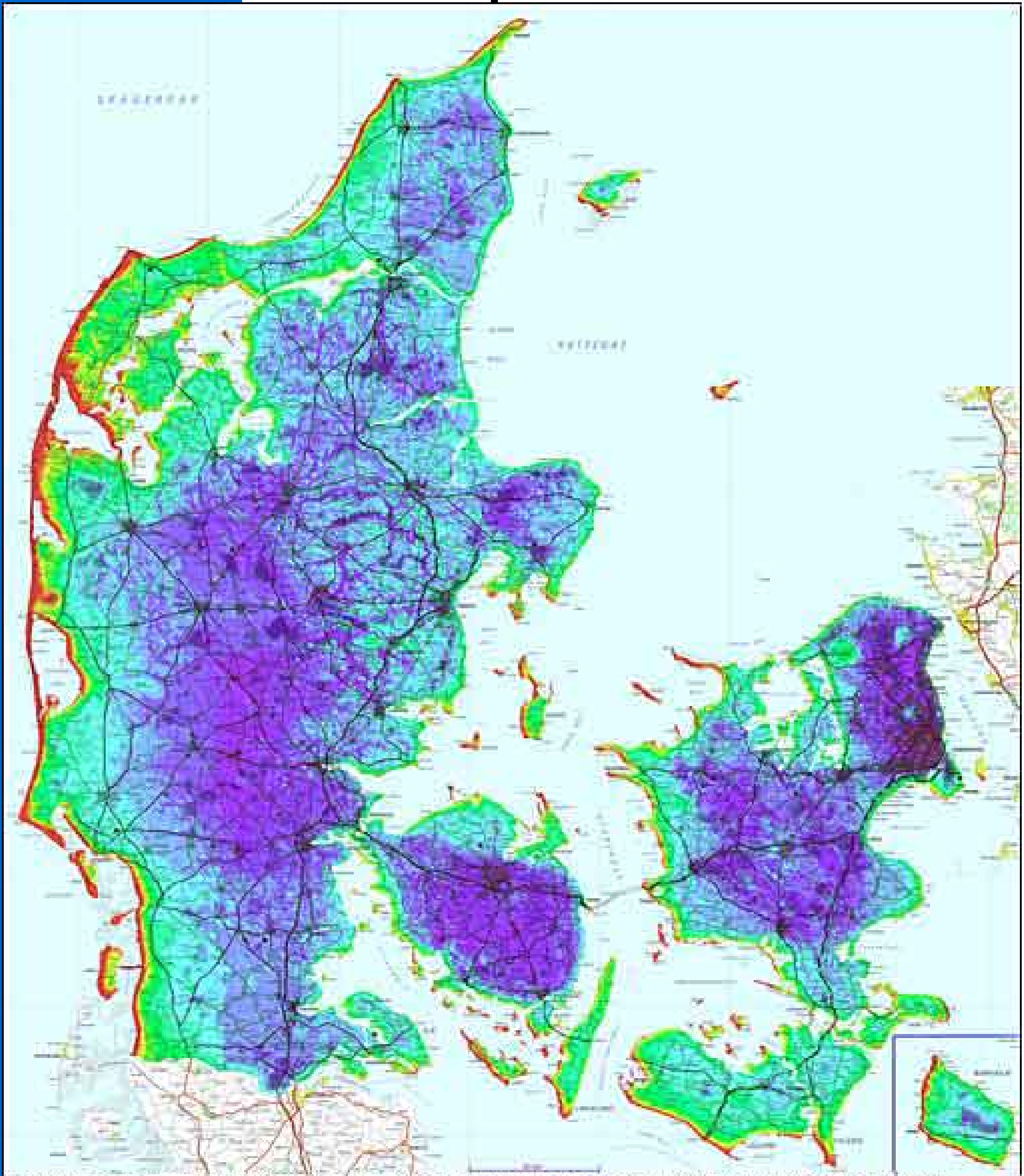
The Power of the Wind

In case you cannot explain why the calculated mean power of the wind in the table is approximately twice the power of the wind at the given mean wind speed, you should read the four to six pages starting with the Weibull Distribution.

Reality is More Complicated

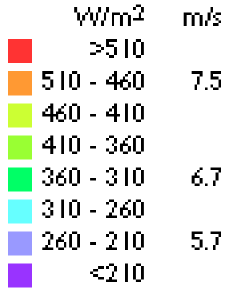
Actual local differences in the terrain will mean that the picture will be much more complicated, if we take a closer look. As an example, we will now take a closeup view of Denmark on the next page.

Wind Map of Denmark



Wind Map of Denmark © 1999 Danish Energy Agency, Energy & Environmental Data, Risoe National Laboratory

How to Read the Wind Map of Denmark



This unique map of Danish wind speeds takes local terrain (speed up effects) and roughness into account. It shows a much more detailed picture of wind conditions than we saw on the previous page. We can clearly see that West and Southwest are the prevailing wind direction in Denmark, since West and Southwest facing coastal sites have by far the highest energy content of the wind (the red and yellow areas).

The map is actually a very high resolution map, where the area of the whole country (44,000 km^2 area) was divided into 1.1 million squares 200 by 200 m each (220 by 220 yards), and the mean wind speed was calculated for each square. You may download the map in various resolutions from the web site of Energy & Environmental Data in Denmark, if you wish (it is also available on CD-ROM).

Using the Wind Map for Planning

This wind map was developed to assist the Danish municipalities in their planning (zoning) work for wind turbines. Each municipality in Denmark is responsible for allocating suitable areas for wind turbines in order that the Government may fulfill its plans to supply 50% of the country's electricity consumption by wind energy in 2030.

Using the Wind Map for Wind Prospecting

The map is obviously also a gift to wind project developers, who can see the (probable) best wind fields in the country directly. One could therefore hardly imagine it being financed and published by any other institution than a government.

The map, however, is not sufficient for actually locating a wind turbine, since it was generated mechanically, without detailed verification in the terrain. In order to make proper calculation of annual electricity output one would have to go to the prospective site and verify e.g. the roughness and locate obstacles and check for new buildings, trees etc.

State of the Art Methods of Wind Assessment

This map was produced for the Danish Energy Agency by Energy & Environmental Data, a wind energy software and consultancy firm in collaboration with the Wind Energy Department of Risoe National Laboratory, which developed the basic fluid dynamics software used for the wind calculations, the WAsP programme.

Calculating such a detailed wind map of a large area is actually an enormous task: The map was made on the basis of extremely detailed digital maps at the scale of 1:25000. The maps in reality consist of 7 layers, with one layer representing altitude contours (orography), another forests and fences (and even individual large trees), a third layer buildings, a fourth layer lakes and rivers etc. The programme that generates roughness data for the WAsP programme determines terrain contours and contiguous areas of forests, lakes, cities etc. in neighbouring squares of each square out to a distance of 20,000 m in all wind directions.

The results were subsequently recalibrated using statistics from several hundred wind turbines scattered throughout the country for which energy output data are available. Thus it has been possible to compensate for the fact that the mean wind speeds in Denmark tend to decrease, as we move towards the East.

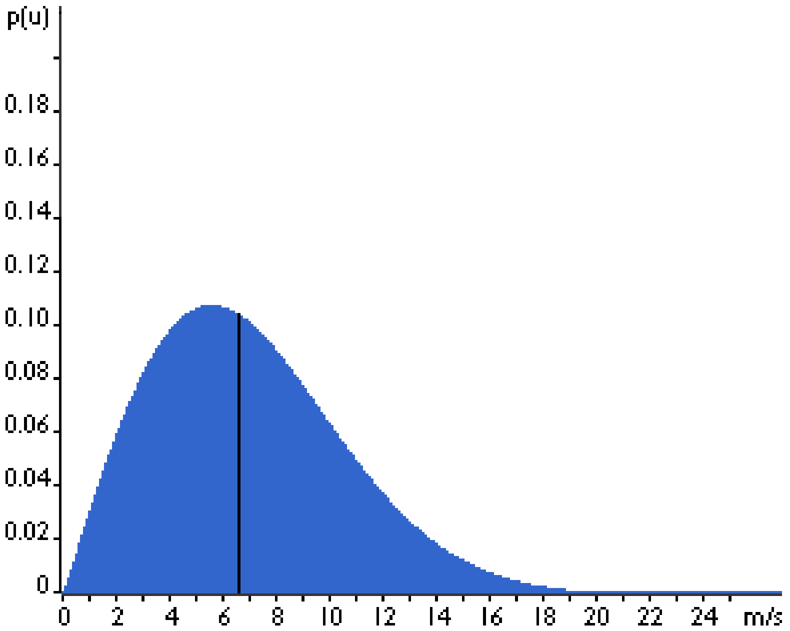
Updated 6 August 2000
http://www.windpower.org/tour/wres/dkmap.htm

Home

Describing Wind Variations: Weibull Distribution

The General Pattern of Wind Speed Variations

It is very important for the wind industry to be able to describe the variation of wind speeds. Turbine designers need the information to optimise the design of their turbines, so as to minimise generating costs. Turbine investors need the information to estimate their income from electricity generation.



If you measure wind speeds throughout a year, you will notice that in most areas strong gale force winds are rare, while moderate and fresh winds are quite common.

The wind variation for a typical site is usually described using the so-called **Weibull distribution**, as shown in the image. This particular site has a mean wind speed of 7 metres per second, and the shape of the curve is determined by a so called **shape parameter** of 2.

Statistical Description of Wind Speeds

People who are familiar with statistics will realise that the graph shows a **probability density distribution**. The area under the curve is always exactly 1, since the probability that the wind will be blowing at some wind speed including zero must be 100 per cent.

Half of the blue area is to the left of the vertical black line at 6.6 metres per second. The 6.6 m/s is called the **median** of the distribution. This means that half the time it will be blowing less than 6.6 metres per second, the other half it will be blowing faster than 6.6 metres per second.

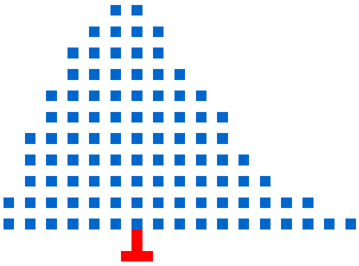
You may wonder then, why we say that the **mean** wind speed is 7 metres per second. The **mean** wind speed is actually the **average** of the wind speed observations we will get at this site.

As you can see, the distribution of wind speeds is **skewed**, i.e. it is not symmetrical. Sometimes you will have very high wind speeds, but they are very rare. Wind speeds of 5.5 metres per second, on the other hand, are the most common ones. 5.5 metres is called the **modal** value of the distribution. If we multiply each tiny wind speed interval by the probability of getting that particular wind speed, and add it all up, we get the **mean** wind speed.

The statistical distribution of wind speeds varies from place to place around the globe, depending upon local climate conditions, the landscape, and its surface. The Weibull distribution may thus vary, both in its shape, and in its mean value.

If the shape parameter is exactly 2, as in the graph on this page, the distribution is known as a **Rayleigh distribution**. Wind turbine manufacturers often give standard performance figures for their machines using the Rayleigh distribution.

Balancing the Weibull Distribution



Another way of finding the **mean wind speed** is to balance the pile of blue bricks to the right, which shows exactly the same as the graph above. Each brick represents the probability that the wind will be blowing at that speed during 1 per cent of the time during the year. 1 m/s wind speeds are in the pile to the far left, 17 m/s is to the far right.

The point at which the whole pile will balance exactly will be at the 7th pile, i.e. the mean wind speed is 7 m/s.

Try This!

If you have a Netscape 3, 4 or Internet Explorer 4 browser, the next page will let you experiment with different values for the Weibull parameters to get a grasp of what the **wind speed probability distribution** looks like.

Guided Tour ▶

Updated 6 August 2000
http://www.windpower.org/tour/wres/Weibull.htm

Weibull Distribution Plotter Programme

(Requires Netscape 3.0)

This page will give you an idea of the way different Weibull distributions look. The **mean wind speed** or the **scale parameter,** A, is used to indicate how windy the site is, on average. The **shape parameter**, k, tells how **peaked** the distibution is, i.e. if the wind speeds always tend to be very close to a certain value, the distibution will have a high k value, and be very peaked.

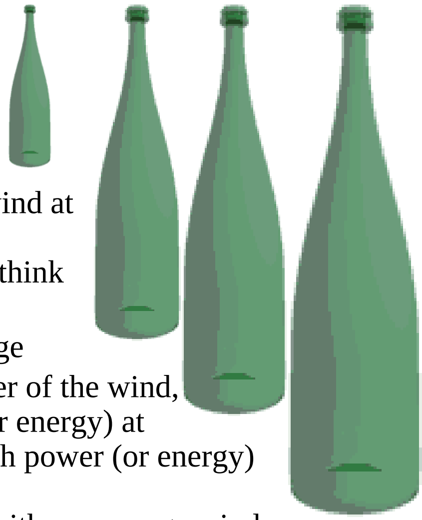
Start by clicking Weibull in the control panel below, to see the result of our example on the previous page. Then try changing one parameter at a time, and watch what happens.

Updated 6 August 2000
http://www.windpower.org/tour/wres/weibull.htm

Choose between entering **mean wind speed** (2.0-12.0 m/s) ◉ or **scale parameter A** ○ in the first box 7.0 ,

then enter **shape k** (1.0-3.0) = 2.0 After entering your data, click to draw. http://www.windpower.org/wres/weibull/index.htm

The Average Bottle Fallacy



What is the average energy content of the wind at your wind turbine site?

Most people who are new to wind energy think they could easily live without the Weibull distribution. After all, if we know the average wind speed, we also know the average power of the wind, don't we? So, can't we just use the power (or energy) at the mean wind speed to figure out how much power (or energy) will hit the wind turbine?

In other words, couldn't we just say, that with an average wind speed of 7 m/s we get an average power input of 210 Watts per square metre of rotor area? (You may find that figure in the table on the power of the wind in the Reference Manual).

The answer is no! We would underestimate wind resources by almost 100 per cent. If we did that, we would be victims of what we could call the Average Bottle Fallacy: Look at the smallest and largest bottle in the picture. Both have exactly the same shape. One is 0.24 m tall, the other is 0.76 m tall. How tall is the average bottle?

If you answer 0.5 m tall, you are a victim of the Average Bottle Fallacy. Bottles are interesting because of their **volume**, of course. But the volume varies with the cube (the third power) of their size. So, even though the largest bottle is only 3.17 times larger than the small bottle, its volume is actually 3.17^3=32 times larger than the small bottle.

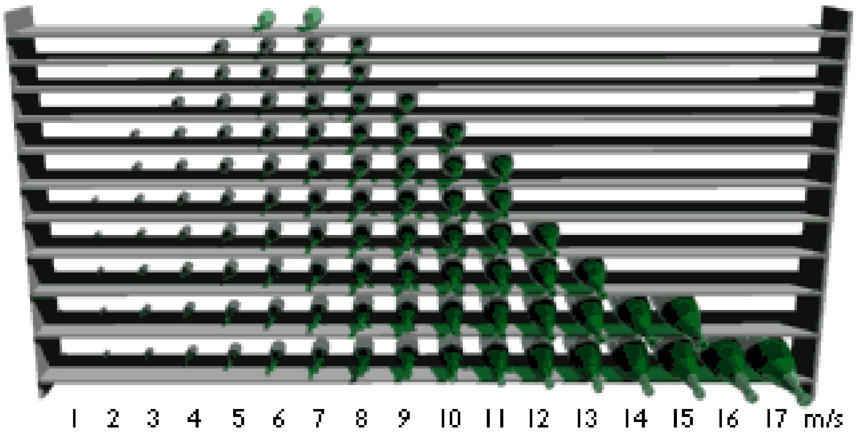
The average volume is therefore 16.5 times that of the small bottle. This means that a bottle with an average volume would have to be 2.55 times the height of the small bottle, i.e. 0.61 m tall. (Since $2.55^3 = 16.5$).

The point we are trying to make, is that you cannot simply take an average of wind speeds, and then use the average wind speed for your power calculations. You have to **weigh** each wind speed probability with the corresponding amount of power. On the next two pages we shall calculate the energy in the wind. First we use the bottle example to grasp the idea, then we use simple math.

Mean (Average) Power of the Wind

Balancing the Power Distribution

The reason why we care about wind speeds is their energy content, just like with the bottles on the previous page: We cared about their content in terms of volume. Now, the volume of a bottle varies with the cube of the size, just like wind power varies with the cube of the wind speed.



Let us take the Weibull distribution of wind speeds, and for each speed we place a bottle on a shelf each time we have a 1 per cent probability of getting that wind speed. The size of each bottle corresponds to the wind speed, so the weight of each bottle corresponds to the amount of energy in the wind.

To the right, at 17 m/s we have some really heavy bottles, which weigh almost 5000 times as much as the bottles at 1 m/s. (At 1 m/s the wind has a power of 0.61 W/m^2. At 17 m/s its power is 3009 W/m^2).

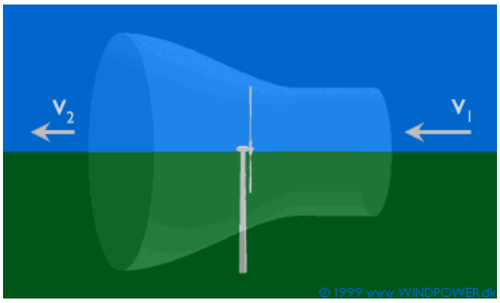
Finding the wind speed at which we get the mean of the **power** distribution is equivalent to balancing the bookshelves. (Remember how we did the balancing act on the Weibull distribution page?). In this case, as you can see, although high winds are rare, they weigh in with a lot of energy.

So, in this case with an average wind speed of 7 m/s, the **power weighted average** of wind speeds is 8.7 m/s. At that wind speed the power of the wind is 402 W/m^2, which is almost twice as much as we figured out in our naive calculation on the top of the previous page.

On the next pages we will use a more convenient method of finding the power in the wind than hauling bottles around...

Betz' Law

The Ideal Braking of the Wind



The more kinetic energy a wind turbine pulls out of the wind, the more the wind will be slowed down as it leaves the left side of the turbine in the picture. (If you wonder about the stream tube in the picture, you have not read the page on how the wind turbine deflects the wind).

If we tried to extract all the energy from the wind, the air would move away with the speed zero, i.e. the air could not leave the turbine. In that case we would not extract any energy at all, since all of the air would obviously also be prevented from entering the rotor of the turbine.

In the other extreme case, the wind could pass though our tube above without being hindered at all. In this case we would likewise not have extracted any energy from the wind.

We can therefore assume that there must be some way of braking the wind which is in between these two extremes, and is more efficient in converting the energy in the wind to useful mechanical energy. It turns out that there is a surprisingly simple answer to this: **An ideal wind turbine would slow down the wind by 2/3 of its original speed**. To understand why, we have to use the fundamental physical law for the aerodynamics of wind turbines:

Betz' Law

Betz' law says that **you can only convert less than 16/27 (or 59%) of the kinetic energy in the wind to mechanical energy using a wind turbine**.

Betz' law was first formulated by the German Physicist Albert Betz in 1919. His book "Wind-Energie" published in 1926 gives a good account of the knowledge of wind energy and wind turbines at that moment.

It is quite surprising that one can make such a sweeping, general statement which applies to any wind turbine with a disc-like rotor.

To prove the theorem requires a bit of math and physics, but don't be put off by that, as Betz himself writes in his book. Betz' own proof of the theorem is included in the Reference Manual on this web site.


Wind-Energie

und ihre Ausnutzung durch Windmühlen

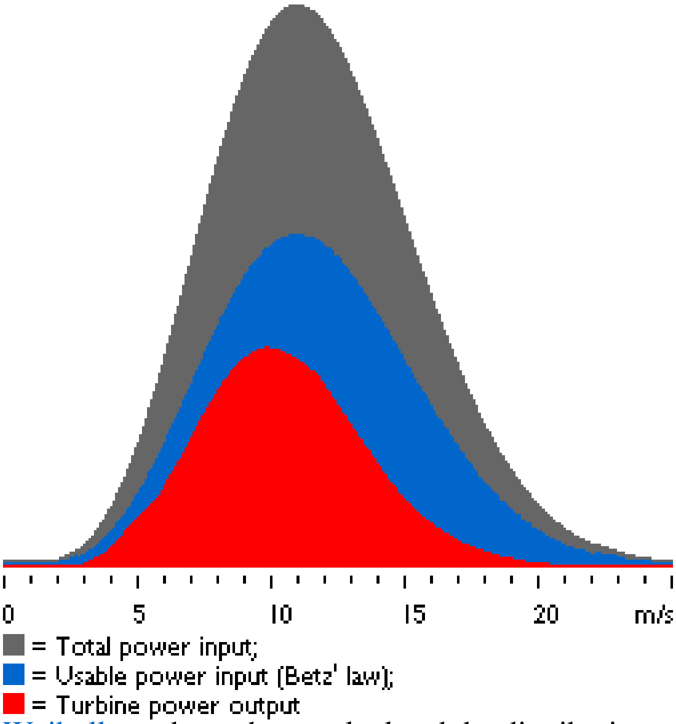
Dipl.-Ing. Dr. Albert Betz

Göttingen :: Vandenhoeck & Ruprecht :: 1926

Updated 6 August 2000
http://www.windpower.org/tour/wres/betz.htm

Power Density Function

Power of the Wind



From the page on the energy in the wind, we know that the energy potential per second (the power) varies in proportion to the cube (the third power) of the wind speed, and in proportion to the density of the air. (Its weight per unit of volume).

We may now combine everything we have learned so far: If we multiply the power of each wind speed with the **probability of each wind speed** from the Weibull graph, we have calculated the distribution of wind energy at different wind speeds = **the power density**.

Notice, that the previous Weibull curve changes shape, because the high wind speeds have most of the power of the wind.

From Power Density to Power Output

This graph was drawn using the wind turbine power calculator on this web site. The **area** under the grey curve (all the way to the axis at the bottom) gives us the amount of wind power per square metre wind flow we may expect at this particular site. In this case we have a mean wind speed of 7 m/s and a Weibull k=2, so we get 402 W/m^2. You should note that this is almost **twice** as much power as the wind has when it is blowing constantly at the average wind speed.

The graph consists of a number of narrow vertical columns, one for each 0.1 m/s wind speed interval. The height of each column is the power (number of watts per square metre), which that particular wind speed contributes to the total amount of power available per square metre.

The area under the blue curve tells us how much of the wind power we can theoretically convert to mechanical power. (According to Betz' law, this is 16/27 of the total power in the wind).

The total area under the red curve tells us how much electrical power a certain wind turbine will produce at this site. We will learn how to figure that out in a moment when we get to the page on power curves.

The Important Messages in the Graph

The most important thing to notice is that the bulk of wind energy will be found at wind speeds **above** the mean (average) wind speed at the site.

This is not as surprising as it sounds, because we know that high wind speeds have much higher energy content than low wind speeds.

The Cut In Wind Speed

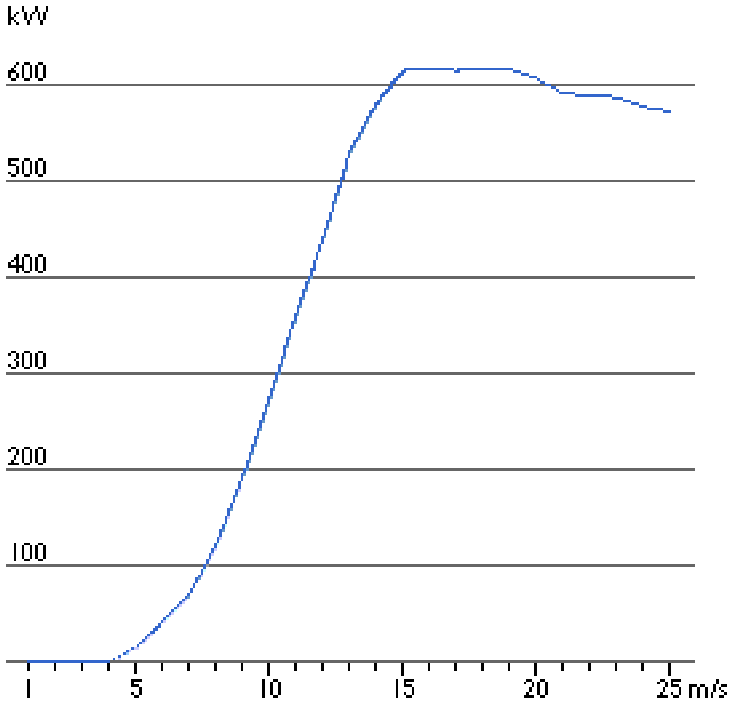
Usually, wind turbines are designed to start running at wind speeds somewhere around 3 to 5 metres per second. This is called the **cut in wind speed**. The blue area to the left shows the small amount of power we lose due to the fact the turbine only cuts in after, say 5 m/s.

The Cut Out Wind Speed

The wind turbine will be programmed to stop at high wind speeds above, say 25 metres per second, in order to avoid damaging the turbine or its surroundings. The stop wind speed is called the **cut out wind speed**. The tiny blue area to the right represents that loss of power.

Updated 6 August 2000
http://www.windpower.org/tour/wres/powdensi.htm

The Power Curve of a Wind Turbine



The power curve of a wind turbine is a graph that indicates how large the electrical power output will be for the turbine at different wind speeds.

The graph shows a power curve for a typical Danish 600 kW wind turbine.

Power curves are found by field measurements, where an anemometer is placed on a mast reasonably close to the wind turbine (not on the turbine itself or too close to it, since the turbine rotor may create turbulence, and make wind speed measurement unreliable).

If the wind speed is not fluctuating too rapidly, then one may use the wind speed measurements from the anemometer and read the electrical power output from the wind turbine and plot the two values together in a graph like the one to the left.

Uncertainty in Measurement of Power Curves

In reality, one will see a swarm of points spread around the blue line, and not the neat curve in the graph.

The reason is that in practice the wind speed always fluctuates, and one cannot measure exactly the column of wind that passes through the rotor of the turbine.

(It is not a workable solution just to place an anemometer in front of the turbine, since the turbine will also cast a "wind shadow" and brake the wind in front of itself).

In practice, therefore, one has to take an average of the different measurements for each wind speed, and plot the graph through these averages.

Furthermore, it is difficult to make exact measurements of the wind speed itself. If one has a 3 per cent error in wind speed measurement, then the energy in the wind may be 9 per cent higher or lower (remember that the energy content varies with the third power of the wind speed).

Consequently, there may be errors up to plus or minus 10 per cent even in certified power curves.

Verifying Power Curves

Power curves are based on measurements in areas with low turbulence intensity, and with the wind coming directly towards the front of the turbine. Local turbulence and complex terrain (e.g. turbines placed on a rugged slope) may mean that wind gusts hit the rotor from varying directions. It may therefore be difficult to reproduce the power curve exactly in any given location.

Pitfalls in Using Power Curves

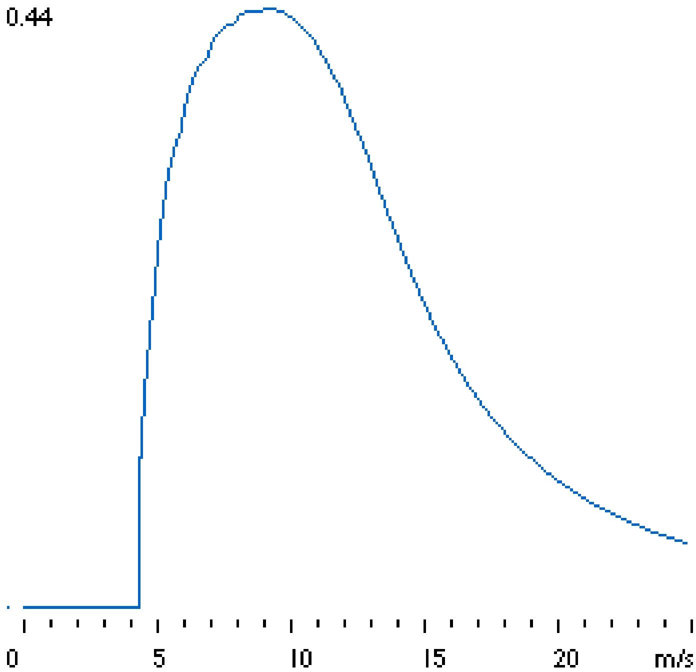
A power curve does **not** tell you how much power a wind turbine will produce at a certain average wind speed. You would not even be close, if you used that method!

Remember, that the energy content of the wind varies very strongly with the wind speed, as we saw in the section on the energy in the wind. So, it matters a lot how that average came about, i.e. if winds vary a lot, or if the wind blows at a relatively constant speed.

Also, you may remember from the example in the section on the power density function, that most of the wind energy is available at wind speeds which are **twice** the most common wind speed at the site.

Finally, we need to account for the fact that the turbine may not be running at standard air pressure and temperature, and consequently make corrections for changes in the density of air.

The Power Coefficient



The power coefficient tells you how efficiently a turbine converts the energy in the wind to electricity. Very simply, we just divide the **electrical power output** by the **wind energy input** to measure how technically efficient a wind turbine is.

In other words, we take the power curve, and divide it by the area of the rotor to get the power output per square metre of rotor area. For each wind speed, we then divide the result by the amount of power in the wind per square metre.

The graph shows a power coefficient curve for a typical Danish wind turbine. Although the average efficiency for these turbines is somewhat above 20 per cent, the efficiency varies very much with the wind speed. (If there are small kinks in the curve, they are usually due to measurement errors).

As you can see, the mechanical efficiency of the turbine is largest (in this case 44 per cent) at a wind speed around some 9 m/s. This is a deliberate choice by the engineers who designed the turbine. At low wind speeds efficiency is not so important, because there is not much energy to harvest. At high wind speeds the turbine **must** waste any excess energy above what the generator was designed for. Efficiency therefore matters most in the region of wind speeds where most of the energy is to be found.

Higher Technical Efficiency is not Necessarily the Way Forward

It is **not** an aim in itself to have a high **technical** efficiency of a wind turbine. What matters, really, is the **cost** of pulling kilowatt hours out of the winds during the next 20 years. Since the fuel is free, there is no need to save it. The optimal turbine is therefore not necessarily the turbine with the highest energy output per year.

On the other hand, each square metre of rotor area costs money, so it is of course necessary to harvest whatever energy you can - as long as you can keep costs per kilowatt hour down. We return to that subject later on the page about optimising wind turbines.

Home

Guided Tour

Updated 9 September 2000
http://www.windpower.org/tour/wres/cp.htm

Guide to the Wind Turbine Power Calculator

If you have room on your screen, you may open another browser window with the calculator, in order to look at it while you look at this guide. If you do not want to read all of these instructions, please read the advice at the bottom of the page in any case.

Using the Power Curve and the Weibull distribution to Estimate Power and Energy Output

In order to use the power curve properly, you have to combine your knowledge of the Weibull distribution with the power curve. This is what we will be doing using the power density calculator on the next page:

For each tiny 0.1 metre interval of wind speeds we multiply the probability of that wind speed interval (from the Weibull curve) with the value from the power curve of the wind turbine.

We then take the sum of all these multiplications to get the mean (or average) **power** output.

If we multiply the **power** by 365.25 by 24 (the number of hours in a year) we get the total **energy** output for an average year.

Site Data

Use the pop up menu to fill out European wind distribution data automatically. The data calculated for roughness classes 0, 1, 2, and 3 was taken from the European wind atlas. If you use roughness class 1.5, we interpolate to find the data. If you have data for other parts of the world you would like to have included, please e-mail us.

Air Density Data

As we learned on a previous page, the energy in the wind varies in proportion to the density of air. Try changing the air temperature from, say 40 degrees Celsius, to -20 degrees Celsius. There are almost 25 per cent more air molecules in a cubic metre of the cold air than in a cubic metre of the warm air, so watch what happens to the energy output...

If you wish to change the altitude above sea level, then start setting the temperature at sea level first. The programme will then automatically compute the likely temperature and pressure at the altitude you set.

You may set the air density directly, if you know what you are doing. The programme then computes a likely set of data for the other variables. (You may also change the air pressure, but you'd better leave it alone. Your air pressure obviously has to fit to the local altitude and temperature).

Wind Distribution Data

The Weibull shape parameter is generally around 2 in Northern Europe, but situations vary, so you may really need a wind atlas to set this more accurately. You can either enter the mean wind speed, or the Weibull scale parameter (the programme then automatically computes) the other.

The measurement height for your wind speed is very important, because wind speeds increase with heights above ground level, cf. the page on wind shear. Meteorology observations are generally made at 10 m height, but anemometer studies are often made at hub height of the wind turbine (in our example 50 metres).

The average roughness of the surrounding terrain is important to determine the wind speed at turbine hub height, if it differs from the height at which wind speed measurements were made. You may either set the roughness length or the roughness class, depending on the local landscape type. (See the Reference Manual for guidelines on roughness classes).

Wind Turbine Data

This section of the calculator lets you specify the rated power of the main generator, the rotor diameter, the cut in wind speed, and the cut out wind speed, and the hub height of your machine. At the bottom of the page you may then specify the power curve of your machine.

It is much easier, however, to use the first pop up menu which allows you to set all turbine specifications using a built-in table of data for typical Danish wind turbines. We have already put data for a typical 600 kW machine in the form for you, but you may experiment by looking at other machines.

The second pop up menu will allow you to choose from the available hub heights for the machine you have chosen. You may also enter a hub height of your own, if you wish.

Try experimenting a bit with different hub heights, and see how energy output varies. The effect is particularly noticeable if the machine is located in terrain with a high roughness class. (You can modify the roughness class in the wind distribution data to see for yourself).

If you modify the standard machine specifications, the text on the first pop up menu changes to **User example**, to show that you are not dealing with a standard machine. It is safe to play with all of the variables, but it does **not** make much sense to change the generator size or rotor diameter for a standard machine, unless you also change the power curve. We only use the rotor diameter to show the power input, and to compute the efficiency of the machine (in terms of the power coefficient). We only use the rated power of the generator to compute the capacity factor.

Wind Turbine Power Curve

For practical reasons (keeping your input data and your results in view at the same time) we have placed the listing of the turbine power curve at the bottom of the page. You can use this area to specify a turbine which is not listed in the built-in table. The only requirement is that wind speeds be ordered sequentially in ascending (increasing) order.

The programme approximates the power curve with a straight line between each two successive points which have non zero values for the power output.

Note: The programme only uses wind speeds up to 40 m/s in its calculations of the wind climate, so do not bother about fantasy machines that work beyond 30 m/s.

Control Buttons

Calculate recalculates the results on the form. You may also click anywhere else or use the tab key after you have entered data to activate the calculator. Note that if you change the power curve, the machine will not recalculate your data until you click calculate, or change other data.

Reset Data sets the data back to the user example you first encountered on your screen.

Power Density plots the power density graph for this site and machine in a separate window.

Power Curve plots the power curve for the machine you have selected in a separate window.

Power Coefficient plots the power coefficient, i.e. the efficiency of the machine at different wind speeds.

Site Power Input Results

Power input per square metre rotor area shows the amount of energy in the wind which theoretically would flow through the circle containing the rotor area, if the rotor were not present. (In reality, part of the airflow will be diverted outside the rotor area due to the high pressure area in front of the rotor).

Maximum power input at x m/s shows at what wind speed we achieve the highest contribution to total power output. The figure is usually much higher than average wind speed, cf. the page on the power density function.

Mean hub height wind speed shows how the programme recalculates your wind data to the proper hub height. If you have specified a hub height which is different from the height at which wind measurements were taken, the programme automatically recalculates all wind speeds in the Weibull distribution in accordance with the roughness class (or roughness length) you have specified.

Turbine Power Output Results

Power output per square metre of rotor area tells us how much of the power input per square metre the machine will convert to electricity. Generally, you will find that it is cost effective to build the machine to use about 30 per cent of the power available. (Please note, that the figure for site power **input** includes the power for wind speeds outside the cut in/cut out wind speed range, so you cannot divide by that figure to obtain the average power coefficient).

Energy output per square metre rotor area per year, is simply the mean power output per square metre rotor area multiplied by the number of hours in a year.

Energy output in kWh per year, tells us how much electrical energy the wind turbine will produce in an average year. That is probably the figure the owner cares more about than the rest. When the owner considers that figure, however, he will also have to take the price of the machine, its reliability, and the cost of operation and maintenance. We return to those subjects in the section on the economics of wind energy.

The annual energy output calculated here may be slightly different from the real figures from the manufacturer. This is particularly the case if you vary the density of air. In that case the manufacturer will calculate different power curves for each density of air. The reason is, that with a pitch controlled turbine the pitching mechanism will automatically change the pitch angle of the blade with the change of air density, while for a stall controlled turbine, the manufacturer will set the angle of the blade slightly differently depending on the local average air density. This programme may be up to 3.6% below the correct figure from the manufacturer for low air densities, and up to 1.6% above the manufacturers' figures for high air densities.

Capacity factor tells us how much the turbine uses the rated capacity of its (main) generator. You may read more on the page on annual energy output from a wind turbine.

Note 1: Make sure that you use the same hub height, if you wish to compare how two machines with the same rotor diameter perform.

Note 2: If you wish to compare machines with different rotor diameters you should look at the energy output per square metre of rotor area instead (you should still use the same hub height).

Note 3: Low wind machines (large rotor diameter relative to generator size) will generally perform badly at high wind sites and vice versa. Most low wind machines are not designed for use in high wind areas with strong gusts.

Wind Turbine Power Calculator

This calculator requires a Netscape 3.01 or IE 4 or later browser to work. If you are using Navigator 3.01 or later or Internet Explorer 4 or later, and you see this message, you need to enable JavaScript. In Netscape, choose Options | Network Preferences, choose the Languages tab, and click Enable JavaScript. Then click reload on your browser. In Internet Explorer, choose Edit | Preferences | Java, and enable Java, select the Microsoft virtual machine, and enable the "Just in time compiler". Then click reload on your browser. Do not operate the form until this page and its programme have loaded completely. If you are too fast, the programme will complain about missing data, and you'll have to click reload. **Note1:** Energy output results from calculation programmes like this may differ slightly from the results given by manufacturers. **Note 2**: Power curves are found by field measurements which may be uncertain. Therefore these results should be interpreted with great care, as the may be some +/-10 per cent uncertainty in these measurements. **Note 3**: Turbine manufacturers may have site specific turbine models available which are not listed here. **Note 4**: The site data below was not chosen as being particularly suitable for wind turbines, but was taken directly from the anemometer locations used in the European Wind Atlas. In the case of e.g. Frankfurt (D), one may e.g. find locations on neighbouring hills to the South with twice as high an annual production as you would get at the airport where the anemometer is located. In the case of e.g. Northwestern Ireland, sites on rounded hills in the area may yield 20-25 per cent higher energy output.

You may experiment by changing the figures in the example below. You can fill in any box, except the result boxes marked with an asterisk (*). After changing data, use the tab key, click the Calculate button, or click anywhere on the page outside the field you have updated to see the results. Click on the question marks for help. (If a plot windows disappears, it is probably hidden behind this window).

Site Data

Select Site Data ?

Air Density Data

15.0 C temp at 0 m altitude (= 101.33 kPa pressure) 1.225 kg/m^3 density ?

Wind Distribution Data for Site

2.0 Weibull shape parameter

7.0 m/s mean = 7.9 Weibull scale parameter ?

50.0 m height, Roughness length 0.055 m = class 1.5

Wind Turbine Data

Specify Manually 600 kW

5.0 m/s cut in wind speed, 25.0 m/s cut out wind speed ?

43.0 m rotor diameter, 50.0 m hub height

Reset Data ?

Site Power Input Results

Power input* W/m2 rotor area

Max. power input at* m/s

Mean hub ht wind speed* m/s

Turbine Power output Results

Power output* W/m2 rotor area

Energy output* kWh/m2/year

Energy output* kWh/year

Capacity factor* per cent

?

?

Wind Turbine Power Curve

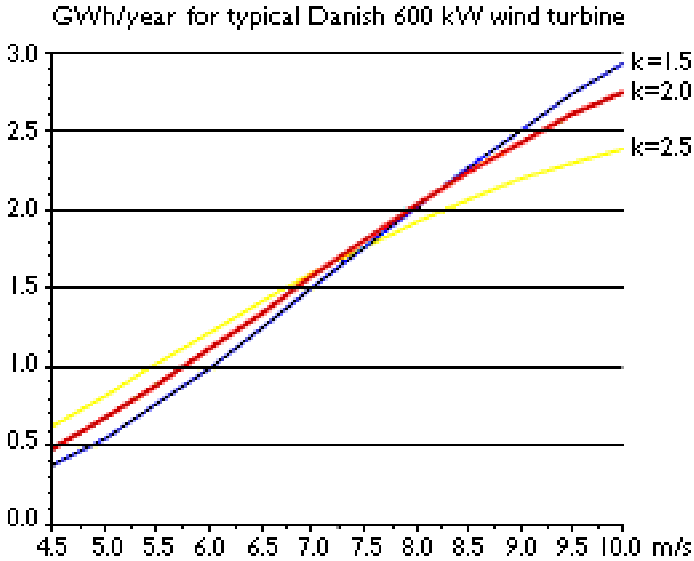
m/s	kW	m/s	kW	m/s	kW
1	0	11	444	21	592
2	0	12	533	22	590
3	2	13	584	23	580
4	17	14	618	24	575
5	45	15	619	25	570
6	72	16	618	26	0
7	124	17	619	27	0
8	196	18	620	28	0
9	277	19	610	29	0
10	364	20	594	30	0

Note: This calculator may be used together with the Wind Energy Economics Calculator. If you open the economics calculator from this page, they will both be on screen, and this calculator will automatically feed its energy output result into the economics calculator.

◀ Guided Tour ▶

Annual Energy Output from a Wind Turbine

We are now ready to calculate the relationship between average wind speeds and annual energy output from a wind turbine.



To draw the graph to the right, we have used the power calculator on the previous page, and the power curve from the default example 600 kW wind turbine. We have used a standard atmosphere with an air density of 1.225 kg/m^3.

For each of the Weibull parameters 1.5, 2.0, and 2.5 we have calculated the annual energy output for different average wind speeds at turbine hub height.

As you can see, output may vary up to 50 per cent depending on the shape parameter at a low average wind speed of 4.5 m/s, while it may vary some 30 per cent at a very high average wind speed of 10 m/s at hub height.

Output varies *almost* with the cube of the wind speed

Now, let us look at the red curve with k=2, which is the curve normally shown by manufacturers:

With an average wind speed of 4.5 m/s at hub height the machine will generate about 0.5 GWh per year, i.e. 500,000 kWh per year. With an average wind speed of 9 metres per second it will generate 2.4 GWh/year = 2,400,000 kWh per year. Thus, doubling the average wind speed has increased energy output 4.8 times.

If we had compared 5 and 10 metres per second instead, we would have obtained almost exactly 4 times as much energy output.

The reason why we do not obtain exactly the same results in the two cases, is that the efficiency of the wind turbine varies with the wind speeds, as described by the power curve. Note, that the uncertainty that applies to the power curve also applies to the result above.

You may refine your calculations by accounting for the fact that e.g. in temperate climates the wind tends to be stronger in winter than in summer, and stronger during the daytime than at night.

The Capacity Factor

Another way of stating the annual energy output from a wind turbine is to look at the **capacity factor** for the turbine in its particular location. By capacity factor we mean its actual **annual energy output** divided by the **theoretical maximum output**, if the machine were running at its rated (maximum) power during all of the 8766 hours of the year.

Example: If a 600 kW turbine produces 1.5 million kWh in a year, its capacity factor is = 1500000 : (365.25 * 24 * 600) = 1500000 : 5259600 = 0.285 = 28.5 per cent.

Capacity factors may theoretically vary from 0 to 100 per cent, but in practice they will usually range from 20 to 70 per cent, and mostly be around 25-30 per cent.

The Capacity Factor Paradox

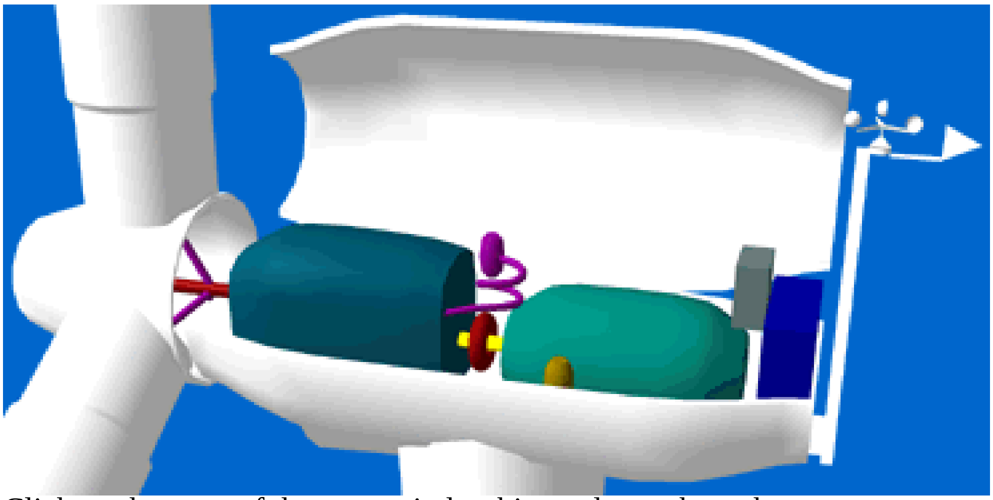
Although one would generally prefer to have a large capacity factor, it may not always be an economic advantage. This is often confusing to people used to conventional or nuclear technology.

In a very windy location, for instance, it may be an advantage to use a larger generator with the same rotor diameter (or a smaller rotor diameter for a given generator size). This would tend to lower the capacity factor (using less of the capacity of a relatively larger generator), but it may mean a substantially larger annual production, as you can verify using the Power calculator on this web site.

Whether it is worthwhile to go for a lower capacity factor with a relatively larger generator, depends both on wind conditions, and on the price of the different turbine models of course.

Another way of looking at the capacity factor paradox is to say, that to a certain extent you may have a choice between a relatively **stable power output** (close to the design limit of the generator) with a high capacity factor - or a **high energy output** (which will fluctuate) with a low capacity factor.

Wind Turbine Components



Click on the parts of the open wind turbine to learn about the nacelle, rotor blades, hub, low speed shaft, gearbox, high speed shaft with its mechanical brake, electrical generator, yaw mechanism, electronic controller, hydraulics system, cooling unit, tower, anemometer and wind vane.

Updated 26 September 2000
http://www.windpower.org/tour/wtrb/comp/index.htm

The **nacelle** contains the key components of the wind turbine, including the gearbox, and the electrical generator. Service personnel may enter the nacelle from the tower of the turbine. To the left of the nacelle we have the wind turbine rotor, i.e. the rotor blades and the hub.

The rotor blades capture the wind and transfer its power to the rotor hub. On a modern 600 kW wind turbine each rotor blade measures about 20 metres (66 ft.) in length and is designed much like a wing of an aeroplane.

The **hub** of the rotor is attached to the low speed shaft of the wind turbine.

The **low speed shaft** of the wind turbine connects the rotor hub to the gearbox. On a modern 600 kW wind turbine the rotor rotates relatively slowly, about 19 to 30 revolutions per minute (RPM). The shaft contains pipes for the hydraulics system to enable the aerodynamic brakes to operate.

The gearbox has the low speed shaft to the left. It makes the high speed shaft to the right turn approximately 50 times faster than the low speed shaft.

The **high speed shaft** rotates with approximately. 1,500 revolutions per minute (RPM) and drives the electrical generator. It is equipped with an emergency **mechanical disc brake**. The mechanical brake is used in case of failure of the aerodynamic brake, or when the turbine is being serviced.

The electrical generator is usually a so-called induction generator or asynchronous generator. On a modern wind turbine the maximum electric power is usually between 500 and 1,500 kilowatts (kW).

The electronic controller contains a computer which continuously monitors the condition of the wind turbine and controls the yaw mechanism. In case of any malfunction, (e.g. overheating of the gearbox or the generator), it automatically stops the wind turbine and calls the turbine operator's computer via a telephone modem link.

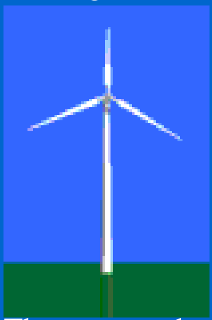
The **hydraulics system** is used to reset the aerodynamic brakes of the wind turbine.

The cooling unit contains an electric fan which is used to cool the electrical generator. In addition, it contains an oil cooling unit which is used to cool the oil in the gearbox. Some turbines have water-cooled generators.

The tower of the wind turbine carries the nacelle and the rotor. Generally, it is an advantage to have a high tower, since wind speeds increase farther away from the ground. A typical modern 600 kW turbine will have a tower of 40 to 60 metres (132 to 198 ft.) (the height of

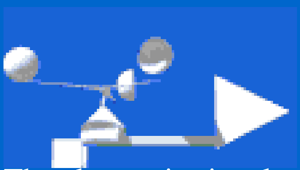
a 13-20 story building).
Towers may be either tubular towers (such as the one in the picture) or lattice towers. Tubular towers are safer for the personnel that have to maintain the turbines, as they may use an inside ladder to get to the top of the turbine. The advantage of lattice towers is primarily that they are cheaper.

The yaw mechanism uses electrical motors to turn the nacelle with the rotor against the wind.



The yaw mechanism is operated by the electronic controller which senses the wind direction using the wind vane. The picture shows the turbine yawing. Normally, the turbine will yaw only a few degrees at a time, when the wind changes its direction.

The anemometer and the wind wane are used to measure the speed and the direction of the wind.



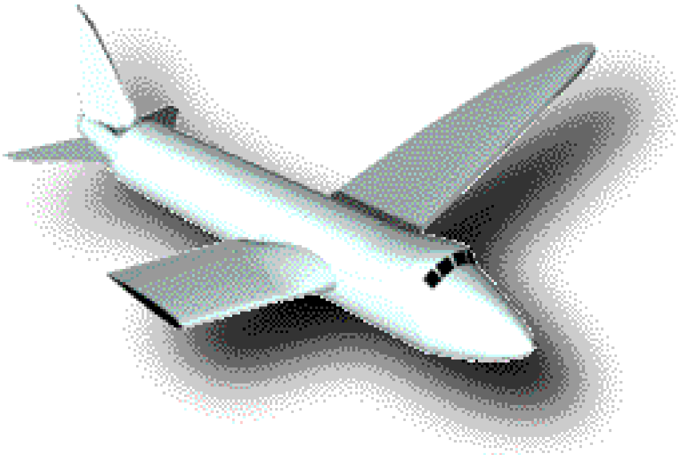
The electronic signals from the anemometer are used by the wind turbine's electronic controller to start the wind turbine when the wind speed reaches approximately 5 metres per second (10 knots). The computers stops the wind turbine automatically if the wind speed exceeds 25 metres per second (50 knots) in order to protect the turbine and its surroundings.

The wind vane signals are used by the wind turbine's electronic controller to turn the wind turbine against the wind, using the yaw mechanism.

Aerodynamics of Wind Turbines: Lift

The **rotor** consisting of the rotor blades and the hub are placed upwind of the tower and the nacelle on most modern wind turbines. This is primarily done because the air current behind the tower is very irregular (turbulent).

What makes the rotor turn?



The answer seems obvious - the wind.

But actually, it is a bit more complicated than just the air molecules hitting the front of the rotor blades. Modern wind turbines borrow technologies known from aeroplanes and helicopters, plus a few advanced tricks of their own, because wind turbines actually work in a very different environment with changing wind speeds and changing wind directions.

Lift

Have a look at the animation of the cut-off profile (cross section) of the wing of an aircraft. The reason why an aeroplane can fly is that the air sliding along the upper surface of the wing will move faster than on the lower surface.

This means that the pressure will be lowest on the upper surface. This creates the **lift**, i.e. the force pulling upwards that enables the plane to fly.

The lift is perpendicular to the direction of the wind. The **lift** phenomenon has been well known for centuries to people who do roofing work: They know from experience that roof material on the lee side of the roof (the side not facing the wind) is torn off quickly, if the roofing material is not properly attached to its substructure.

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http://www.windpower.org/tout/wtrb/lift.htm

Aerodynamics of Wind Turbines: Stall and Drag

Stall

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Now, what happens if an aircraft tilts backward in an attempt to climb higher into the sky quickly? The lift of the wing will indeed increase, as the wing is tilted backwards, but in the picture you can see that all of a sudden the air flow on the upper surface stops sticking to the surface of the wing. Instead the air whirls around in an irregular vortex (a condition which is also known as turbulence). All of a sudden the lift from the low pressure on the upper surface of the wing disappears. This phenomenon is known as **stall**.

An aircraft wing will stall, if the shape of the wing tapers off too quickly as the air moves along its general direction of motion. (The wing itself, of course, does not change its shape, but the angle of the the wing in relation to the general direction of the airflow (also known as the **angle of attack**) has been increased in our picture above). Notice that the turbulence is created on the **back side** of the wing in relation to the air current.

Stall can be provoked if the surface of the aircraft wing - or the wind turbine rotor blade - is not completely even and smooth. A dent in the wing or rotor blade, or a piece of self-adhesive tape can be enough to start the turbulence on the backside, even if the angle of attack is fairly small. Aircraft designers obviously try to avoid stall at all costs, since an aeroplane without the lift from its wings will fall like a rock.

On the page on power control we shall return to the subject of how wind turbine engineers deliberately make use of the stall phenomenon when designing rotor blades.

Drag

Aircraft designers and rotor blade designers are not just concerned with lift and stall, however.

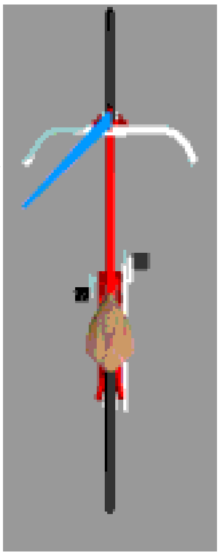
They are also concerned with air resistance, in technical jargon of aerodynamics known as **drag**. Drag will normally increase if the area facing the direction of motion increases.

Aerodynamics of Wind Turbines

Adding Wind Speeds and Directions (Wind Velocities)

The wind which hits the rotor blades of a wind turbine will not come from the direction in which the wind is blowing in the landscape, i.e. from the front of the turbine. This is because the rotor blades themselves are moving.

To understand this, consider the picture of a bicycle which is equipped with a blue banner (or a wind vane) to indicate the direction of the wind: If we have completely calm weather, and the bicycles moves forwards, with, say, 7 metres per second (14 knots), the bicycle will be moving through the air at 7 metres per second. On the bicycle we can measure a wind speed of 7 metres per second relative to the bicycle. The banner will point straight backwards, because the wind will come directly from the front of the bicycle.



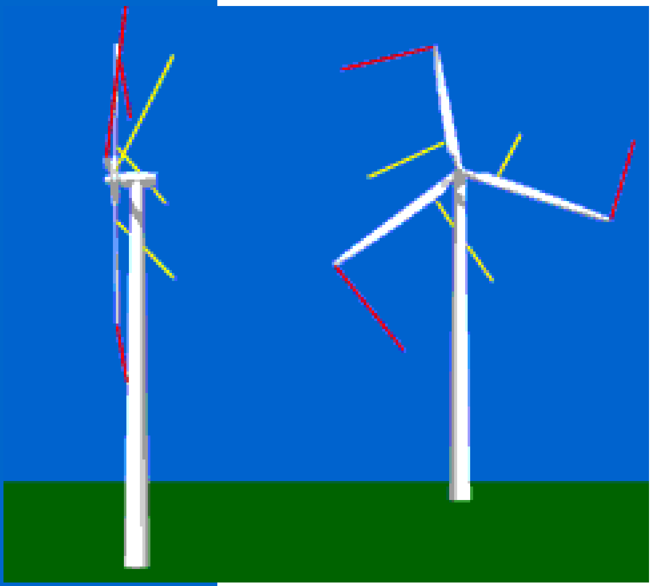
Now, let us look at the bicycle again directly from above, and let us assume that the bicycle moves forward at a constant speed of, once again, 7 metres per second. If the wind is blowing directly from the right, also at 7 metres per second, the banner will clearly be blown partly to the left, at a 45 degree angle relative to the bicycle. With a bit less wind, e.g. 5 metres per second, the banner will be blown less to the left, and the angle will be some 35 degrees. As you can see from the picture, the direction of the wind, **the resulting wind** as measured from the bicycle, will change whenever the speed of the wind changes.

What about the wind speed measured from the bicycle?

The wind is, so to speak, blowing at a rate of 7 metres per second from the front and 5 to 7 metres per second from the right. If you know a bit of geometry or trigonometry you can work out that the wind speed measured on the bicycle will be between 8.6 and 9.9 metres per second.

Enough about changing wind directions, now what about the wind turbine rotor?

Rotor Aerodynamics



To study how the wind moves relative to the rotor blades of a wind turbine, we have fixed red ribbons to the tip of the rotor blades of our model wind turbine, and yellow ribbons some 1/4 out the length of the blade from the hub. We then let the ribbons float freely in the air (in the cartoon we abstract from the air currents created by the blades themselves, and the centrifugal force).

The two images on this page give you one view from the side of the turbine, and another view from the front of the turbine.

Since most wind turbines have constant rotational speed, the speed with which the tip of the rotor blade moves through the air (the tip speed) is typically some 64 m/s, while at the centre of the hub it is zero. 1/4 out the length of the blade, the speed will then be some 16 m/s.

The yellow ribbons close to the hub of the rotor will be blown more towards the back of the turbine than the red ribbons at the tips of the blades. This is obviously because at the tip of the blades the speed is some 8 times higher than the speed of the wind hitting the front of the turbine.

Why are Rotor Blades Twisted?

Rotor blades for large wind turbines are always twisted.

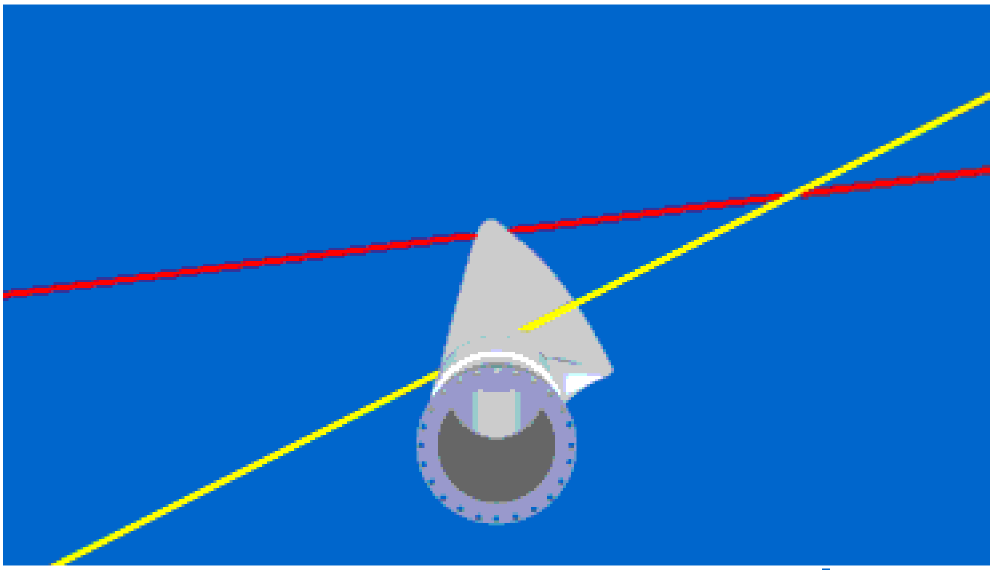
Seen from the rotor blade, the wind will be coming from a much steeper angle (more from the general wind direction in the landscape), as you move towards the root of the blade, and the centre of the rotor.

As you learned on the page on stall, a rotor blade will stop giving lift, if the blade is hit at an angle of attack which is too steep.

Therefore, the rotor blade has to be **twisted**, so as to acheive an optimal angle of attack throughout the length of the blade. However, in the case of stall controlled wind turbines in particular, it is important that the blade is built so that it will stall gradually from the blade root and outwards at high wind speeds.

Updated 29 August 2000
http://windpower.dk/tour/wtrb/rotor.htm

Rotor Blades



Changing the Wind Speed Changes Wind Direction Relative to the Rotor Blade

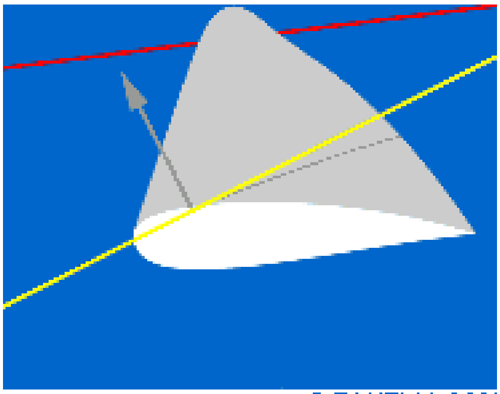
In this next picture we have taken one rotor blade from the previous page off its hub, and we look from the hub towards the tip, at the back side (the lee side) of the rotor blade. The wind in the landscape blows between, say 8 m/s and 16 m/s (from the bottom of the picture), while the tip of the blade rotates towards the left side of the picture.

In the picture you can see how the angle of attack of the wind changes much more dramatically at the root of the blade (yellow line) than at the tip of the blade (red line), as the wind changes. If the wind becomes powerful enough to make the blade stall, it will start stalling at the root of the blade.

Lift Direction

Now, let us cut the rotor blade at the point with the yellow line. In the next picture the grey arrow shows the direction of the lift at this point.

The lift is perpendicular to the direction of the wind. As you can see, the lift pulls the blade partly in the direction we want, i.e. to the left. It also bends the rotor blade somewhat, however.



Rotor Blade Profiles (Cross Sections)

As you can see, wind turbine rotor blades look a lot like the wings of an aircraft. In fact, rotor blade designers often use classical aircraft wing profiles as cross sections in the outermost part of the blade.

The thick profiles in the innermost part of the blade, however, are usually designed specifically for wind turbines. Choosing profiles for rotor blades involves a number of compromises including reliable lift and stall characteristics, and the profile's ability to perform well even if there is some dirt on the surface (which may be a problem in areas where there is little rain).

Rotor Blade Materials

Most modern rotor blades on large wind turbines are made of **glass fibre reinforced plastics**, (GRP), i.e. glass fibre reinforced polyester or epoxy.

Using carbon fibre or aramid (Kevlar) as reinforcing material is another possibility, but usually such blades are uneconomic for large turbines.

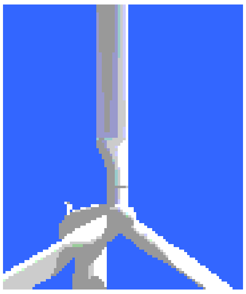
Wood, wood-epoxy, or wood-fibre-epoxy composites have not penetrated the market for rotor blades, although there is still development going on in this area. Steel and aluminium alloys have problems of weight and metal fatigue respectively. They are currently only used for very small wind turbines.

Power Control of Wind Turbines

Wind turbines are designed to produce electrical energy as cheaply as possible. Wind turbines are therefore generally designed so that they yield maximum output at wind speeds around 15 metres per second. (30 knots or 33 mph). Its does not pay to design turbines that maximise their output at stronger winds, because such strong winds are rare.

In case of stronger winds it is necessary to waste part of the excess energy of the wind in order to avoid damaging the wind turbine. All wind turbines are therefore designed with some sort of **power control**. There are two different ways of doing this safely on modern wind turbines.

Pitch Controlled Wind Turbines



On a pitch controlled wind turbine the turbine's electronic controller checks the power output of the turbine several times per second. When the power output becomes too high, it sends an order to the blade pitch mechanism which immediately pitches (turns) the rotor blades slightly out of the wind. Conversely, the blades are turned back into the wind whenever the wind drops again.

The rotor blades thus have to be able to turn around their longitudinal axis (to pitch) as shown in the picture.
Note, that the picture is exaggerated:

During normal operation the blades will pitch a fraction of a degree at a time - and the rotor will be turning at the same time.

Designing a pitch controlled wind turbine requires some clever engineering to make sure that the rotor blades pitch exactly the amount required. On a pitch controlled wind turbine, the computer will generally pitch the blades a few degrees every time the wind changes in order to keep the rotor blades at the optimum angle in order to maximise output for all wind speeds.

The pitch mechanism is usually operated using hydraulics.

Stall Controlled Wind Turbines

(Passive) stall controlled wind turbines have the rotor blades bolted onto the hub at a fixed angle.

The geometry of the rotor blade profile, however has been aerodynamically designed to ensure that the moment the wind speed becomes too high, it creates turbulence on the side of the rotor blade which is not facing the wind as shown in the picture on the previous page. This **stall** prevents the lifting force of the rotor blade from acting on the rotor.

If you have read the section on aerodynamics and aerodynamics and stall, you will realise that as the actual wind speed in the area increases, the angle of attack of the rotor blade will increase, until at some point it starts to stall.

If you look closely at a rotor blade for a stall controlled wind turbine you will notice that the blade is **twisted** slightly as you move along its longitudinal axis. This is partly done in order to ensure that the rotor blade stalls gradually rather than abruptly when the wind speed reaches its critical value. (Other reasons for twisting the blade are mentioned in the previous section on aerodynamics).

The basic advantage of stall control is that one avoids moving parts in the rotor itself, and a complex control system. On the other hand, stall control represents a very complex aerodynamic design problem, and related design challenges in the structural dynamics of the whole wind turbine, e.g. to avoid stall-induced vibrations. Around two thirds of the wind turbines currently being installed in the world are stall controlled machines.

Active Stall Controlled Wind Turbines

An increasing number of larger wind turbines (1 MW and up) are being developed with an active stall power control mechanism.

Technically the active stall machines resemble pitch controlled machines, since they have pitchable blades. In order to get a reasonably large torque (turning force) at low wind speeds, the machines will usually be programmed to pitch their blades much like a pitch controlled machine at low wind speeds. (Often they use only a few fixed steps depending upon the wind speed).

When the machine reaches its rated power, however, you will notice an important difference from the pitch controlled machines: If the generator is about to be overloaded, the machine will pitch its blades in the opposite direction from what a pitch controlled machine does. In other words, it will increase the angle of attack of the rotor blades in order to make the blades go into a deeper stall, thus wasting the excess energy in the wind.

One of the advantages of active stall is that one can control the power output more accurately than with passive stall, so as to avoid overshooting the rated power of the machine at the beginning of a gust of wind. Another advantage is that the machine can be run almost exactly at rated power at all high wind speeds. A normal passive stall controlled wind turbine will usually have a drop in the electrical power output for higher wind speeds, as the rotor blades go into deeper stall.

The pitch mechanism is usually operated using hydraulics or electric stepper motors.

As with pitch control it is largely an economic question whether it is worthwhile to pay for the added complexity of the machine, when the blade pitch mechanism is added.

Other Power Control Methods

Some older wind turbines use **ailerons** (flaps) to control the power of the rotor, just like aircraft use flaps to alter the geometry of the wings to provide extra lift at takeoff.

Another theoretical possibility is to yaw the rotor partly out of the wind to decrease power. This technique of yaw control is in practice used only for tiny wind turbines (1 kW or less), as it subjects the rotor to cyclically varying stress which may ultimately damage the entire structure.

Updated 6 August 2000
http://www.windpower.org/tour/wtrb/powerreg.htm

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.

Yaw Mechanism

Photograph

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.

Wind Turbine Towers

Wind turbine towers,
Navarra, Spain
Photograph
© 1999 Soren Krohn

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.)

Tubular Steel Towers

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.

Photograph © NEG-Micon A/S 1998

Lattice Towers

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.

Photograph © Nordex A/S 1998

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.

Photograph © Soren Krohn 1999

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.

Photograph © Bonus Energy A/S 1998

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.

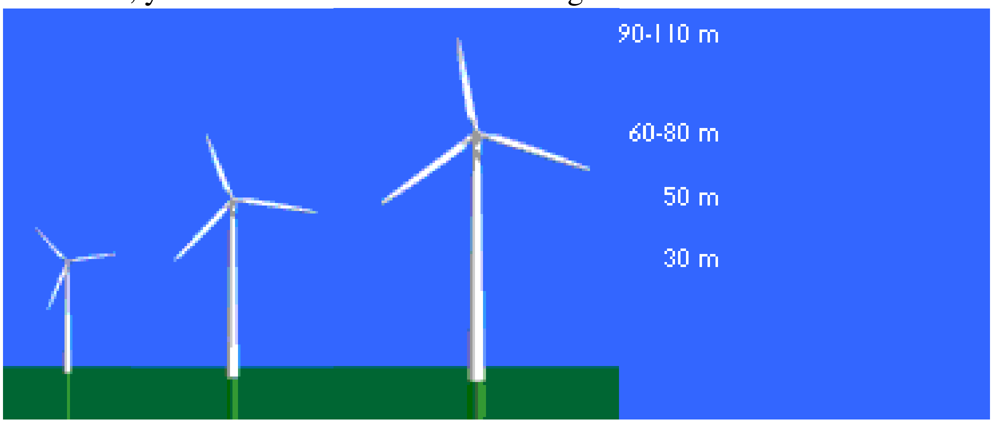
Lattice towers and guyed pole towers have the advantage of giving less wind shade than a massive tower.

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

1. tower costs per metre (10 metre extra tower will presently cost you about 15,000 USD)
2. 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),
3. 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.

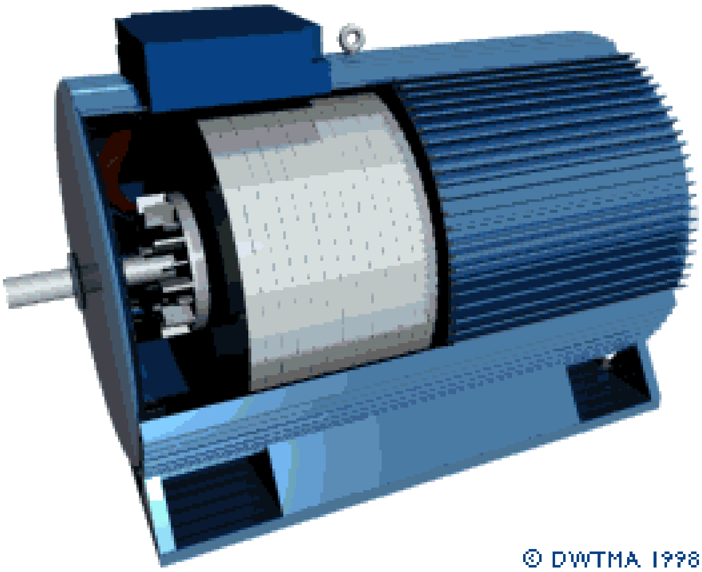
Occupational Safety Considerations

The choice of tower type has consequences for occupational safety: This is discussed in detail on the page on Wind Turbines and Occupational Safety.

Updated 9 September 2000
http://www.windpower.org/tour/wtrb/tower.htm

You can see the internal cooling fan moving inside this generator. It is mounted at the end of the **rotor**, which is hidden inside the shining magnetic steel cylinder, called the **stator**. The radiator-like surface cools the generator.
It is hard to see the details on a real life generator like the one to the right.
Therefore, we'll take it apart and make some simplified models on the next pages.

Wind Turbine Generators



The wind turbine generator converts mechanical energy to electrical energy.
Wind turbine generators are a bit unusual, compared to other generating units you ordinarily find attached to the electrical grid. One reason is that the generator has to work with a power source (the wind turbine rotor) which supplies very fluctuating mechanical power (torque).
These pages assumes that you are familiar with the basics of electricity, electromagnetism, and in particular alternating current. If any of the expressions volt (V), phase, three phase, frequency, or Hertz (Hz) sound strange to you, you should take a look at the Reference Manual on Electricity, and read about alternating current, three phase alternating current, electromagnetism, and induction, before you proceed with the following pages.

Generating Voltage (tension)

On large wind turbines (above 100-150 kW) the voltage (tension) generated by the turbine is usually 690 V three-phase alternating current (AC). The current is subsequently sent through a transformer next to the wind turbine (or inside the tower) to raise the voltage to somewhere between 10,000 and 30,000 volts, depending on the standard in the local electrical grid.
Large manufacturers will supply both 50 Hz wind turbine models (for the electrical grids in most of the world) and 60 Hz models (for the electrical grid in America).

Cooling System

Generators need cooling while they work. On most turbines this is accomplished by encapsulating the generator in a duct, using a large fan for air cooling, but a few manufacturers use water cooled generators. Water cooled generators may be built more compactly, which also gives some electrical efficiency advantages, but they require a radiator in the nacelle to get rid of the heat from the liquid cooling system.

Starting and Stopping the Generator

If you connected (or disconnected) a large wind turbine generator to the grid by flicking an ordinary switch, you would be quite likely to damage both the generator, the gearbox and the current in the grid in the neighbourhood.

You will learn how turbine designers deal with this challenge in the page on Power Quality Issues, later.

Design Choices in Generators and Grid Connection

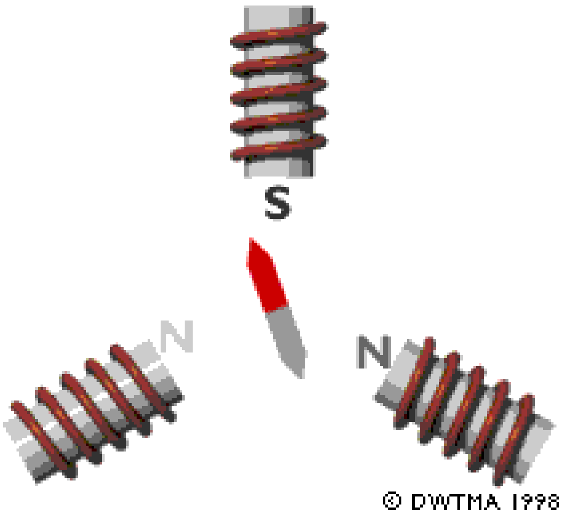
Wind turbines may be designed with either synchronous or asynchronous generators, and with various forms of direct or indirect grid connection of the generator.

Direct grid connection mean that the generator is connected directly to the (usually 3-phase) alternating current grid.

Indirect grid connection means that the current from the turbine passes through a series of electric devices which adjust the current to match that of the grid. With an asynchronous generator this occurs automatically.

Synchronous Generators

3-Phase Generator (or Motor) Principles



All 3-phase generators (or motors) use a rotating magnetic field.

In the picture to the left we have installed three electromagnets around a circle. Each of the three magnets is connected to its own phase in the three phase electrical grid.

As you can see, each of the three electromagnets alternate between producing a South pole and a North pole towards the centre. The letters are shown in black when the magnetism is strong, and in light grey when the magnetism is weak. The fluctuation in magnetism corresponds exactly to the fluctuation in voltage of each phase. When one phase is at its peak, the other two have the current running in the opposite direction, at half the voltage. Since the timing of current in the three magnets is one third of a cycle apart, the magnetic field will make one complete revolution per cycle.

Synchronous Motor Operation

The compass needle (with the North pole painted red) will follow the magnetic field exactly, and make one revolution per cycle. With a 50 Hz grid, the needle will make 50 revolutions per second, i.e. 50 times 60 = 3000 rpm (revolutions per minute).

In the picture above, we have in fact managed to build what is called a 2-pole permanent magnet synchronous motor. The reason why it is called a **synchronous** motor, is that the magnet in the centre will rotate at a constant speed which is synchronous with (running exactly like the cycle in) the rotation of the magnetic field.

The reason why it is called a **2-pole** motor is that it has one North and one South pole. It may look like three poles to you, but in fact the compass needle feels the pull from the sum of the magnetic fields around its own magnetic field. So, if the magnet at the top is a strong South pole, the two magnets at the bottom will add up to a strong North pole.

The reason why it is called a **permanent magnet** motor is that the compass needle in the centre is a permanent magnet, not an electromagnet. (You could make a real motor by replacing the compass needle by a powerful permanent magnet, or an electromagnet which maintains its magnetism through a coil (wound around an iron core) which is fed with direct current).

The setup with the three electromagnets is called the **stator** in the motor, because this part of the motor remains static (in the same place). The compass needle in the centre is called the **rotor**, obviously because it rotates.

Synchronous Generator Operation

If you start forcing the magnet around (instead of letting the current from the grid move it), you will discover that it works like a generator, sending alternating current back into the grid. (You should have a more powerful magnet to produce much electricity). The more force (torque) you apply, the more electricity you generate, but the generator will still run at the same speed dictated by the frequency of the electrical grid.

You may disconnect the generator completely from the grid, and start your own private 3-phase electricity grid, hooking your lamps up to the three coils around the electromagnets. (Remember the principle of magnetic / electrical induction from the reference manual section of this web site). If you disconnect the generator from the main grid, however, you will have to crank it at a constant rotational speed in order to produce alternating current with a constant frequency. Consequently, with this type of generator you will normally want to use an indirect grid connection of the generator.

In practice, permanent magnet synchronous generators are not used very much. There are several reasons for this. One reason is that permanent magnets tend to become demagnetised by working in the powerful magnetic fields inside a generator. Another reason is that powerful magnets (made of rare earth metals, e.g. Neodynium) are quite expensive, even if prices have dropped lately.

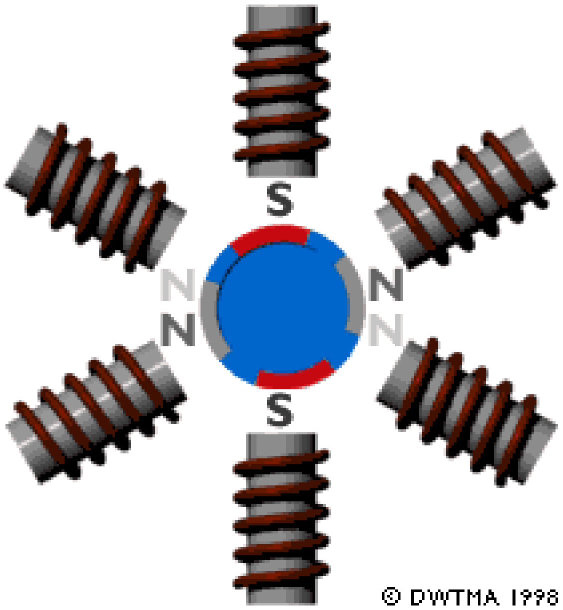
Wind Turbines With Synchronous Generators

Wind turbines which use synchronous generators normally use electromagnets in the rotor which are fed by direct current from the electrical grid. Since the grid supplies alternating current, they first have to convert alternating current to direct current before sending it into the coil windings around the electromagnets in the rotor.

The rotor electromagnets are connected to the current by using brushes and slip rings on the axle (shaft) of the generator.

Changing Generator Rotational Speed

A Four Pole Generator



The speed of a generator (or motor) which is directly connected to a three-phase grid is constant, and dictated by the frequency of the grid, as we learned on the previous page.

If you double the number of magnets in the stator, however, you can ensure that the magnetic field rotates at half the speed.

In the picture to the left, you see how the magnetic field now moves clockwise for **half** a revolution before it reaches the same magnetic pole as before. We have simply connected the six magnets to the three phases in a clockwise order.

This generator (or motor) has **four** poles at all times, two South and two North. Since a four pole generator will only take half a revolution per cycle, it will obviously make 25 revolutions per second on a 50 Hz grid, or 1500 revolutions per minute (rpm).

When we double the number of poles in the stator of a synchronous generator we will have to double the number of magnets in the rotor, as you see on the picture. Otherwise the poles will not match. (We could use to two bent "horseshoe" magnets in this case).

Other Numbers of Poles

Obviously, we could repeat what we just did, and introduce another pair of poles, by adding 3 more electromagnets to the stator. With 9 magnets we get a 6 pole machine, which will run at 1000 rpm on a 50 Hz grid. The general result is the following:

Synchronous Generator Speeds (rpm)

Pole number	50 Hz	60 Hz
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
10	600	720
12	500	600

The term "synchronous generator speed" thus refers to the speed of the generator when it is running synchronously with the grid frequency. It applies to all sorts of generators, however: In the case of asynchronous (induction) generators it is equivalent to the idle speed of the generator.

High or Low Speed Generators?

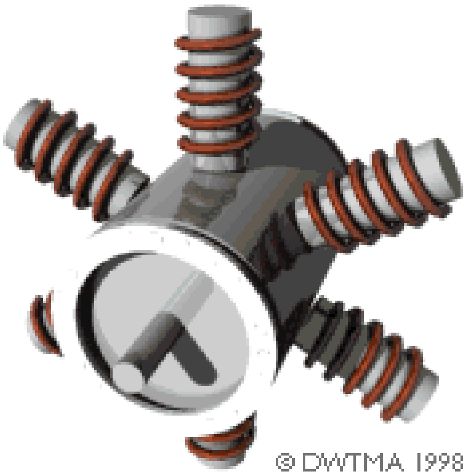
Most wind turbines use generators with four or six poles. The reasons for using these relatively high-speed generators are savings on size and cost.

The maximum force (torque) a generator can handle depends on the rotor volume. For a given power output you then have the choice between a slow-moving, large (expensive) generator, or a high-speed (cheaper) smaller generator.

Asynchronous (Induction) Generators

The picture to the right illustrates the basic principles in the asynchronous generator, much as we saw it presented on the previous pages.

In reality, only the rotor part looks different, as you will see on the this page.



Note: Before reading this page, you should have completed the previous three pages on Wind Turbine Generators.

Most wind turbines in the world use a so-called three phase asynchronous (cage wound) generator, also called an **induction generator** to generate alternating current. This type of generator is not widely used outside the wind turbine industry, and in small hydropower units, but the world has a lot of experience in dealing with it anyway:

The curious thing about this type of generator is that it was really originally designed as an electric motor. In fact, one third of the world's electricity consumption is used for running induction motors driving machinery in factories, pumps, fans, compressors, elevators, and other applications where you need to convert electrical energy to mechanical energy.

One reason for choosing this type of generator is that it is very reliable, and tends to be comparatively inexpensive. The generator also has some mechanical properties which are useful for wind turbines. (Generator slip, and a certain overload capability).

The Cage Rotor

The key component of the asynchronous generator is the **cage rotor**.

(It used to be called a **squirrel cage rotor** but after it became politically incorrect to exercise your domestic rodents in a treadmill, we only have this less captivating name).

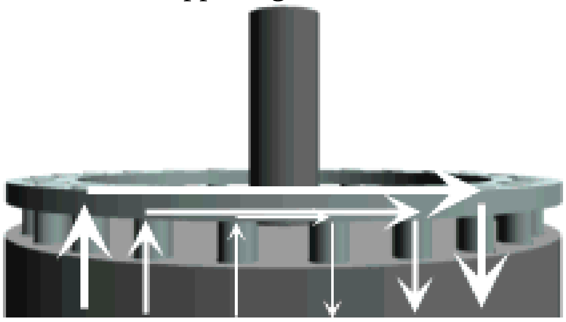
It is the rotor that makes the asynchronous generator different from the synchronous generator. The rotor consists of a number of copper or aluminium bars which are connected electrically by aluminium end rings, as you see in the picture to the left.

In the picture at the top of the page you see how the rotor is provided with an "iron" core, using a stack of thin insulated steel laminations, with holes punched for the conducting aluminium bars. The rotor is placed in the middle of the stator, which in this case, once again, is a 4-pole stator which is directly connected to the three phases of the electrical grid.

Motor Operation

When the current is connected, the machine will start turning like a motor at a speed which is just slightly below the synchronous speed of the rotating magnetic field from the stator. Now, what is happening?

If we look at the rotor bars from above (in the picture to the right) we have a magnetic field which moves relative to the rotor. This induces a very strong current in the rotor bars which offer very little resistance to the current, since they are short circuited by the end rings.



The rotor then develops its own magnetic poles, which in turn become dragged along by the electromagnetic force from the rotating magnetic field in the stator.

Generator Operation

Now, what happens if we manually crank this rotor around at exactly the synchronous speed of the generator, e.g. 1500 rpm (revolutions per minute), as we saw for the 4-pole synchronous generator on the previous page? The answer is: Nothing. Since the magnetic field rotates at exactly the same speed as the rotor, we see no induction phenomena in the rotor, and it will not interact with the stator.

But what if we increase speed above 1500 rpm? In that case the rotor moves faster than the rotating magnetic field from the stator, which means that once again the stator induces a strong current in the rotor. The harder you crank the rotor, the more power will be transferred as an electromagnetic force to the stator, and in turn converted to electricity which is fed into the electrical grid.

Generator Slip

The speed of the asynchronous generator will vary with the turning force (moment, or torque) applied to it. In practice, the difference between the rotational speed at peak power and at idle is very small, about 1 per cent. This difference in per cent of the synchronous speed, is called the generator's **slip**. Thus a 4-pole generator will run idle at 1500 rpm if it is attached to a grid with a 50 Hz current. If the generator is producing at its maximum power, it will be running at 1515 rpm.

It is a very useful mechanical property that the generator will increase or decrease its speed slightly if the torque varies. This means that there will be less tear and wear on the gearbox. (Lower peak torque). This is one of the most important reasons for using an asynchronous generator rather than a synchronous generator on a wind turbine which is directly connected to the electrical grid.

Automatic Pole Adjustment of the Rotor

Did you notice that we did not specify the number of poles in the stator when we described the rotor? The clever thing about the cage rotor is that it adapts itself to the number of poles in the stator automatically. The same rotor can therefore be used with a wide variety of pole numbers.

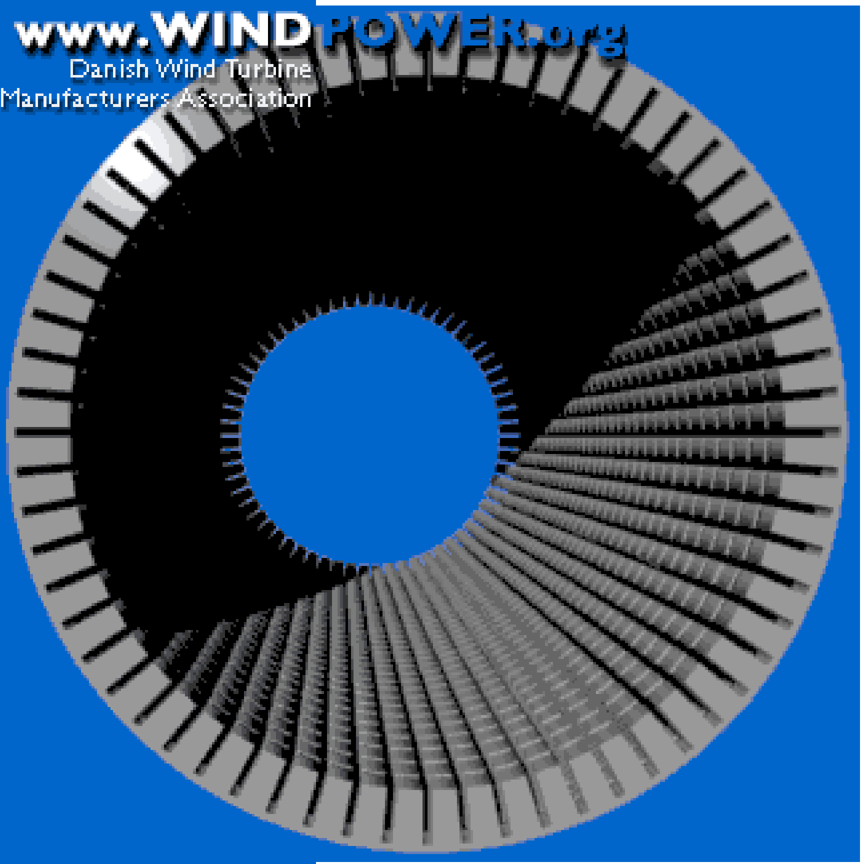
Home

Grid Connection Required

On the page about the permanent magnet synchronous generator we showed that it could run as a generator without connection to the public grid.

An asynchronous generator is different, because it requires the stator to be magnetised from the grid before it works.

You can run an asynchronous generator in a stand alone system, however, if it is provided with capacitors which supply the necessary magnetisation current. It also requires that there be some remanence in the rotor iron, i.e. some leftover magnetism when you start the turbine. Otherwise you will need a battery and power electronics, or a small diesel generator to start the system).



Changing the Number of Generator Poles

You may be thinking that a stator with twice as many magnets would be twice as expensive, but that is not really the case. Generators (and motors) are usually made with a very large number of stator magnets anyway, as you see in the picture. (We have not yet added the stator coil windings on the iron).

The reason for this stator arrangement is that we wish to minimise the air gap between the rotor and the stator. At the the same time we need to provide cooling of the magnets. The stator iron in reality consists of a large number of thin (0.5 mm) insulated steel sheets which are stacked to form the stator iron. This layering is done to prevent current eddies in the stator iron from decreasing the efficiency of the generator.

The problem of providing more generator poles on an asynchronous cage wound generator then really boils down to connecting the neighbouring magnets differently: Either we take a bunch of magnets at a time, connecting them to the same phase as we move around the stator, or else we change to the next phase every time we get to the next magnet.

Very Like a Whale
In reality, the stator of a generator consists of a very large number of electromagnets.

Two Speed, Pole Changing Generators

Some manufacturers fit their turbines with two generators, a small one for periods of low winds, and a large one for periods of high winds.

A more common design on newer machines is pole changing generators, i.e. generators which (depending on how their stator magnets are connected) may run with a different number of poles, and thus a different rotational speed.

Some electrical generators are custom built as two-in-one, i.e. they are able to run as e.g. either 150 kW or 600 kW generators, and at two different speeds. This design has become ever more widespread throughout the industry.

Whether it is worthwhile to use a double generator or a higher number of poles for low winds depends on the local wind speed distribution, and the extra cost of the pole changing generator compared to the price the turbine owner gets for the electricity. (You should keep in mind that the energy content of low winds is very small).

A good reason for having a dual generator system, however, is that you may run your turbine at a lower rotational speed at low wind speeds. This is both more efficient (aerodynamically), and it means less noise from the rotor blades (which is usually only a problem at **low** wind speeds).

Incidentally, you may have a few pole changing motors in your house without even knowing it: Washing machines which can also spin dry clothes usually have pole changing motors which are able to run at low speed for washing and at high speed for spinning. Similarly, exhaust fans in your kitchen may be built for two or three different speeds. (In the latter case with a variable speed fan, you can use what you have learned about the energy in the wind: If you want to move twice as much air out of your house per minute using the same fan, it will cost you eight times as much electricity).

Variable Slip Generators for Wind Turbines

Manufacturers of electric motors have for many years been faced with the problem that their motors can only run at certain almost fixed speeds determined by the number of poles in the motor.

As we learned on the previous page, the motor (or generator) slip in an asynchronous (induction) machine is usually very small for reasons of efficiency, so the rotational speed will vary with around 1 per cent between idle and full load.

The slip, however is a function of the (DC) resistance (measured in ohms) in the rotor windings of the generator. The higher resistance, the higher the slip. so one way of varying the slip is to vary the resistance in the rotor. In this way one may increase generator slip to e.g. 10 per cent.

On motors, this is usually done by having a wound rotor, i.e. a rotor with copper wire windings which are connected in a star, and connected with external variable resistors, plus an electronic control system to operate the resistors. The connection has usually been done with brushes and slip rings, which is a clear drawback over the elegantly simple technical design of an cage wound rotor machine. It also introduces parts which wear down in the generator, and thus the generator requires extra maintenance.

Opti Slip

An interesting variation of the variable slip induction generator avoids the problem of introducing slip rings, brushes, external resistors, and maintenance altogether.

By mounting the external resistors on the rotor itself, and mounting the electronic control system on the rotor as well, you still have the problem of how to communicate the amount of slip you need to the rotor. This communication can be done very elegantly, however, using optical fibre communications, and sending the signal across to the rotor electronics each time it passes a stationary optical fibre.

Running a Pitch Controlled Turbine at Variable Speed

As mentioned on the next page, there are a number of advantages of being able to run a wind turbine at variable speed.

One good reason for wanting to be able to run a turbine partially at variable speed is the fact that pitch control (controlling the torque in order not to overload the gearbox and generator by pitching the wind turbine blades) is a mechanical process. This means that the reaction time for the pitch mechanism becomes a critical factor in turbine design.

If you have a variable slip generator, however, you may start increasing its slip once you are close to the rated power of the turbine. The control strategy applied in a widely used Danish turbine design (600 kW and up) is to run the generator at half of its maximum slip when the turbine is operating near the rated power. When a wind gust occurs, the control mechanism signals to increase generator slip to allow the rotor to run a bit faster while the pitch mechanism begins to cope with the situation by pitching the blades more out of the wind. Once the pitch mechanism has done its work, the slip is decreased again. In case the wind suddenly drops, the process is applied in reverse.

Although these concepts may sound simple, it is quite a technical challenge to ensure that the two power control mechanisms co-operate efficiently.

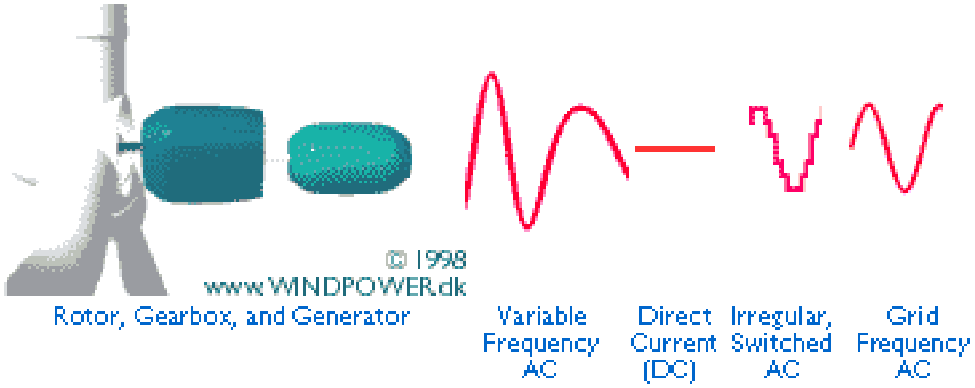
Improving Power Quality

You may protest that running a generator at high slip releases more heat from the generator, which runs less efficiently. That is not a problem in itself, however, since the only alternative is to waste the excess wind energy by pitching the rotor blades out of the wind.

One of the real benefits of using the control strategy mentioned here is that you get a better power quality, since the fluctuations in power output are "eaten up" or "topped up" by varying the generator slip and storing or releasing part of the energy as rotational energy in the wind turbine rotor.

Updated 6 August 2000
http://www.windpower.org/tour/wtrb/varislip.htm

Indirect Grid Connection of Wind Turbines



Generating Alternating Current (AC) at Variable Frequency

Most wind turbines run at almost constant speed with direct grid connection. With **indirect** grid connection, however, the wind turbine generator runs in its own, separate mini AC-grid, as illustrated in the graphic. This grid is controlled electronically (using an inverter), so that the frequency of the alternating current in the stator of the generator may be varied. In this way it is possible to run the turbine at variable rotational speed. Thus the turbine will generate alternating current at exactly the variable frequency applied to the stator.

The generator may be either a synchronous generator or an asynchronous generator, and the turbine may have a gearbox, as in the image above, or run without a gearbox if the generator has many poles, as explained on the next page.

Conversion to Direct Current (DC)

AC current with a variable frequency cannot be handled by the public electrical grid. We therefore start by rectifying it, i.e. we convert it into direct current, DC. The conversion from variable frequency AC to DC can be done using thyristors or large power transistors.

Conversion to Fixed Frequency AC

We then convert the (fluctuating) direct current to an alternating current (using an inverter) with exactly the same frequency as the public electrical grid. This conversion to AC in the inverter can also be done using either thyristors or transistors.

Thyristors or power transistors are large semiconductor switches that operate without mechanical parts. The kind of alternating current one gets out of an inverter looks quite ugly at first sight - nothing like the smooth sinusoidal curve we learned about when studying alternating current. Instead, we get a series of sudden jumps in the voltage and current, as you saw in the animation above.

Filtering the AC

The rectangular shaped waves can be smoothed out, however, using appropriate inductances and capacitors, in a so-called AC filter mechanism. The somewhat jagged appearance of the voltage does not disappear completely, however, as explained below.

Advantages of Indirect Grid Connection: Variable Speed

The advantage of indirect grid connection is that it is possible to run the wind turbine at variable speed.

The primary advantage is that gusts of wind can be allowed to make the rotor turn faster, thus storing part of the excess energy as rotational energy until the gust is over. Obviously, this requires an intelligent control strategy, since we have to be able to differentiate between gusts and higher wind speed in general. Thus it is possible to reduce the peak torque (reducing wear on the gearbox and generator), and we may also reduce the fatigue loads on the tower and rotor blades.

The secondary advantage is that with power electronics one may control reactive power (i.e. the phase shifting of current relative to voltage in the AC grid), so as to improve the power quality in the electrical grid. This may be useful, particularly if a turbine is running on a weak electrical grid.

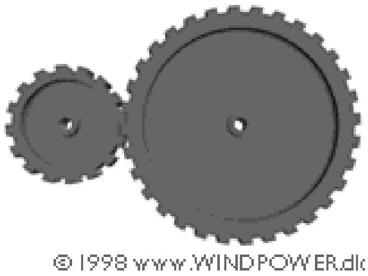
Theoretically, variable speed may also give a slight advantage in terms of annual production, since it is possible to run the machine at an optimal rotational speed, depending on the wind speed. From an economic point of view that advantage is so small, however, that it is hardly worth mentioning.

Disadvantages of Indirect Grid Connection

The basic disadvantage of indirect grid connection is cost. As we just learned, the turbine will need a rectifier and two inverters, one to control the stator current, and another to generate the output current. Presently, it seems that the cost of power electronics exceeds the gains to be made in building lighter turbines, but that may change as the cost of power electronics decreases. Looking at operating statistics from wind turbines using power electronics (published by the the German ISET Institute), it also seems that availability rates for these machines tend to be somewhat lower than conventional machines, due to failures in the power electronics.

Other disadvantages are the energy lost in the AC-DC-AC conversion process, and the fact that power electronics may introduce harmonic distortion of the alternating current in the electrical grid, thus reducing power quality. The problem of harmonic distortion arises because the filtering process mentioned above is not perfect, and it may leave some "overtones" (multiples of the grid frequency) in the output current.

Gearboxes for Wind Turbines



Why Use a Gearbox?

The power from the rotation of the wind turbine rotor is transferred to the generator through the power train, i.e. through the main shaft, the gearbox and the high speed shaft, as we saw on the page with the Components of a Wind Turbine.

But why use a gearbox? Couldn't we just drive the generator directly with the power from the main shaft?

If we used an ordinary generator, directly connected to a 50 Hz AC (alternating current) three phase grid with two, four, or six poles, we would have to have an extremely high speed turbine with between 1000 and 3000 revolutions per minute (rpm), as we can see in the page on Changing Generator Rotational Speed. With a 43 metre rotor diameter that would imply a tip speed of the rotor of far more than twice the speed of sound, so we might as well forget it.

Another possibility is to build a slow-moving AC generator with many poles. But if you wanted to connect the generator directly to the grid, you would end up with a 200 pole generator (i.e. 300 magnets) to arrive at a reasonable rotational speed of 30 rpm.

Another problem is, that the mass of the rotor of the generator has to be roughly proportional to the amount of torque (moment, or turning force) it has to handle. So a directly driven generator will be very heavy (and expensive) in any case.

Less Torque, More Speed

The practical solution, which is used in the opposite direction in lots of industrial machinery, and in connection with car engines is to use a gearbox. With a gearbox you convert between slowly rotating, high torque power which you get from the wind turbine rotor - and high speed, low torque power, which you use for the generator.

The gearbox in a wind turbine does not "change gears". It normally has a single gear ratio between the rotation of the rotor and the generator. For a 600 or 750 kW machine, the gear ratio is typically approximately 1 to 50.

The picture below shows a 1.5 MW gearbox for a wind turbine. This particular gearbox is somewhat unusual, since it has flanges for two generators on the high speed side (to the right). The orange gadgets just below the generator attachments to the right are the hydraulically operated emergency disc brakes. In the background you see the lower part of a nacelle for a 1.5 MW turbine.

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Updated 25 October 2000
http://www.windpower.org/tour/wtrb/powtrain.htm

The Electronic Wind Turbine Controller

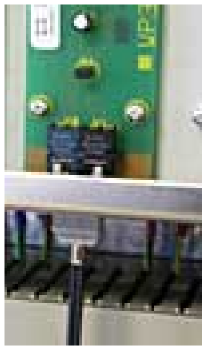
The wind turbine controller consists of a number of computers which continuously monitor the condition of the wind turbine and collect statistics on its operation. As the name implies, the controller also controls a large number of switches, hydraulic pumps, valves, and motors within the wind turbine.

As wind turbine sizes increase to megawatt machines, it becomes even more important that they have a high availability rate, i.e. that they function reliably all the time.

Communicating with the Outside World

The controller communicates with the owner or operator of the wind turbine via a communications link, e.g. sending alarms or requests for service over the telephone or a radio link. It is also possible to call the wind turbine to collect statistics, and check its present status. In wind parks one of the turbines will usually be equipped with a PC from which it is possible to control and collect data from the rest of the wind turbines in the park. This PC can be called over a telephone line or a radio link.

Internal Communications



There is usually a controller both at the bottom of the tower and in the nacelle. On recent wind turbine models, the communication between the controllers is usually done using fibre optics. The image to the right shows a fibre optics communications unit. On some recent models, there is a third controller placed in the hub of the rotor. That unit usually communicates with the nacelle unit using serial communications through a cable connected with slip rings and brushes on the main shaft.

Fail Safe Mechanisms and Redundancy

Computers and sensors are usually duplicated (redundant) in all safety or operation sensitive areas of newer, large machines. The controller continuously compares the readings from measurements throughout the wind turbine to ensure that both the sensors and the computers themselves are OK. The picture at the top of the page shows the controller of a megawatt machine, and has two central computers. (We removed the cover on one of the two computers to show the electronics).

What is Monitored?

It is possible to monitor or set somewhere between 100 and 500 parameter values in a modern wind turbine. The controller may e.g. check the rotational speed of the rotor, the generator, its voltage and current. In addition, lightning strikes and their charge may be registered. Furthermore measurements may be made of of outside air temperature, temperature in the electronic cabinets, oil temperature in the gearbox, the temperature of the generator windings, the temperature in the gearbox bearings, hydraulic pressure, the pitch angle of each rotor blade (for pitch controlled or active stall controlled machines), the yaw angle (by counting the number of teeth on yaw wheel), the number of power cable twists, wind direction, wind speed from the anemometer, the size and frequency of vibrations in the nacelle and the rotor blades, the thickness of the brake linings, whether the tower door is open or closed (alarm system).

Control Strategies

Many of the business secrets of the wind turbine manufacturers are to be found in the way the controller interacts with the wind turbine components. Improved control strategies are responsible for an important part of the increase in wind turbine productivity in recent years.

An interesting strategy pursued by some manufacturers is to adapt the operational strategy to the local wind climate. In this way it may e.g. be possible to minimise uneconomic tear and wear on the machine during (rare) periods of rough weather.

Updated 6 August 2000
http://www.windpower.org/tour/wtrb/control.htm

Controlling Power Quality from Wind Turbines

Most people think of the controller as the unit which runs the wind turbine, e.g. yaws it against the wind, checks that the safety systems are OK, and starts the turbine.

The controller does indeed do all these things, but it also looks after the power quality of the current generated by the wind turbine.

Grid Connection and Power Quality

In the section about power quality you will learn how electricity companies require that wind turbines connect "softly" to the grid, and how they have certain requirements that the alternating current and voltage move in step with one another.

The image to the right shows the high voltage section of a controller for a megawatt machine. This part of the controller operates e.g. the thyristors which ensure soft coupling to the electrical grid.

Reactive Power Control

Voltage and current are typically measured 128 times per alternating current cycle, (i.e. 50 x 128 times per second or 60 x 128 times per second, depending on the electrical grid frequency). On this basis, a so called DSP processor calculates the stability of the grid frequency and the active and reactive power of the turbine. (The reactive power component is basically a question of whether the voltage and the current are in phase or not).

In order to ensure the proper power quality, the controller may switch on or switch off a large number of electrical capacitors which adjust the reactive power, (i.e. the phase angle between the voltage and the current). As you can see in the image to the left, the switchable capacitor bank is quite a large control unit in itself in a megawatt sized machine.

Electromagnetic Compatibility (EMC)

There are very powerful electromagnetic fields around power cables and generators in a wind turbine. This means that the electronics in the controller system has to be insensitive to electromagnetic fields.

Conversely, the electronics should not emit electromagnetic radiation which can inhibit the functioning of other electronic equipment. The image to the left shows a radiation free room with metal walls in the laboratory of one of the largest wind turbine controller manufacturers. The equipment in the room is used to measure electromagnetic emissions from the components of the controllers.

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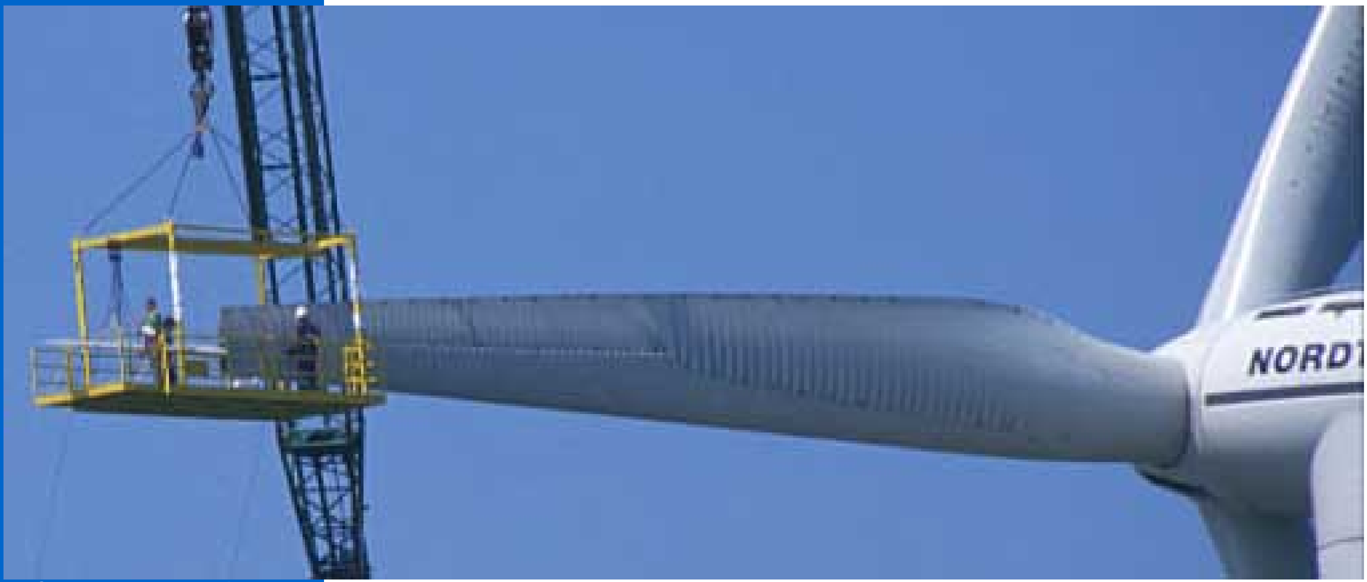
http://www.windpower.org/tour/wtrb/control2.htm

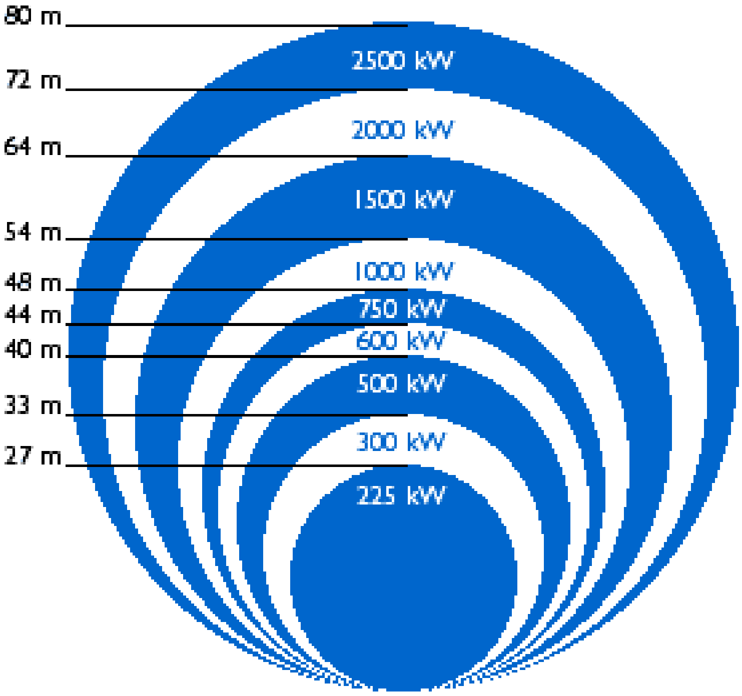
Size of Wind Turbines



Service crew working on a 32 m rotor blade on a 1.5 MW wind turbine

Photograph © 2000 Christian Kjaer

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**.

You may take a look at some megawatt-sized wind turbines in the picture gallery.

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. (See the section on wind turbines in the landscape).

Updated 6 August 2000
http://www.windpower.org/tour/wtrb/size.htm

Wind Turbine Safety


Photograph

The components of a wind turbine are designed to last 20 years. This means that they will have to endure more than 120,000 operating hours, often under stormy weather conditions.

If you compare with an ordinary automobile engine, it usually only operates only some 5,000 hours during its lifetime. Large wind turbines are equipped with a number of safety devices to ensure safe operation during their lifetime.

Sensors

One of the classical, and most simple safety devices in a wind turbine is the **vibration sensor** in the image above, which was first installed in the Gedser wind turbine. It simply consists of a ball resting on a ring. The ball is connected to a switch through a chain. If the turbine starts shaking, the ball will fall off the ring and switch the turbine off.

There are many other sensors in the nacelle, e.g. electronic thermometers which check the oil temperature in the gearbox and the temperature of the generator.

Rotor Blades

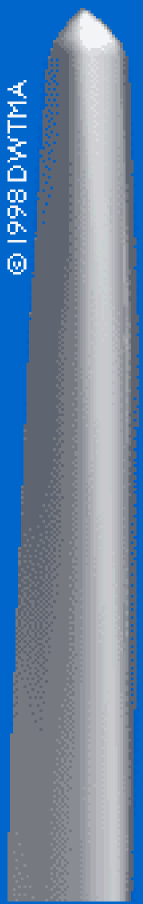
Safety regulations for wind turbines vary between countries. Denmark is the only country in which the law requires that all new rotor blades are tested both **statically**, i.e. applying weights to bend the blade, and **dynamically**, i.e. testing the blade's ability to withstand fatigue from repeated bending more than five million times. You may read more about this on the page on Testing Wind Turbine Rotor Blades.

Overspeed Protection

It is essential that wind turbines stop automatically in case of malfunction of a critical component. E.g. if the generator overheats or is disconnected from the electrical grid it will stop braking the rotation of the rotor, and the rotor will start accelerating rapidly within a matter of seconds.

In such a case it is essential to have an overspeed protection system. Danish wind turbines are requited by law to have **two independent fail safe brake mechanisms** to stop the turbine.

Click to Activate Tip Brake



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Aerodynamic Braking System: Tip Brakes

The primary braking system for most modern wind turbines is the **aerodynamic braking system**, which essentially consists in turning the rotor blades about 90 degrees along their longitudinal axis (in the case of a pitch controlled turbine or an active stall controlled turbine), or in turning the **rotor blade tips** 90 degrees (in the case of a stall controlled turbine).

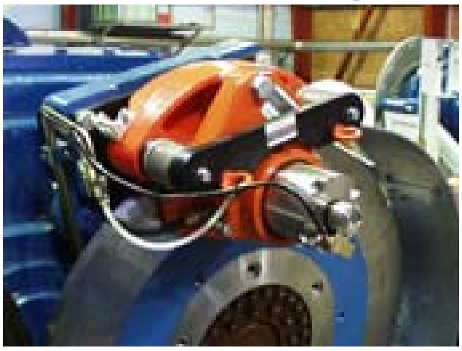
These systems are usually spring operated, in order to work even in case of electrical power failure, and they are automatically activated if the hydraulic system in the turbine loses pressure. The hydraulic system in the turbine is used turn the blades or blade tips back in place once the dangerous situation is over.

Experience has proved that aerodynamic braking systems are extremely safe.

They will stop the turbine in a matter of a couple of rotations, at the most. In addition, they offer a very gentle way of braking the turbine without any major stress, tear and wear on the tower and the machinery.

The normal way of stopping a modern turbine (for any reason) is therefore to use the aerodynamic braking system.

Mechanical Braking System



The mechanical brake is used as a backup system for the aerodynamic braking system, and as a parking brake, once the turbine is stopped in the case of a stall controlled turbine.

Pitch controlled turbines rarely need to activate the mechanical brake (except for maintenance work), as the rotor cannot move very much once the rotor blades are pitched 90 degrees.

Wind Turbine Occupational Safety

Towers

Large, modern wind turbines normally use conical tubular steel towers. The primary advantage of this tower over a lattice tower is that it makes it safer and far more comfortable for service personnel to access the wind turbine for repair and maintenance. The disadvantage is cost.

The primary danger in working with wind turbines is the height above ground during installation work and when doing maintenance work.

New Danish wind turbines are required to have **fall protection devices**, i.e. the person climbing the turbine has to wear a parachutist-like set of straps.

The straps are connected with a steel wire to an anchoring system that follows the person while climbing or descending the turbine.

The wire system has to include a shock absorber, so that persons are reasonably safe in case of a fall.

Photograph
© 1999 Soren Krohn

A Danish tradition (which has later been taken up by other manufacturers), is to place the access ladders at a certain distance from the wall. This enables service personnel to climb the tower while being able to rest the shoulders against the inside wall of the tower.

In this image you see the editor of our Spanish web site verifying that this is actually a very practical solution.

Protection from the machinery, fire protection and electrical insulation protection is governed by a number of national and international standards.

During servicing it is essential that the machinery can be stopped completely. In addition to a mechanical brake, the rotor can be locked in place with a pin, to prevent any movement of the mechanical parts whatsoever.

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Updated 9 September 2000
http://www.windpower.org/tour/wtrb/safety2.htm

www.WINDPOWER.org
Danish Wind Turbine Manufacturers Association

Guided Tour

Wind Turbine Design: Basic Load Considerations

Water pumping windmill, South Australia, Photograph © 1997 Soren Krohn

Whether you are building wind turbines or helicopters, you have to take the strength, the dynamic behaviour, and the fatigue properties of your materials and the entire assembly into consideration.

Extreme Loads (Forces)

Comodoro Rivadavia, Argentina (NEG Micon 750 kW turbines) Photograph © 1998 Soren Krohn

Wind turbines are built to catch the wind's kinetic (motion) energy. You may therefore wonder why modern wind turbines are not built with a lot of rotor blades, like the old "American" windmills you have seen in the Western movies.

Turbines with **many** blades or very **wide** blades, i.e. turbines with a very **solid** rotor, however, will be subject to very large forces, when the wind blows at a hurricane speed. (Remember, that the energy content of the wind varies with the **third** power (the cube) of the wind speed).

Wind turbine manufacturers have to certify that their turbines are built, so that they can withstand **extreme winds** which occur, say, during 10 minutes once every 50 years.

To limit the influence of the extreme winds turbine manufacturers therefore generally prefer to build turbines with a few, long, narrow blades.

In order to make up for the narrowness of the blades facing the wind, turbine manufacturers prefer to let the turbines rotate relatively quickly.

Fatigue Loads (Forces)

Wind turbines are subject to fluctuating winds, and hence fluctuating forces. This is particularly the case if they are located in a very turbulent wind climate.

Components which are subject to repeated bending, such as rotor blades, may eventually develop cracks which ultimately may make the component break. A historical example is the huge German Growian machine (100 m rotor diameter) which had to be taken out of service after less than three weeks of operation. Metal **fatigue** is a well known problem in many industries. Metal is therefore generally not favoured as a material for rotor blades.

When designing a wind turbine it is extremely important to calculate in advance how the different components will vibrate, both individually, and jointly. It is also important to calculate the forces involved in each bending or stretching of a component.

This is the subject of **structural dynamics**, where physicists have developed mathematical computer models that analyse the behaviour of an entire wind turbine.

These models are used by wind turbine manufacturers to design their machines safely.

Structural Dynamics: An Example *)

A 50 metre tall wind turbine tower will have a tendency to swing back and forth, say, every three seconds. The frequency with which the tower oscillates back and forth is also known as the **eigenfrequency** of the tower. The eigenfrequency depends on both the height of the tower, the thickness of its walls, the type of steel, and the weight of the nacelle and rotor.

Now, each time a rotor blade passes the wind shade of the tower, the rotor will push slightly less against the tower.

If the rotor turns with a rotational speed such that a rotor blade passes the tower each time the tower is in one of its extreme positions, then the rotor blade may either **dampen** or **amplify** (reinforce) the oscillations of the tower.

The rotor blades themselves are also flexible, and may have a tendency to vibrate, say, once per second. As you can see, it is very important to know the eigenfreqencies of each component in order to design a safe turbine that does not oscillate out of control.

*) A very dramatic example of structural dynamic forces at work under influence of the wind (undampened torsion oscillations) is the famous crash of the Tacoma Bridge close to Seattle in the United States. You may find a short movie clip (700 K) on the disaster on the Internet.

Wind Turbines: Horizontal or Vertical Axis Machines?

Horizontal Axis Wind Turbines

Most of the technology described on these pages is related to horizontal axis wind turbines (HAWTs, as some people like to call them).

The reason is simple: All grid-connected commercial wind turbines today are built with a propeller-type rotor on a horizontal axis (i.e. a horizontal main shaft).

The purpose of the rotor, of course, is to convert the linear motion of the wind into rotational energy that can be used to drive a generator. The same basic principle is used in a modern water turbine, where the flow of water is parallel to the rotational axis of the turbine blades.

Vertical Axis Wind Turbines

Eole C, a 4200 kW Vertical axis Darrieus wind turbine with 100 m rotor diameter at Cap Chat, Qu bec, Canada. The machine (which is the world's largest wind turbine) is no longer operational.

Photograph © 1997 Soren Krohn

As you will probably recall, classical water wheels let the water arrive at a right angle (perpendicular) to the rotational axis (shaft) of the water wheel.

Vertical axis wind turbines (VAWTs as some people call them) are a bit like water wheels in that sense. (Some vertical axis turbine types could actually work with a horizontal axis as well, but they would hardly be able to beat the efficiency of a propeller-type turbine).

The only vertical axis turbine which has ever been manufactured commercially at any volume is the **Darrieus machine**, named after the French engineer Georges Darrieus who patented the design in 1931. (It was manufactured by the U.S. company FloWind which went bankrupt in 1997). The Darrieus machine is characterised by its C-shaped rotor blades which make it look a bit like an eggbeater. It is normally built with two or three blades.

The basic theoretical advantages of a vertical axis machine are
1) you may place the generator, gearbox etc. on the ground, and you may not need a tower for the machine.
2) you do not need a yaw mechanism to turn the rotor against the wind.

The basic disadvantages are
1) Wind speeds are very low close to ground level, so although you may save a tower, your wind speeds will be very low on the lower part of your rotor.
2) The overall efficiency of the vertical axis machines is not impressive.
3) The machine is not self-starting (e.g. a Darrieus machine will need a "push" before it starts. This is only a minor inconvenience for a grid

connected turbine, however, since you may use the generator as a motor drawing current from the grid to to start the machine).
4) The machine may need guy wires to hold it up, but guy wires are impractical in heavily farmed areas.
5) Replacing the main bearing for the rotor necessitates removing the rotor on both a horizontal and a vertical axis machine. In the case of the latter, it means tearing the whole machine down. (That is why EOLE 4 in the picture is standing idle).

Wind Turbines:
Upwind or Downwind Machines?

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

Small downwind turbine (22 kW).
You may notice that the rotor is "coning" away from the tower.
Photograph
© 1998 Soren Krohn

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.

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Updated 19 January 2001
http://www.windpower.org/tour/design/updown.htm

Wind Turbines:
How many blades?

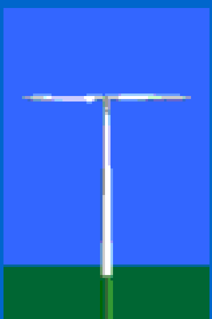
Why Not an Even Number of Blades?

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.

The Danish Three-Bladed Concept

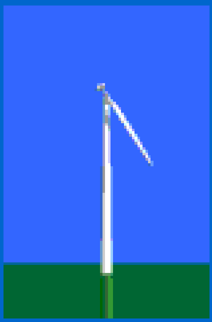
Most modern wind turbines are three-bladed designs with the rotor position maintained **upwind** (on the windy side of the tower) using electrical motors in their yaw mechanism. This design is usually called the classical *Danish concept*, and tends to be a standard against which other concepts are evaluated. 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.



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, partly 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.

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 blades 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.



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.

Updated 3 January 2001
http://www.windpower.org/tour/design/concepts.htm

Optimising Wind Turbines

Optimisation and Economics

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.
Photograph © 1998 by Soren Krohn

The water pumping windmills to the left 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. In the next sections we shall look at some of the choices manufacturers have to make.

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.

Tower Heights

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.

Designing for Low Mechanical Noise from Wind Turbines

Sound emissions from wind turbines may have two different origins: Mechanical noise which we deal with on this page, and aerodynamic noise which we deal with on the next page.

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.

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.

As explained in the tour section on Research and Development, 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 wind modern turbines on the market today, although it can be useful to minimise 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.

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.

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.

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Updated 9 September 2000

http://www.windpower.org/tour/design/quietae.htm

Manufacturing Wind Turbine Nacelles

Photographs

Take a 360 Panoramic View (QuickTime VR) into a Wind Turbine Factory

Hold the mouse down on the picture and **drag** gently right, left, up or down to pan or tilt the camera. Use the **shift** key to zoom in, use the **ctrl** key to zoom out. This image (364K) requires a QuickTime plugin in your browser. You may download the necessary plugin and a QuickTime player from Apple's web site.

Testing Wind Turbine Rotor Blades

Fatigue Testing of Rotor Blades

Video
© 1999 Soren Krohn

Click on image to restart video

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 Spark r 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).

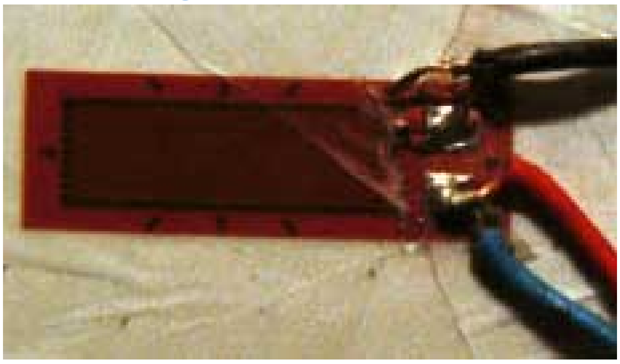
Rotor Blade Materials

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.

Measuring Strains

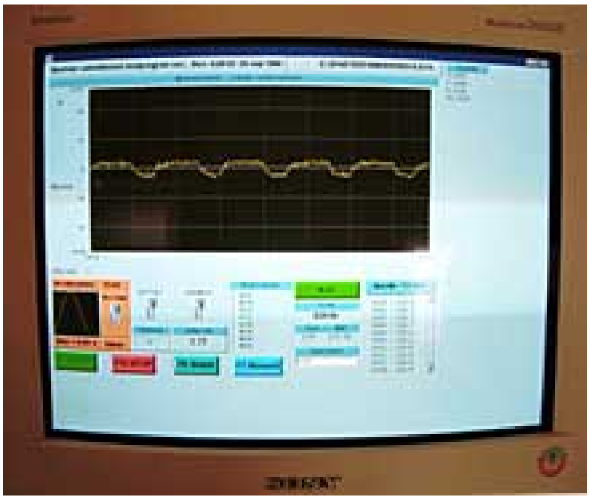


Photograph
© 1999 Soren Krohn

Strain gauges, (i.e. flat electrical resistors which are glued on to the surface of the rotor blades being tested), are used to measure very accurately the bending and stretching of the rotor blades.

Monitoring Fatigue Testing

The measurement results from the strain gauges are continuously monitored on computers. Nonlinear variations in the pattern of bending may reveal a damage in the rotor blade structure.



Photograph
© 1999 Soren Krohn

Infrared Inspection (Thermography)

Infrared cameras are used to reveal local build-up of heat in the blade. This may either indicate an area with **structural dampening**, i.e. an area where the blade designer has deliberately laid out fibres which convert the bending energy into heat in order to stabilise the blade, or it may indicate an area of delamination or an area which is moving toward the breaking point for the fibres.

Modal Forms of Rotor Blade Vibrations

From the year 2000 blade testing (in Denmark) also includes a verification of the different **modal forms** of vibration of each blade. This is done using a special type of equipment which excites the blade vibrations at different frequencies and in different directions.

Different modal forms of oscillation are also known when building musical instruments: A string on a violin may oscillate with is **basic tone**, i.e. the centre of the string moving up and down, but it will usually also oscillate with the first **overtone** or first harmonic, with two centres of oscillation located at a distance of 1/4 from each end of the string, moving at twice the frequency of the basic tone or natural frequency.

The reason why manufacturers of wind turbines are interested in studying and verifying the various forms of vibration frequencies in rotor blades, is that they have to make sure that the turbine on which the blade is to be mounted does not have some of the same natural frequencies as the rotor blade. Otherwise, a **resonance** may occur in the whole structure of the turbine, leading to **undampened vibrations** which may eventually wreck the whole wind turbine. We will return to this issue on the page on structural dynamics in the design section later in this guided tour.

Static Testing of Rotor Blades

Rotor blades are also tested for strength (and thus their ability to withstand extreme loads) by being bent once with a very large force. This test is made after the blades has been subject to fatigue testing, in order to verify the strength for a blade which has been in operation for a substantial amount of time.

Manufacturing Wind Turbine Towers

Rolling Conical Tower Sections

Most modern wind turbine towers are conical tubular steel towers, as we learned on the page about wind turbine towers.

This image from a tower manufacturer's workshop shows how a steel plate is rolled into a conical subsection for a wind turbine tower. It is a bit tricky to achieve the conical shape, since the tension (pressure) of the steel rollers has to be different at the two sides in order to make the plate bend properly.

Towers are assembled from these smaller, conical subsections which are cut and rolled into the right shape, and then welded together.

Towers are usually manufactured in 20 to 30 m sections (65 to 100 ft.), the limiting factor being transportation on roads or rail. Typical modern tower weights are 40 metric tonnes for a 50 m (165 ft.) tower for a turbine with a 44 m rotor diameter (600 kW), and 80 metric tonnes for a 60 metre tower for a 72 m rotor diameter (2000 kW).

Designed by the Turbine Manufacturer

Towers for wind turbines are generally designed by each turbine manufacturer, since the entire wind turbine has to be type approved as a unit. (The reasons are explained in the page about structural dynamics). So even if some towers are manufactured by independent producers, they are always specific for each manufacturer.

Independent tower manufacturers are often also manufacturers of oil tanks or pressure vessels, since the machinery and safety inspection procedures are very similar.

Weight Matters

Tower weights (per installed power in kW) have declined by about 50% during the past five years due to more advanced design methods. Still, towers are a fairly heavy part of the wind turbine, so transportation costs are important. For larger markets it generally does not pay to transport towers more than 1000 km (600 miles) by road. In case the distance is larger (and the project is a large one), towers are usually manufactured locally.

Banana Peel Shaped Plates

In order to end up with a cone-shaped section, the plate used for rolling has to be curved along the longest edges, and the short edges are not parallel. Most tower manufacturers use programmable laser cutting tools in order to obtain the appropriate shape for the steel plate.

Updated 6 August 2000
http://www.windpower.org/tour/manu/towerm.htm

Welding Wind Turbine Towers

Steel Sections are Powder Welded

Each tower section is welded with a seam lengthwise, plus a circular welding seam to connect to the next section of the tower. This is done by placing the tower sections on a rolling bed which slowly rotates the tower, while an operator with a powder welding machine welds the sections from the outside... ...and another operator welds a corresponding set of seams on the inside.

Checking Welding Seams for Safety

Welding seams in towers are checked using ultrasonic or x-ray devices. Important seams are checked 100%, while other seams are checked on a sample basis.

Installing and Assembling Wind Turbine Towers

Attaching Towers to their Foundations

Towers are usually bolted onto the concrete foundations on which they are placed.

There are other methods, however, as in this case where part of the bottom section of the tower is cast into the concrete foundation, and where the lowest section of the tower is subsequently welded together directly on the site.

This method requires that the tower be fitted with special guides and clamps to hold the two tower sections in place while the welding is being done. It also requires a small mobile tower factory including a generator, welding gear, and x-ray inspection equipment for checking the welding seams.

Flanges

Wind turbine tower sections are bolted together using hot rolled steel flanges, which are welded to the end of each tower section.

The flanges are made from killed steel. The image shows a pair of flanges.

Bolt Assembly

The next image shows how the tower sections are bolted together inside the tower.

The quality of the flanges and the bolt tensions are important parameters for the safety of wind turbine towers.

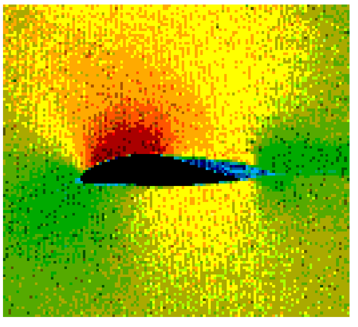
Updated 9 September 2000

http://www.windpower.org/tour/manu/towrassy.htm

Research and Development in Wind Energy

For wind turbine manufacturers, the basic aim of research and development of wind turbines is to be able to manufacture ever more cost effective machines.

Basic Aerodynamics Research



Photograph of computer simulation of airflows around a rotor blade © Risoe National Laboratory, Denmark

Wind turbines engineers use techniques such as stall, which aircraft designers try to avoid at all costs. Stall is a very complex phenomenon, because it involves airflows in three dimensions on wind turbine rotor blades. (e.g. the centrifugal force will induce an airflow which makes the air molecules move radially along the rotor blade from its root towards the tip of the blade).

3D computer simulations of airflows are rarely used in the aircraft industry, so wind turbine researchers have to develop new methods and computer simulation models to deal with these issues.

Computational Fluid Dynamics, or CFD, is a group of methods that deal with simulating airflows around e.g. rotor blades for wind turbines.
The picture shows a computer simulation of the airflows and pressure distributions around a wind turbine rotor blade moving towards the left.

Aerodynamic Improvement Devices

A number of technologies known from the aircraft industry are increasingly being applied to improve the performance of wind turbine rotors.
One example is **vortex generators**, which are small fins, often only about 0.01 metre (0.4 inch) tall, which are fitted to the surface of aircraft wings. The fins are alternately slightly skewed a few degrees to the right and the left. The fins create a thin current of turbulent air on the surface of the wings. The spacing of the fins is very accurate to ensure that the turbulent layer automatically dissolves at the back edge of the wing.
Curiously, this creation of minute turbulence prevents the aircraft wing from stalling at low wind speeds.
Wind turbine blades are prone to stalling even at low wind speeds close to the root of the blade where the profiles are thick.
Consequently, on some of the newest rotor blades you may find a stretch of one metre or so along the back side of the blade (near the root) equipped with a number of vortex generators.

(Picture © LM Glasfiber A/S).

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Updated 19 January 2001
http://www.windpower.org/tour/rd/index.htm

Offshore Wind Power Research

Vindeby Offshore Wind Farm Photograph © 1992 Bonus Energy A/S

Megawatt sized wind turbines, cheaper foundations and new knowledge about offshore wind conditions is improving the economics of offshore wind power.

While wind energy is already economic in good onshore locations, wind energy is about to cross another frontier: The economic frontier set by shorelines. Researchers and developers are about to challenge conventional wisdom on electricity generating technologies: Offshore wind energy is rapidly becoming competitive with other power generating technologies.

The Danish Plan 21

According to *The Danish Governments' Action Plan for Energy, Energy 21* (see the Links page), 4,000 MW of offshore wind power should be installed before year 2030. With another 1,500 MW installed onshore Denmark will then be able to cover more than 50 per cent of total electricity consumption by wind energy. In comparison, the current wind power capacity in Denmark is 1,100 MW (mid 1998).

A total of 5,500 MW of wind power in the Danish electricity system means that the wind turbines periodically will cover more than 100 per cent of Danish electricity demand. Therefore, the future Danish offshore power plants should be an integrated part of the Scandinavian electricity system, which is based on huge amounts on hydro power.

With a total investment of some 48 billion DKK (= 7 billion USD) for the 4,000 MW offshore capacity the Danish action plan will be the world's largest investment in wind power ever.

Offshore Timetable in Denmark

Danish power companies have already applied for planning permission for 750 MW of offshore wind parks. According to their timetable more than 4,000 megawatts of wind power will be installed offshore in Denmark before 2027. The first stage is likely to be a smaller 40 MW offshore park just of the coast of Copenhagen in year 2000.

A report drafted by the Danish power companies for the Minister of Environment and Energy identifies four main areas in Danish sea territory suitable for wind power with a potential of 8,000 MW. The philosophy behind the selected areas is simple: For environmental reasons the Committee has concentrated the capacity in few and remote areas with water depths between 5 and 11 metres.

The areas have been selected to avoid national park areas, shipping routes, microwave links, military areas, etc. The distance from coastal areas varies from 7 to 40 km. This also minimises the visual impact onshore.

The most recent research into foundations indicates that it may be economic to install offshore turbines even at 15 metres water depth. This mean that the offshore potential is some 16,000 MW in the selected areas in the Danish Waters.

Wind Turbine Offshore Foundations

The major challenge for offshore wind energy is cutting costs: Undersea cabling and foundations have until recently made offshore wind energy an expensive option.

New studies of foundation technology, however, plus megawatt-sized wind turbines are now on the point of making offshore wind energy competitive with onshore sites, at least for shallow water depths up to 15 metres (50 ft.).

Since offshore wind turbines generally yield 50 per cent higher output than turbines on nearby onshore sites (on flat land), offshore siting may be quite attractive, cf. the page on offshore wind conditions.

Steel is Cheaper Than Concrete

Two Danish power company groups and three engineering firms made a pioneering study on the design and costing of offshore wind turbine foundations in 1996-1997. The report concluded that steel is far more competitive than concrete for larger offshore wind farms.

It appears that all of the new technologies will be economic until at least 15 metres water depth, and possibly beyond such depths. In any case, the marginal cost of moving into deeper waters is far smaller than what was previously estimated.

With these concepts foundation and grid connection costs for large 1.5 megawatt turbines are only 10 to 20 per cent higher than the corresponding costs for the 450-500 kW turbines used at Vindeby and Tun Knob offshore wind parks in Denmark.

50 Year Design Lifetime

Contrary to popular belief, **corrosion** is not a major concern with offshore steel structures. Experience from offshore oil rigs has shown that they can be adequately protected using cathodic (electrical) corrosion protection.

Surface protection (paint) on offshore wind turbines will routinely be delivered with a higher protection class than for onshore turbines.

Oil rig foundations are normally built to last 50 years. This is also the design lifetime for the steel foundations used in these studies.

Reference Turbine

The reference turbine for the study is a modern 1.5 MW three-bladed upwind turbine with a hub height of about 55 metres (180 ft.) and a rotor diameter of some 64 metres (210 ft.).

The hub height of the reference turbine is low compared with the typical onshore turbine of that size. In Northern Germany the typical hub height of a 1.5 MW turbine varies from 60 to 80 m (200 to 260 ft.). Because of the very smooth surface (low roughness) of water surfaces it is cost-efficient to use lower towers. You may verify these conclusions using the Wind Turbine Power Calculator which already has a built in example of a 1.5 MW offshore wind turbine.

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Offshore Foundations: Traditional Concrete

Foundation being floated out to Tunoe Knob
Photograph © 1996 by Flemming Hagensen

The first offshore pilot projects in Denmark (and the world) used concrete gravity caisson foundations.

As the name indicates, the gravity foundation relies on gravity to keep the turbine in an upright position.

Vindeby and Tunoe Knob Offshore Wind Farms

Vindeby Offshore Wind Farm and Tunoe Knob Wind Farm are examples of this traditional foundation technique. The caisson foundations were built in dry dock near the sites using armed concrete and were floated to their final destination before being filled with sand and gravel to achieve the necessary weight. The principle is thus much like that of traditional bridge building.

The foundations used at these two sites are conical to act as breakers for pack ice. This is necessary because solid ice is regularly observed in the Baltic Sea and the Kattegat during cold winters.

Disadvantage of Concrete

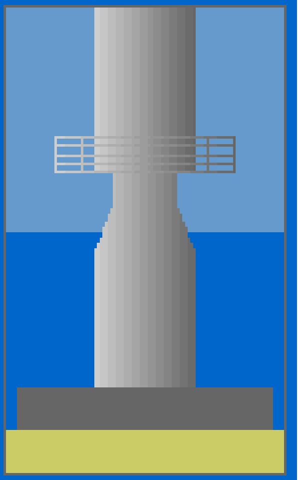
Using traditional concrete foundation techniques the cost of the completed foundation is approximately proportional with the water depth squared - the quadratic rule.

The water depths at Vindeby and Tunoe Knob vary from 2.5 m to 7.5 m. This implies that each concrete foundation has an average weight of some 1050 metric tonnes.

According to the quadratic rule the concrete platforms tend to become prohibitively heavy and expensive to install at water depths above 10 metres. Therefore, alternative techniques had to be developed in order to break through the cost barrier, as we shall see on the next pages.

Updated 9 September 2000
http://www.wind power.dk/tour/rd/concrete.htm

Offshore Foundations: Gravitation + Steel



Most of the existing offshore wind parks use gravitation foundations. A new technology offers a similar method to that of the concrete gravity caisson. Instead of armed concrete it uses a cylindrical steel tube placed on a flat steel box on the sea bed.

Weight Considerations

A steel gravity foundation is considerably lighter than concrete foundations. Although the finished foundation has to have a weight of around 1,000 tonnes, the steel structure will only weigh some 80 to 100 tonnes for water depths between 4 and 10 m. (Another 10 tonnes have to be added for structures in the Baltic Sea, which require pack ice protection).

The relatively low weight allows barges to transport and install many foundations rapidly, using the same fairly lightweight crane used for the erection of the turbines.

The gravity foundations are filled with olivine, a very dense mineral, which gives the foundations sufficient weight to withstand waves and ice pressure.

Size Considerations

The base of a foundation of this type will be 14 by 14 m (or a diameter of 15 m for a circular base) for water depths from 4 to 10 m. (Calculation based on a wind turbine with a rotor diameter of 65 m).

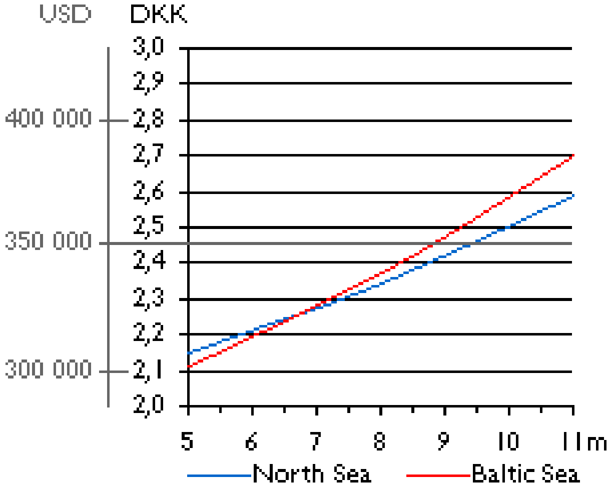
Seabed Preparation

The advantage of the steel caisson solution is that the foundation can be made onshore, and may be used on all types of seabed although seabed preparations are required. Silt has to be removed and a smooth horizontal bed of shingles has to be prepared by divers before the foundation can be placed on the site.

Erosion Protection

The seabed around the base of the foundation will normally have to be protected against erosion by placing boulders or rocks around the edges of the base. This is, of course, also the case for the concrete version of the gravitation foundation. This makes the foundation type relatively costlier in areas with significant erosion.

Costs by Water Depth for Steel Gravitational Foundations



The cost penalty of moving to larger water depths is minimal compared to traditional concrete foundations. The reason is, that the foundation base does not have to increase in size proportion to the water depth to lean against ice pressure or waves.

The cost estimates for this type of foundation is for instance 2,343,000 DKK (= 335,000 USD) for a 1.5 MW machine placed at 8 m water depth in the Baltic Sea (1997 figures). The costs include installation.

The graph shows how the cost varies with water depth. Interestingly, the dimensioning factor (which decides the required strength and weight of the foundation) is not the turbine itself but ice and wave pressure forces.

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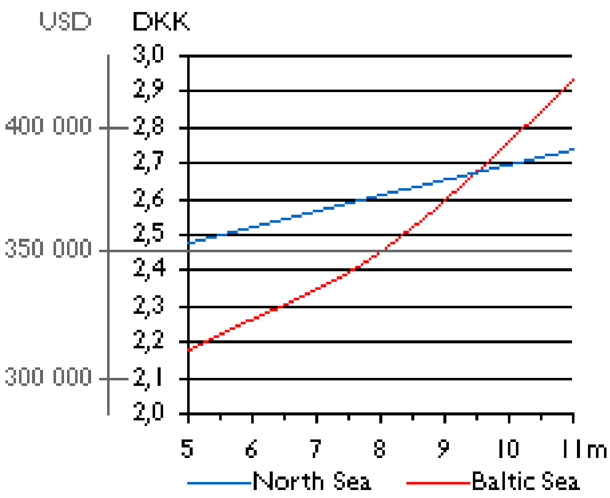
Offshore Foundations: Mono Pile

The mono pile foundation is a simple construction. The foundation consists of a steel pile with a diameter of between 3.5 and 4.5 metres. The pile is driven some 10 to 20 metres into the seabed depending on the type of underground. The mono pile foundation is effectively extending the turbine tower under water and into the seabed.

An important advantage of this foundation is that no preparations of the seabed are necessary. On the other hand, it requires heavy duty piling equipment, and the foundation type is not suitable for locations with many large boulders in the seabed. If a large boulder is encountered during piling, it is possible to drill down to the boulder and blast it with explosives.

Costs by Water Depth for Mono Pile Foundations



The dimensioning factor of the foundation varies from the North Sea to the Baltic Sea. In the North Sea it is the wave size that determines the dimension of the mono pile. In the Baltic Sea the pack ice pressure decides the size of the foundation. This is the reason why the mono pile foundation cost increases more rapidly in the Baltic Sea than in the North Sea. The costs include installation (1997 prices).

Erosion Considerations

Erosion will normally not be a problem with this type of foundation.

Swedish Offshore Project

A 2.5 MW pilot project with five Danish wind turbines using the mono pile technology has been installed in the Baltic sea south of the Swedish island of Gotland.

Using the mono pile foundation technique at Gotland involved drilling a hole of 8 to 10 metres depth for each of the turbines (Wind World 500 kW). Each steel pile is slotted into the the solid rock. When the foundations are in place the turbines can be bolted on top of the mono piles.

The whole operation takes about 35 days under average Baltic weather conditions.

Updated 9 September 2000
http://www.wind power.dk/tour/rd/monopile.htm

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Offshore Foundations: Tripod

Image © 1997 Ramboll

The tripod foundation draws on the experiences with light weight and cost efficient three-legged steel jackets for marginal offshore fields in the oil industry.

From a steel pile below the turbine tower emanates a steel frame which transfers the forces from the tower into three steel piles. The three piles are driven 10 to 20 metres into the seabed depending on soil conditions and ice loads.

Advantages of the Tripod

The advantage of the three-legged model is that it is suitable for larger water depths. At the same time only a minimum of preparations are required at the site before installation.

Multi-pile technology

The foundation is anchored into the seabed using a relatively small steel pile (0.9 m diameter) in each corner. Because of the piling requirement, the tripod foundation is not suited for locations with many large boulders.

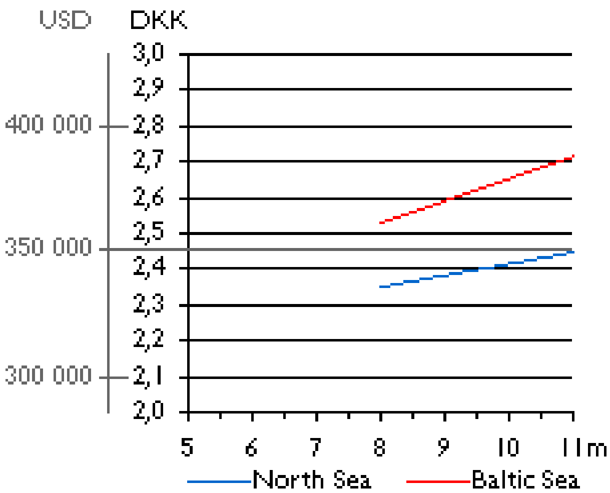
Erosion Considerations

Erosion will normally not be a problem with this type of foundation.

Suitable for Larger Water Depths

This type of foundation is not suitable at water depths lower than 6-7 metres. The main reason for this is that service vessels at low water depths will face problems approaching the foundation due to the steel frame.

Cost by Water Depth for Tripod Foundations



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As in previous page, the basic difference between costs in the North Sea and the Baltic Sea is that waves determine dimensioning in the North Sea, whereas ice is decisive in the Baltic Sea. The costs include installation (1997 prices).

Building Gravity Foundations for Offshore Wind Turbines (QuickTime Video)

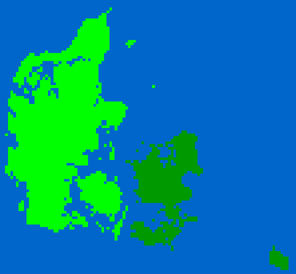
Video

This video shows workers casting concrete for the gravity foundations of the Middelgrunden wind turbine park off the coast of Copenhagen. (The video runs for 1 minute and 10 seconds, 1087 K, soundtrack included, free QuickTime plugin required).

These foundations are a hybrid between steel and concrete foundations since concrete is only used as the ballast in the bottom section (the cylindrical 17 m slab).

www.WINDPOWER.org
Danish Wind Turbine Manufacturers Association

Guided Tour

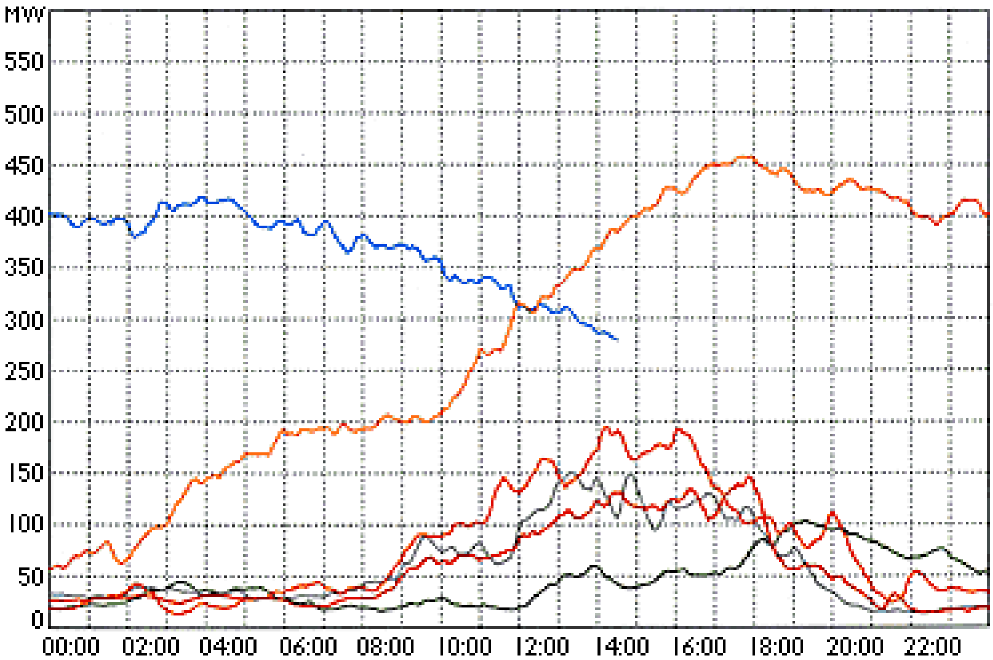


Wind presently covers about 10 per cent of the electricity consumption in the Western part of Denmark.
The ELSAM electricity supply area comprises the Western part of Denmark with the Jutland Peninsula and the neighbouring island of Fyn. The area has a population of 3 million.

Wind Turbines in the Electrical Grid: Wind Energy Variations

The vast majority of the installed power of wind turbines in the world is grid connected, i.e. the turbines feed their electricity directly into the public electrical grid.

Wind Energy Production During a Fine Summer Week



The graph above shows a summer week of electricity output from the 650 MW (megawatts) of wind turbines installed in the Western part of Denmark. The blue curve at the top left shows the power output on 25 June 1997, while the orange curve shows the output the preceding day.

Electrical power consumption was 2,700 MW at the time this curve was printed from the power company control centre. Wind was supplying 270 MW i.e. wind was supplying exactly 10 per cent of the electricity consumption of 3 million people at 13:45 hours when we visited the control centre.

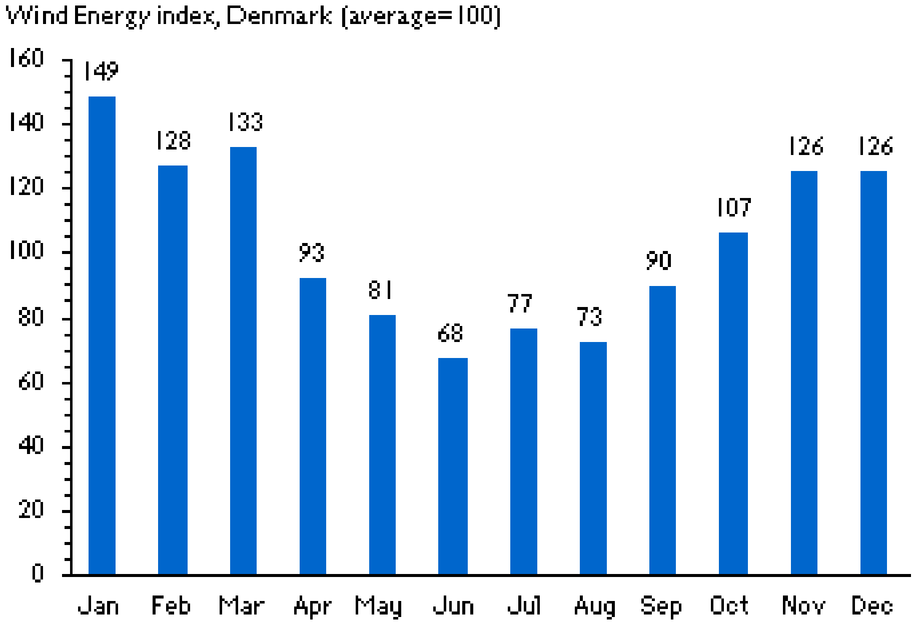
Wind Matches Daily Electricity Consumption Patterns

At the bottom of the graph you can see the power output of the five preceding days. On average, the month of June has the lowest wind power output during the year in Denmark. Some days of fresh winds, however, began in the early morning hours of 24 June.

The typical weather pattern is that winds are low at night, and higher during the day, as you can see from the five days of moderate winds.

This means that wind electricity generally fits well into the electricity consumption pattern, i.e. wind electricity tends to be more valuable to the electrical grid systems than if it were being produced at a random level.

Seasonal Variation in Wind Energy



Wind Matches Seasonal Electricity Consumption Patterns

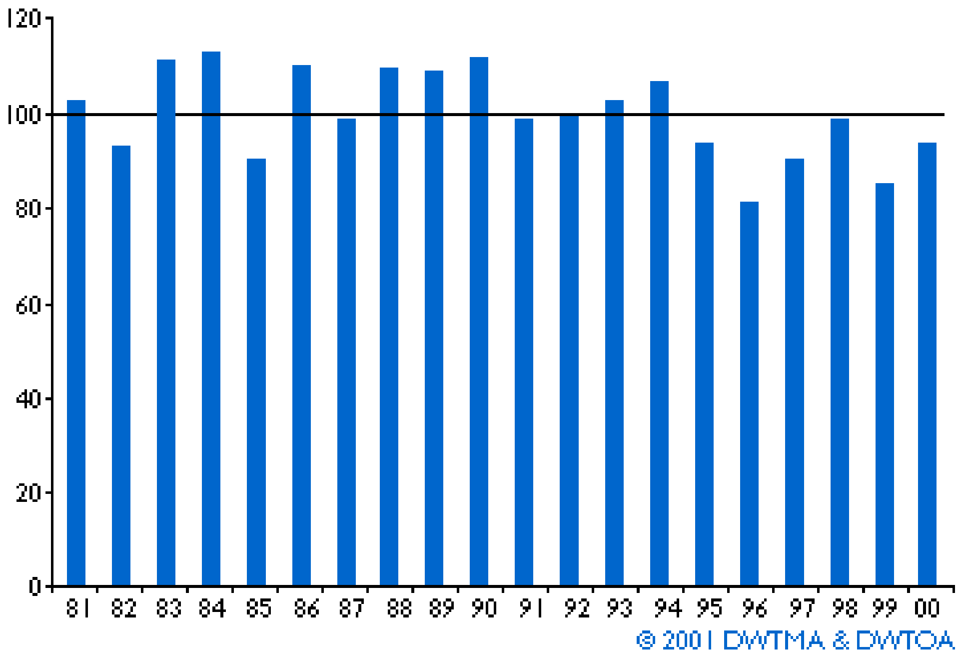
In temperate zones summer winds are generally weak compared to winter winds. Electricity consumption is generally higher in winter than in summer in these regions.

In the cooler areas of the globe, electrical heating is therefore ideal in combination with wind energy, because the cooling of houses varies with the wind speed much like the electricity production of wind turbines vary with wind speeds.

In electricity systems that are **not** based on hydropower and wind there may be good reasons to avoid electrical heating, however:

Conventional power plant wastes a lot of heat, and thus fuel (at least 60%), i.e. for every unit of useful heat consumed by a household, the power station will waste 1.5 units of heat (and fuel).

Annual Variation in Wind Energy



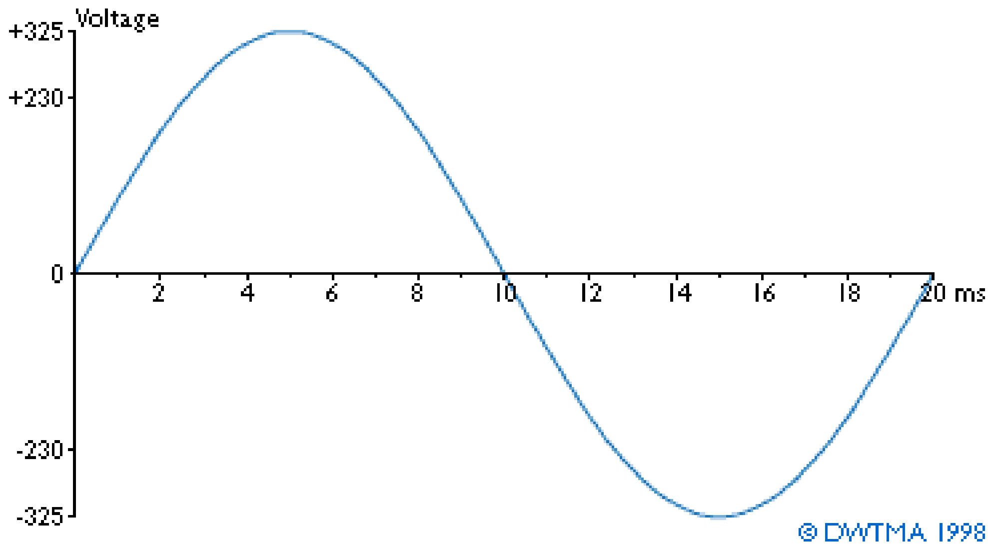
Just like harvest yields vary from year to year in agriculture, you will find that wind patters may vary from year to year. Typically, the variations are less than the changes in agricultural production. In the case of Denmark, you will see that output from wind turbines typically have a variation (a standard deviation) of some 9 to 10 per cent. You may see the monthly and yearly variations in Denmark during more than 20 years on the web site Vindstyrke.

Wind Turbines and Power Quality Issues

The buyer of a wind turbine does not need to concern himself with local technical regulations for wind turbines and other equipment connected to the electrical grid. This responsibility is generally left to the turbine manufacturer and the local power company.

For the people who are technically minded, we go into some of the electrotechnical issues involved in connecting a turbine to the grid on this page.

Power Quality



The term "power quality" refers to the voltage stability, frequency stability, and the absence of various forms of electrical noise (e.g. flicker or harmonic distortion) on the electrical grid. More broadly speaking, power companies (and their customers) prefer an alternating current with a nice sinusoidal shape, such as the one in the image above. (If you are not familiar with the basics of alternating current (AC) it may be useful to consult the Reference Manual about this subject before continuing).

Starting (and Stopping) a Turbine

Most electronic wind turbine controllers are programmed to let the turbine run idle without grid connection at low wind speeds. (If it were grid connected at low wind speeds, it would in fact run as a motor, as you can read about on the generator page). Once the wind becomes powerful enough to turn the rotor and generator at their rated speed, it is important that the turbine generator becomes connected to the electrical grid at the right moment.

Otherwise there will be only the mechanical resistance in the gearbox and generator to prevent the rotor from accelerating, and eventually overspeeding. (There are several safety devices, including fail-safe brakes, in case the correct start procedure fails, which you may have read in the section on Wind Turbine Safety).

Soft Starting with Thyristors

If you switched a large wind turbine on to the grid with a normal switch, the neighbours would see a brownout (because of the current required to magnetise the generator) followed by a power peak due to the generator current surging into the grid. You may see the situation in the drawing in the accompanying browser window, where you see the flickering of the lamp when you operate the switch to start the wind turbine. The same effect can possibly be seen when you switch on your computer, and the transformer in its power supply all of a sudden becomes magnetised.

Another unpleasant side effect of using a "hard" switch would be to put a lot of extra wear on the gearbox, since the cut-in of the generator would work as if you all of a sudden slammed on the mechanical brake of the turbine.

Large power thyristors in wind turbines get very hot when they are activated. They have to be equipped with aluminium heat sinks and fans as you see in the picture to the right. Photograph © 1998 Soren Krohn

To prevent this situation, modern wind turbines are **soft starting**, i.e. they connect and disconnect gradually to the grid using **thyristors**, a type of semiconductor continuous switches which may be controlled electronically. (You may in fact have a thyristor in your own home, if you own a modern light dimmer, where you can adjust the voltage on your lamps continuously).

Thyristors waste about 1 to 2 per cent of the energy running through them. Modern wind turbines are therefore normally equipped with a so called **bypass switch**, i.e. a mechanical switch which is activated after the turbine has been soft started. In this way the amount of energy wasted will be minimised.

Weak Grids, Grid Reinforcement

If a turbine is connected to a weak electrical grid, (i.e. it is vary far away in a remote corner of the electrical grid with a low power-carrying ability), there may be some brownout / power surge problems of the sort mentioned above. In such cases it may be necessary to reinforce the grid, in order to carry the fluctuating current from the wind turbine.

Your local power company has experience in dealing with these potential problems, because they are the exact mirror-image of connecting a large electricity user, (e.g. a factory with large electrical motors) to the grid.

Flicker

Flicker is an engineering expression for short lived voltage variations in the electrical grid which may cause light bulbs to flicker. This phenomenon may be relevant if a wind turbine is connected to a weak grid, since short-lived wind variations will cause variations in power output. There are various ways of dealing with this issue in the design of the turbine, mechanically, electrically, and using power electronics.

Preventing "Islanding"

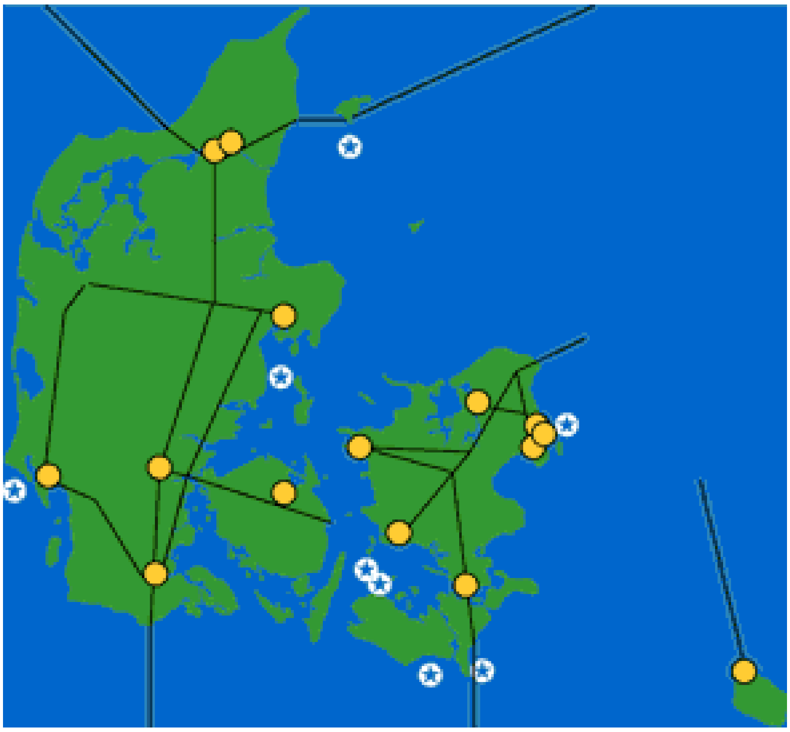
Islanding is a situation which may occur if a section of the electrical grid becomes disconnected from the main electrical grid, e.g. because of accidental or intended tripping of a large circuit breaker in the grid (e.g. due to lightning strikes or short circuits in the grid). If wind turbines keep on running in the isolated part of the grid, then it is very likely that the two separate grids will not be in phase after a short while.

Once the connection to the main grid is re-established it may cause huge current surges in the grid and the wind turbine generator. It would also cause a large release of energy in the mechanical drive train (i.e. the shafts, the gear box and the rotor of the wind turbine) much like "hard switching" the turbine generator onto the grid would do.

The electronic controller of the wind turbine will therefore constantly have to monitor the voltage and frequency of the alternating current in the grid. In case the voltage or frequency of the local grid drift outside certain limits within a fraction of a second, the turbine will automatically disconnect from the grid, and stop itself immediately afterwards. (Normally by activating the aerodynamic brakes as explained in the section on wind turbine safety).

Grid Connection of Offshore Wind Parks

The Grid



The picture to the right shows the Danish electrical transmission grid. Major power stations are shown in yellow.

Total generating capacity was some 10,000 MW in 1998.

Present and future offshore wind parks with a total of some 4,100 MW are shown in white and blue.

The western and eastern part of the country are not directly connected, but are connected to the German and Swedish electrical transmission systems using AC (alternating currency transmission lines). The rest of the connections to Sweden, Norway, and Germany are DC (direct current) connections.

Grid connection of offshore wind parks is not a major technical problem *per se*, in the sense that the technologies which are involved are well known. Optimising these technologies for remote offshore sites will be important, however, to ensure reasonable economics.

The first commercial-sized offshore wind farms in Denmark will be located some 15-40 km (10-25 miles) from shore, at water depths from 5 to 10, possibly 15 metres. The park sizes will range from 120 to 150 MW. The first parks (year 2002) will be built using the present 1.5 MW generation of wind turbines, which by then will have been through an onshore operational period of some five years.

Cabling

Undersea cabling connecting offshore parks to the main electrical grid is a well known technology. Undersea cables will have to be buried in order to reduce the risk of damage due to fishing equipment, anchors, etc. If bottom conditions permit, it will be most economic to wash cables into the seabed (using high pressure water jets) rather than digging or ploughing cables into the bottom of the sea.

Voltages

Inside the large 120-150 MW wind parks being planned in Denmark, it is likely that 30-33 kV connections will be used. In the middle of each park there will probably be a platform with a 30 to 150 kV transformer station, plus possibly a number of service facilities.

Connection to the mainland will be done using 150 kV connections.

Reactive Power is related to phase-shifting of alternating current, which makes it more difficult to transport usable energy through the electrical grid. See the Reference Manual on this web site for the technical details.

Reactive Power, HVDC

The undersea cables will have a high electrical capacitance, which may be useful to supply reactive power to the parks. It may be optimal to have some form of variable reactive power compensation built into the system, depending on the precise grid configuration. If the distance to the main grid is considerable, an interesting alternative could be to connect the parks to the mainland using high voltage direct current connections (HVDC).

Remote Surveillance

Remote surveillance of the parks will obviously be even more important than on land. Radio links for this purpose have already been in operation at the Tunoe Knob and Vindeby offshore wind parks for some years.

With the the large 1.5 MW units foreseen for these parks, it may be economic to install e.g. extra sensors on each piece of equipment, (and continuously analyse its minute vibrations which tend to change their pattern as the part is worn down). This technology which is well known in certain parts of industry to ensure optimum maintenance of machinery.

Preventive Maintenance

Since weather conditions may prevent service personnel from approaching the wind turbines at times of bad weather, it is extremely important to ensure a high availability rate of offshore wind turbines. Preventive maintenance check programmes may need to be optimised for remote offshore locations.

Wind Turbines and the Environment: Landscape

Hints About Landscape Architecture and Wind Turbines

Wind turbines are always highly visible elements in the landscape. Otherwise they are not located properly from a meteorological point of view, cf. the page on wind turbine siting.

The image to the left shows the wind farm at Kappel, Denmark. It is perhaps the most aesthetically pleasing layout of any wind farm known to this author. The shape of the dike along the coastline is repeated in the line of turbines.

There is one disturbing element in the picture above: The single turbine next to the farmhouse, which interrupts the otherwise smooth pattern of turbines. (That turbine was there before the wind farm was built).

Simple Geometrical Patterns

In flat areas it is often a good idea to place turbines in a simple geometrical pattern which is easily perceived by the viewer. Turbines placed equidistantly in a straight line work well, but the example in the picture above may be even more elegant, where landscape contours invite such a solution.

There are limits to the usefulness of being dogmatic about using simple geometrical patterns, however:

In hilly landscapes it is rarely feasible to use a simple pattern, and it usually works better to the the turbines follow the altitude contours of the landscape, or the fencing or other characteristic features of the landscape.

Whenever turbines are placed in several rows, one will rarely be able to perceive the pattern when the park is viewed from normal eye level. Only when one is standing at the end of a row, does it really appear as an ordered layout. In the next panorama picture, you will probably only be able to discern three rows of turbines, while the rest appear to be scattered around the landscape.

Photograph © 1997
by Suzanne Clemmesen

Light Grey Paint

The picture above shows one of the larger groupings of Danish built wind turbines at N sudden on the island of Gotland in Sweden. The grey paint on the turbines make them blend well into the landscape.

Size of Wind Turbines

Large wind turbines enable the same amount of energy to be produced with fewer wind turbines. There may be economic advantages to this, such as lower maintenance costs.

From an aesthetic point of view, large wind turbines may be an advantage in the landscape, because they generally have lower rotational speed than smaller turbines. Large turbines therefore do not attract the eye the way fast-moving objects generally do.

People's Perception of Wind Turbines in the Landscape

To a large extent it is a matter of taste how people perceive that wind turbines fit into the landscape.

Numerous studies in Denmark, the UK, Germany, and the Netherlands have revealed that people who live near wind turbines are generally more favourable towards them than city dwellers. You may find more details about these studies in the article Public Attitudes Toward Wind Power on this web site.

A beautiful book of photographic examples of Wind Turbines in the Landscape may be purchased from Birk Nielsens Tegnestue, Aarhus, Denmark. The price is approximately 150 DKK, plus postage.

Sound from Wind Turbines

Noise is a Minor Problem Today

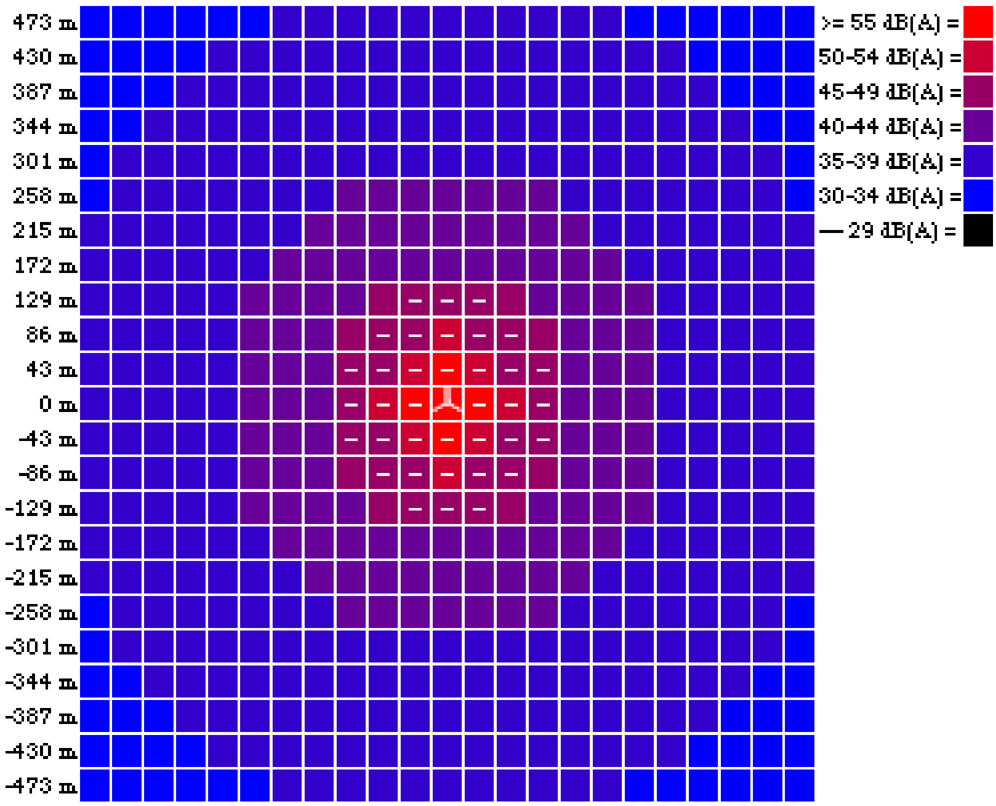
It is interesting to note that the sound emission levels for all new Danish turbine designs tend to cluster around the same values. This seems to indicate that the gains due to new designs of e.g. quieter rotor blade tips are spent in slightly increasing the tip speed (the wind speed measured at the tip of the rotor blade), and thus increasing the energy output from the machines.

In the guided tour section on Wind Turbine Design we have explained how turbines today are engineered to reduce sound emissions.

It thus appears that noise is not a major problem for the industry, given the distance to the closest neighbours (usually a minimum distance of about 7 rotor diameters or 300 m = 1000 ft. is observed).

The concepts of sound perception and measurement are not widely known in the public, but they are fairly easy to understand, once you get to grips with it. You can actually do the calculations yourself in a moment.

Planning Wind Turbine Installation in Regard to Sound



Fortunately, it is usually reasonably easy to predict the sound effect from wind turbines in advance. On one of the following pages you may even try for yourself, using the Sound Map Calculator, which was used to draw the picture.

Each square measures 43 by 43 metres, corresponding to one rotor diameter. The bright red areas are the areas with high sound intensity, above

55 dB(A). The dashed areas indicate areas with sound levels above 45 dB(A), which will normally not be used for housing etc. (We get to the explanation of the sound level and dB(A) in a moment).

As you can see, the zone affected by sound extends only a few rotor diameters' distance from the machine.

Background Noise: Masking Noise Drowns out Turbine Noise

No landscape is ever completely quiet. Birds and human activities emit sound, and at winds speeds around 4-7 m/s and up the noise from the wind in leaves, shrubs, trees, masts etc. will gradually mask (drown out) any potential sound from e.g. wind turbines.

This makes it extremely difficult to measure sound from wind turbines accurately. At wind speeds around 8 m/s and above, it generally becomes a quite abstruse issue to discuss sound emissions from modern wind turbines, since background noise will generally mask any turbine noise completely.

The Influence of the Surroundings on Sound Propagation

Sound reflection or absorption from terrain and building surfaces may make the sound picture different in different locations. Generally, very little sound is heard upwind of wind turbines. The wind rose is therefore important to chart the potential dispersion of sound in different directions.

Human Perception of Sound and Noise

Most people find it pleasant listen to the sound of waves at the seashore, and quite a few of us are annoyed with the noise from the neighbour's radio, even though the actual sound level may be far lower.

Apart from the question of your neighbour's taste in music, there is obviously a difference in terms of information content. Sea waves emit random "white" noise, while you neighbour's radio has some systematic content which your brain cannot avoid discerning and analysing. If you generally dislike your neighbour you will no doubt be even more annoyed with the noise. Sound experts for lack of a better definition define "noise" as "unwanted sound".

Since the distinction between noise and sound is a highly psychological phenomenon, it is not easy to make a simple and universally satisfactory modelling of sound phenomena. In fact, a recent study done by the Danish research institute DK Teknik seems to indicate that people's perception of noise from wind turbines is governed more by their attitude to the source of the noise, rather than the actual noise itself.

Measuring and Calculating Sound Levels

The dB(A) Scale

Public authorities around the world use the so-called dB(A), or *decibel (A)* , scale to quantify sound measurement. To give you an idea of the scale, look at the table below.

Sound Level dB(A)	threshold of hearing	whisper	talking	city traffic	rock concert	jet engine 10 m away
	0	30	60	90	120	150

The dB(A) scale measures the sound intensity over the whole range of different audible frequencies (different pitches), and then it uses a weighing scheme which accounts for the fact that the human ear has a different sensitivity to each different sound frequency. Generally, we hear better at medium (speech range) frequencies than at low or high frequencies. The dB(A) system says, that the sound pressure at the most audible frequencies are to be multiplied by high numbers while the less audible frequencies are multiplied by low numbers, and everything is then added up to get an index number.

(The (A) weighing scheme is used for weak sounds, such as wind turbines. There exist other weighing schemes for loud sounds called (B) and (C), although they are rarely used).

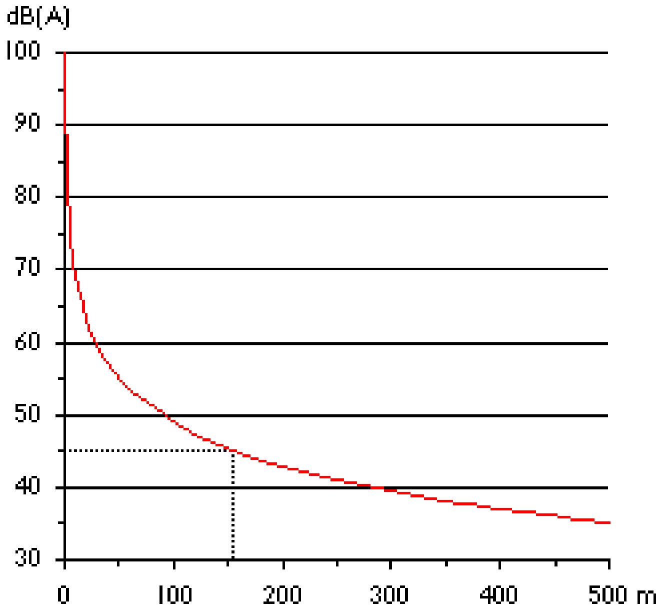
The dB-scale is a logarithmic, or relative scale. This means, that as you double the sound pressure (or the energy in the sound) the index increases by approximately 3. A sound level of 100 dB(A) thus contains twice the energy of a sound level of 97 dB(A). The reason for measuring sound this way is that our ears (and minds) perceive sound in terms of the logarithm of the sound pressure, rather than the sound pressure itself.

Most people will say, that if you increase the dB(A) by 10, you double the subjective **loudness** of the sound.

In case you are interested in the exact definitions, take a look at the Reference Manual on Acoustics of this web site.

Sound Propagation and Distance: Inverse Square Law

The energy in sound waves (and thus the sound intensity) will drop with the square of the distance to the sound source. In other words, if you move 200 m away from a wind turbine, the sound **level** will generally be one quarter of what it is 100 m away. A doubling of your distance will thus make the dB(A) level drop by 6.



At one rotor diameter distance (43 m) from the base of a wind turbine emitting 100 dB(A) you will generally have a sound level of 55-60 dB(A) corresponding to a (European) clothes dryer. 4 rotor diameters (170 m) away you will have 44 dB(A), corresponding to a quiet living room in a house. 6 rotor diameters (260 m) away you will have some 40 dB(A).

The precise relationship between sound level and distance from the sound source is given in a table on the Reference Manual on Acoustics of this web site.

In practice, sound absorption and reflection (from soft or hard surfaces) may play a role on a particular site, and may modify the results shown here.

Adding Sounds from Several Sources

If we have two wind turbines rather than one, located at the same distance from our ears, naturally the sound **energy** reaching us will double. As we have just learned, this means that two turbines will increase the sound **level** by 3 dB(A). Four turbines instead of one (at the same distance) will increase the sound level by 6 dB(A). You will actually need **ten** turbines placed at the same distance from you, in order to perceive that the subjective **loudness** has doubled (i.e. the dB level has increased by 10).

If you wish to learn the details about adding sounds together, take a look at the Reference Manual on Acoustics in this web site.

The Pure Tone Penalty

The fact that the human ear (and mind) discerns pure tones more easily than (random) white noise, means the authorities may wish to take that into account when doing sound estimates. They consequently often have rules which specify that you add a certain number to the dB(A) figure in case you have pure tones present in a sound.

Wind Turbine Noise Information in Practice

In accordance with international standards manufacturers generally specify a theoretical dB(A) level for sound emissions which assumes that all sound originates from a central point, although in practice, of course, it will originate from the whole surface of the machine and its rotor.

Sound pressure thus calculated is typically around 96-101 dB(A) for modern wind turbines. The figure itself is rather uninteresting, since there will not be a single point, where you can experience that sound level! Rather, it is useful for predicting the sound level at different distances from the wind turbine.

Pure tones have generally be eradicated completely for modern wind turbines, at least in the case of the modern turbines listed in the catalogue on the Wind Power Calculator page.

Legal Noise Limits

At distances above 300 m the maximum theoretical noise level from high quality wind turbines will generally be significantly below 45 dB(A) outdoors, corresponding to the legislation in Denmark. (For built-up areas with several houses, a noise limit of 40 dB(A) is the legal limit in Denmark).

Noise regulations vary from country to country. In practice the same machine designs can be used everywhere.

Current Practice: Calculations Rather than Measurement

Calculating potential sound emission from wind turbines is generally important in order to obtain planning permission (from the public authorities) for installing wind turbines in densely populated areas.

Generally speaking, it is far easier to calculate the potential sound emissions than to measure them in practice.

The reason why it is difficult to measure the sound is that the sound level has to be some 10 dB(A) above the background noise in order to measure it properly. The background noise from leaves, birds, and traffic will frequently be above 30 dB(A), however. In most places in the world public authorities therefore rely on calculations rather than measurements, when granting planning permission for wind turbines.

Sound Map Calculator

This calculator requires a Netscape 3.0 or later browser to work. If you are using Navigator 3.0 or later and you see this message, you need to enable JavaScript. Choose Options | Network Preferences, choose the Languages tab, and click Enable JavaScript. Then click reload on your browser. Do not operate the form until this page and its programme have loaded completely, and the picture has appeared in the frame below. Click in grid to insert or remove turbines. Point with mouse to read sound level in dB(A) in your browser's status line. Source sound level for next turbine is set to [100] dB(A), Grid unit size is set to [43] m. (It is convenient to use the rotor diameter as your grid size when placing turbines). Maximum permissible sound level at houses is set to [45] dB(A). This grid has [16] grid points each way. You may use a grid with up to 32 points if you have a fast computer with enough memory allocated for Netscape. If you change a number, press the tab key, click **CALCULATE**, or click outside the field you just entered to start calculations and plot. Click **CLEAR** to delete the turbines and reset to default data.

Updated 6 August 2000
http://www.windpower.org/tour/env/db/dbcalc.htm

Wind Turbine Sound Calculator

This calculator requires a Netscape 3.0 or later browser to work. If you are using Navigator 3.0 or later and you see this message, you need to enable JavaScript. Choose Options | Network Preferences, choose the Languages tab, and click Enable JavaScript. Then click reload on your browser. Do not operate the form until this page and its programme have loaded completely. You may enter source noise and distance for up to ten wind turbines in the worksheet below to calculate the resulting sound at a particular point. The calculator assumes that sound absorption and reflection cancel one another out, although local noise regulations may specify rules for this. You should have read the pages on Sound from Wind Turbines and Measuring and Calculating Sound Levels before using the calculator. You may learn more about the technical details of sound calculations in the Reference Manual on Acoustics.

	Turbine Source dB(A)	Distance m	Resulting dB(A) Sound Level	Sound Power W/m²
1	100	300	39.4654762€	0.0000000088419
2	100	250	41.0491011ε	0.000000012732З
3				
4				
5				
6				
7				
8				
9				
10				
Sum=			43.339374 52	0.000000021574З

Reset

Updated 6 August 2000
http://www.windpower.org/tour/env/db/db2calc.htm

Energy Payback Period for Wind Turbines

Two to Three Months Required

Modern wind turbines rapidly recover all the energy spent in manufacturing, installing, maintaining, and finally scrapping them. Under normal wind conditions it takes between two and three months for a turbine to recover all of the energy involved.

This is one of the main results of a life cycle analysis of wind turbines done by the Danish Wind Turbine Manufacturers Association.

The study includes the energy content in all components of a wind turbine, and it includes the global energy content in all links of the production chain.

You may download the 16 page report from the Publications page on this web site.

Input Output Analysis Method

To find the results, the study employs a so called input output model of the Danish economy published by the Danish Central Bureau of Statistics. The input output model divides the economy into 117 sub sectors, and accounts for the flows of 27 different energy goods (fuels etc.) between the 117 sectors.

The basic advantage of using this method instead of engineering calculations, is that we are able to account properly for the amount of energy used by producers of components and manufacturing equipment, buildings etc. in all links of the production chain. The result is a large 117 by 117 table of energy flows. (Doing a mathematical operation on the table called matrix inversion we obtain the amount of energy per dollar of output).

The Energy Balance for Offshore Wind Turbines

Offshore wind turbines may have a slightly more favourable energy balance than onshore turbines, depending on local wind conditions. In Denmark and the Netherlands, where wind turbines onshore are typically placed in flat terrain, offshore wind turbines will generally yield some 50 per cent more energy than a turbine placed on a nearby onshore site. The reason is the low roughness of the sea surface.

On the other hand, the construction and installation of foundations require 50 per cent more energy than onshore turbines.

It should be remembered, however, that offshore wind turbines have a longer expected lifetime than onshore turbines, in the region of 25 to 30 years. The reason is that the low turbulence at sea gives lower fatigue loads on the wind turbines.

Analysis of 1980 Vintage Turbines

1980 wind turbines do surprisingly well in the studies of the energy balance. The analysis shows that while small Danish 1980 turbines of 10-30 kW took almost a year to recover the energy spent in manufacturing, installing and decommissioning them, turbines of 55 kW took some 6 months to recover all of the energy.

Guided Tour

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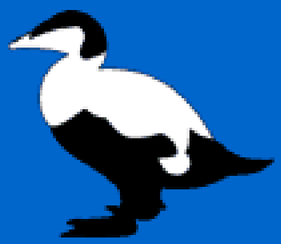
Updated 27 September 2000
http://www.windpower.org/tour/env/enpaybk.htm

Home

www.WINDPOWER.org
Danish Wind Turbine Manufacturers Association


Common Eider
(Somateria Mollissima)
© 1996 S ren Krohn

Birds and Wind Turbines

Birds often collide with high voltage overhead lines, masts, poles, and windows of buildings. They are also killed by cars in the traffic.

Birds are seldom bothered by wind turbines, however. Radar studies from Tjaereborg in the western part of Denmark, where a 2 megawatt wind turbine with 60 metre rotor diameter is installed, show that birds - by day or night - tend to change their flight route some 100-200 metres before the turbine and pass above the turbine at a safe distance.

In Denmark there are several examples of birds (falcons) nesting in cages mounted on wind turbine towers.

The only known site with bird collision problems is located in the Altamont Pass in California. Even there, collisions are not common, but they are of extra concern because the species involved are protected by law.

A study from the Danish Ministry of the Environment says that power lines, including power lines leading to wind farms, are a much greater danger to birds than the wind turbines themselves.

Some birds get accustomed to wind turbines very quickly, others take a somewhat longer time. The possibilities of erecting wind farms next to bird sanctuaries therefore depend on the species in question. Migratory routes of birds will usually be taken into account when siting wind farms, although bird studies from Yukon show that migratory birds do not collide with wind turbines.

Birds and Offshore Wind Turbines

Ornithologists' (Bird watchers) tower erected next to the offshore wind farm at Tun Knob, Denmark, for a three-year avian study which were completed in 1997. Photograph © 1997 by Soren Krohn

Offshore wind turbines have no significant effect on water birds. That is the overall conclusion of a three year offshore bird life study made at the Danish offshore wind farm Tunø Knob.

The offshore wind park has been placed in this particular area because of a very substantial population of eiders *(Somateria mollissima)* and a small population of scoters (*Melanitta nigra*). At Tun Knob more than 90 per cent of the birds are eiders, and about 40 per cent of the North Atlantic population of eiders are wintering in the Danish part of the Kattegat Sea.

The Studies were conducted by the National Environmental Research Institute at Kal , Denmark.

Eight Different Studies

The very thorough study consists of both aerial surveys, bird counts from observation towers, and observations of the spatial distribution of birds at the offshore site as well as at a similar control site in the same region.

In the three year period some eight experiments were carried out. The central experiment was a so called before-after-control-impact study. From a watch tower placed one kilometre from the turbines and from aeroplanes scientists mapped the population of eiders the winter before the erection of the turbines and the following two winters.

Declining Population

During the three year period the number of Eiders declined by 75 per cent and the number of scoters declined by more than 90 per cent. But more interestingly, the population of water birds fell in all of the shoal of the Tun Knob and not just around the turbines. This indicated that other factors than the turbines had to be taken into account.

At the same time the area was repeatedly surveyed by divers in order to determine variations in the amount of blue mussels *(Mytilus edulis)* which the birds prey on.

Less Food

The amount of blue mussels showed also great natural variation over the three years. Especially the population of smaller mussels which are the eiders' preferred prey fell significantly in the three year period. With these findings in mind the scientific group concluded that the changes in size and composition of the blue mussel population could explain the variation in the number of eiders before and after the construction of the wind farm.

Safe Distance

Controlled experiments stopping the wind turbines for a certain period has been performed. In another experiment decoys was used to attract the eiders, which are very social birds.

The result of the experiment using groups of decoys at different distances from the wind farm showed that the eiders were reluctant to pass at distances of 100 m or closer to the turbines.

The on/off experiment showed that there was no detectable effect of revolving rotors on the abundance of eiders in the area. In fact the eiders - like people - apparently prefer rotating turbines (but that result was clearly insignificant).

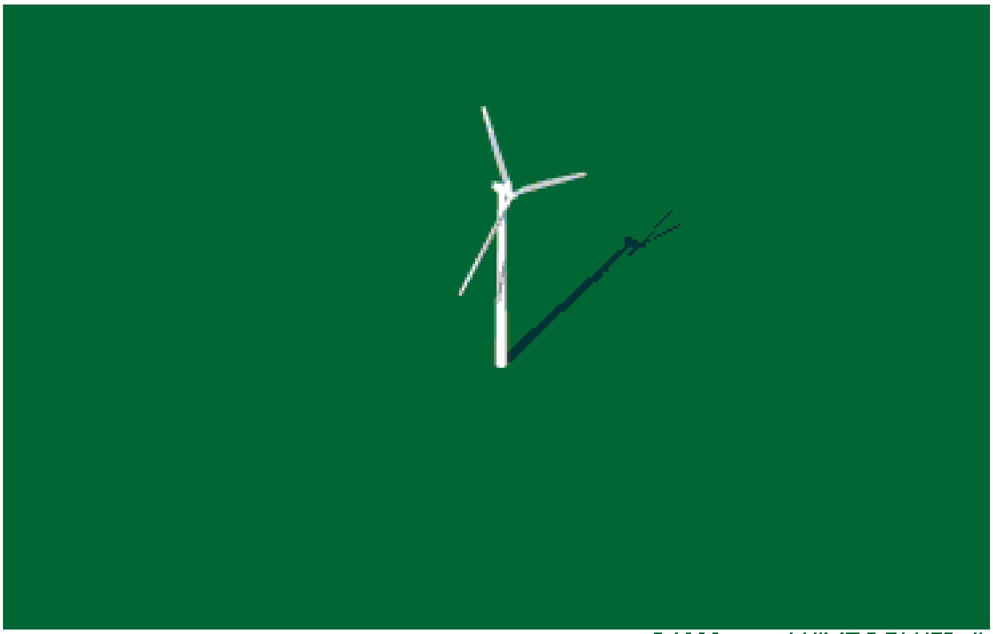
The overall conclusion of the final two experiments were that on one hand the eiders do keep a safe distance to the turbines, but on the other hand they do not get scared away from their foraging areas by revolving rotors. Also, the eiders showed normal landing behaviour until 100 m from the turbines.

Mussels Matter

The prevalence of eiders in the different zones around the turbines could be fully accounted for by the relative abundance of food.

The English edition of this study "Impact Assessment of an Off-shore Wind Park on Sea Ducks, NERI Technical Report No. 227 1998" is available from Milj butikken, i.e. the Sales office of the Danish Ministry of the Environment and Energy.

Shadow Casting from Wind Turbines



Wind turbines, like other tall structures will cast a shadow on the neighbouring area when the sun is visible. If you live very close to the wind turbine, it may be annoying if the rotor blades chop the sunlight, causing a flickering (blinking) effect while the rotor is in motion.

A bit of careful planning, and the use of good software to plan your wind turbine site can help you resolve this problem, however. If you know where the potential flicker effect is of a certain size, you may be able to place the turbines to avoid any major inconvenience for the neighbours.

Few Rules

Shadow casting is generally not regulated explicitly by planning authorities. In Germany, however, there has been a court case in which the judge tolerated 30 hours of actual shadow flicker per year at a certain neighbour's property. In the 30 hours, it appears, one should only include flicker which occur during the hours where the property is actually used by people (who are awake).

Predicting Shadow Flicker

Fortunately, we are able to predict quite accurately the probability of when and for how long there may be a flicker effect. We may not know in advance whether there is wind, or what the wind direction is, but using astronomy and trigonometry we can compute either a likely, or a "worst case" scenario, i.e. a situation where there is always sunshine, when the wind is blowing all the time, and when the wind and the turbine rotor keep tracking the sun by yawing the turbine exactly as the sun moves.

Figuring out the exact shape, place, and time of the shadow from a wind turbine requires a lot of computation, but at least one professional wind software programme can do this very accurately, even in hilly terrain, and with house windows of any size, shape, location and inclination facing in any direction. (See the Links page for the address of wind software companies).

Do it Yourself

On one of the following pages we have included another shadow calculator, which will give you a possibility of computing a shadow map of your particular area in flat terrain. The calculator gives you a lot of options to produce realistic estimates of actual shadow casting. Fortunately, you will discover that shadow casting problems are generally restricted to a few areas close to the turbine.

Since the calculation of shadow casting requires lots of computer power, we have included a number of important general results on the following pages.

Calculating Shadows from Wind Turbines

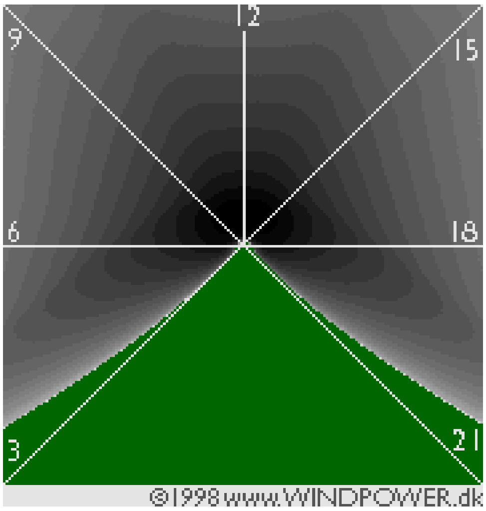
Daily Shadow Variation - Worst Case

This simulation of shadow casting shows how the rotor shadow moves (worst case) from sunrise to sunset on a particular day at a certain location on the globe. The image is seen directly from above, with the centre of the wind turbine tower placed at the tiny black dot in the centre. The shadow positions are shown for every half hour during the day. Shadows, of course, are long around sunrise and sunset, and short at noon.

This particular set of images was made for 55° Northern latitude for 21 September, assuming a 43 m rotor diameter on a 50 m tower, using the shadow simulation programme on this web site.

Doing a worst case simulation we assume that the rotor yaws so as to track the movement of the sun exactly. This is is equivalent to assuming that the rotor is a solid balloon (or a Darrieus turbine).

Annual and Daily Shadows - Worst Case



Map of maximum (worst case) shadows around a 600 kW wind turbine placed at 55 degrees Northern latitude. The turbine has a 43 m rotor diameter and a 50 m tower. The map is 1200 m wide (East - West) and 750 m in the North - South direction. The map was computed using the Wind Turbine Shadow Calculator on this web site.

This map shows how shadows are typically distributed around a wind turbine throughout a year, assuming a worst case direction of the rotor. You will notice a number of kidney-shaped or bell-shaped areas around the wind turbine in the centre of the map. Each of the grey areas represents a certain maximum number of minutes of shadow from the wind turbine rotor. Since this map was computed for 55 degrees latitude in the Northern hemisphere, there is no shadow South of the turbine.

Timing Shadows

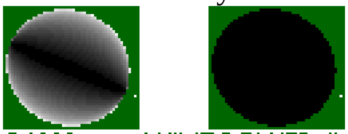
You will notice from the white lines on the map, that we can easily predict the time of day when shadows may occur. The shadow will e.g. obviously be directly North of the turbine at solar noon, when the sun reaches its maximum height in the sky. (Solar noon varies a bit during the year relative to our clocks, but it is fairly close to 12 o' clock, local time). The shadow will be to the bottom left at 4 o'clock in the morning on a summer day, so shadows to the Southwest are a minor problem in the Northern hemisphere. (The shadows occur in summer only, and at 4 in the morning most neighbours will be asleep anyway).

The commercial software we referred to earlier will tell you exactly the dates and times when shadows may occur.

Refining Shadow Calculations for Wind Turbines

Random Rotor Direction (Random Azimuth)

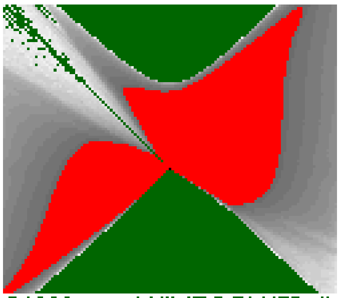
It is very unlikely that the wind and thus the rotor will track the sun in practice. We may therefore get a more realistic result if we modify our calculations by assuming that the rotor can assume any position at any time. In the small picture to the far right you can see a situation where the rotor is directly facing the sun. The tiny white dot near the bottom right is the centre of the wind turbine tower.



Now, let us assume that we yaw the rotor out of its position by one degree, take a snapshot of the shadow image, then yaw it by another degree, take another snapshot etc., until we have done a full 360 degree turn. Then we overlay all our 360 snapshots, and what we end up with will look similar to the small image to the left: The centre will get the most of the shadow, but as we move towards the outer edge (where the vertical edges of the rotor disc cast their shadows) the overall shadow intensity will decrease.

Shadow casting is on average reduced to 63% of the worst case results, if you assume a random rotor direction. Ideally, we should have a wind rose, (preferably hourly for each day or month) to do an exact calculation.

Fixed Rotor Direction (Fixed Azimuth)



In practice the wind turbine rotor will follow the wind direction (if the wind speed is above the cut in speed). This image shows the shape of an area (in red) which gives 10 hours or more of shadows per year at 55° Northern latitude with the rotor yaw (azimuth) fixed at an angle of -45 degrees (i.e. with the wind permanently coming from the Southwest or Northeast). As you can see, there will be almost no shadows at an angle of +45 degrees, i.e. in the direction parallel to the rotor plane.

Shadow casting is typically reduced to around 62% of the worst case results, if we assume a fixed rotor direction.

Actual Rotor Direction (Wind Rose)

Usually we will already have a wind rose with a frequency distribution of the wind in the different directions of the compass when we are planning a wind turbine site. Using that information, we may calculate a more exact shadow picture. In the case of our test example, Copenhagen, shadows are reduced to some 64 per cent of the comparable worst case value.

Turbine Operating Hours

The rotor will not be running all the time, so we may multiply the number of minutes of shadow flicker by a factor of typically 0.75, depending on the local wind climate, (and ideally using the correct factor for daytime during each month).

Actual Sunshine Hours

When studying shadows, we should only count the fraction of the time when the sun is actually shining brightly, ideally using the correct fraction for each hour of the day during the year. In 1853 the first reliable sunshine recording device was invented (and improved in 1879), which means that in many parts of the world the meteorological institutes have very accurate long term statistics on the number of hours of bright sunshine during the year.

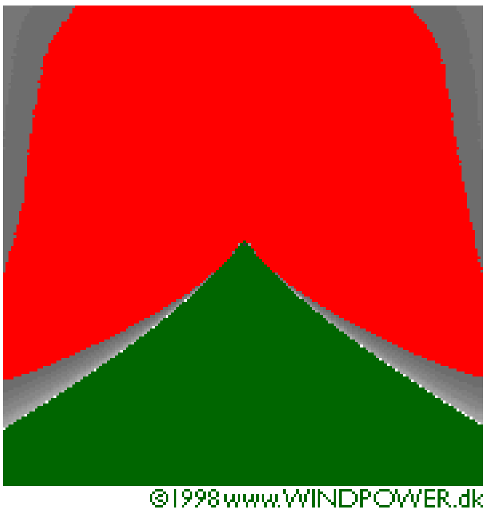
The number of bright sunshine hours varies with the geographical location and the season (summer or winter). We have included data for three Danish sites (Christiansø, Copenhagen, and Viborg) where the number of sunshine hours vary from 44 to 40, and 36 per cent of the time.

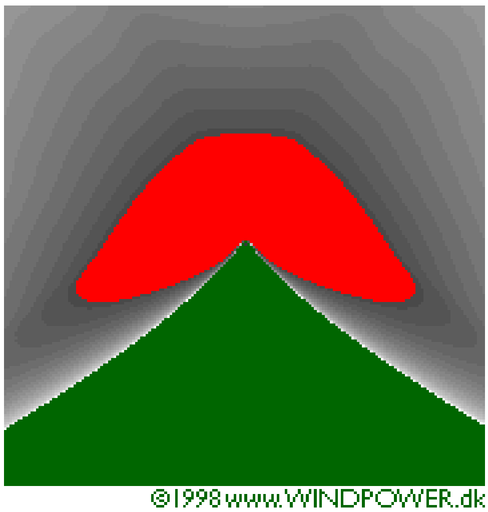
Combining Turbine operating hours, Actual Rotor Direction, and Actual Sunshine Hours

If we use both turbine operating hours, the actual rotor direction, and the actual bright sunshine hours we get a result (in the case of Denmark) which is some 18 per cent of the worst case assumption, using 75% operating hours in both cases. (The percentages given above are the results of simulations for Copenhagen on a 720 by 720 metre square with a turbine in the centre with 43 m rotor diameter and 50 m hub height).

The two images below compare a worst case simulation (with 75% operating hours) with an actual simulation for Copenhagen (also 75% operating hours) using both sunshine and wind statistics. The red area is the zone with 30 hours of shadow or more per year. Each map represents 720 by 720 metres.

The important conclusion of this simulation is that actual sunshine hours play a very important role in diminishing the amount of shadows north of the turbine (in the Northern hemisphere). The reason why this is important is that there are very few hours of sunshine when the sun is low in the sky to the south during winter.

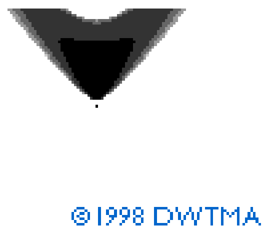




Updated 26 September 2000
http://www.windpower.org/tour/env/shadow/shadowr.htm

Shadow Variations from Wind Turbines

Monthly Shadow Variation



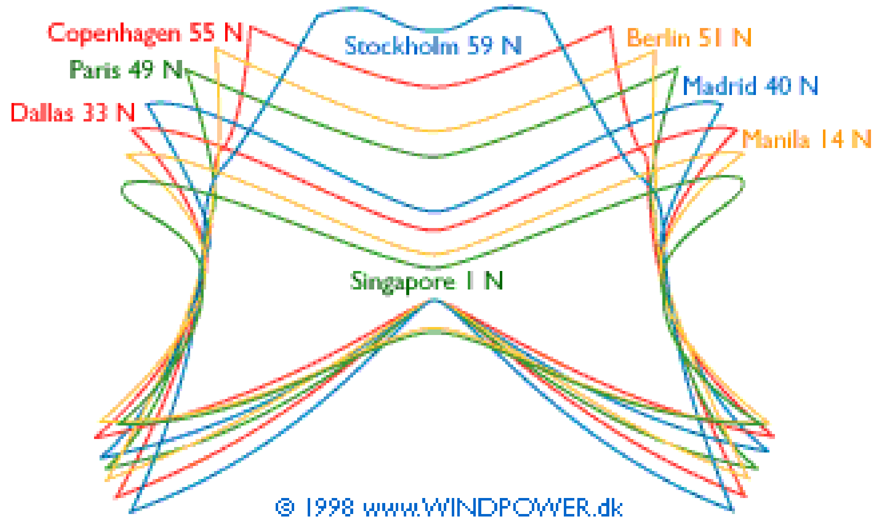
This movie shows the areas affected by shadow casting from a wind turbine. The movie shows how the area varies month by month - in this case in relatively high latitudes (55°) in the Northern hemisphere. The darkest areas represent the areas with most shadows.

In winter the sun stays in the Southern part of the sky, and the shadows are distributed in a V-shaped area to the North of the turbine.

In summer the sun rises very early in the morning to the Northeast and sunset is in the Northwest. This means that the summer shadows will be distributed in an A-shaped area, with the turbine in the tip of the "A".

In locations closer to the equator there will be far less shadow North and South of the turbine.

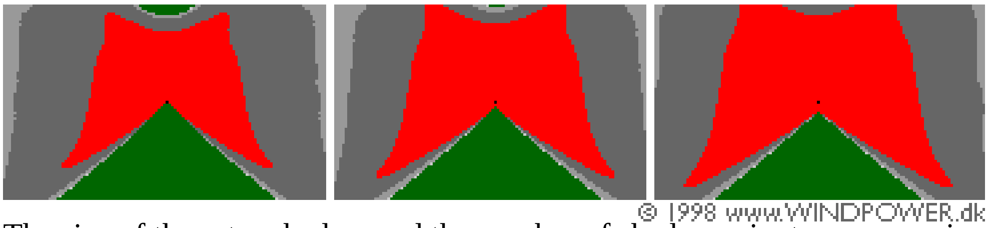
Shadow Geometry Varies by Latitude



Each latitude on the globe has its own shadow signature in terms of the area affected by a certain period of shadows from an object (30 hours per year). Close to the equator the signature resembles a butterfly. Farther away from the equator it becomes more kidney-shaped, and close to the poles it almost becomes a circle.

All of the graphs above were computed using the shadow calculator on this web site, and assume a "worst case" or a random rotor position.

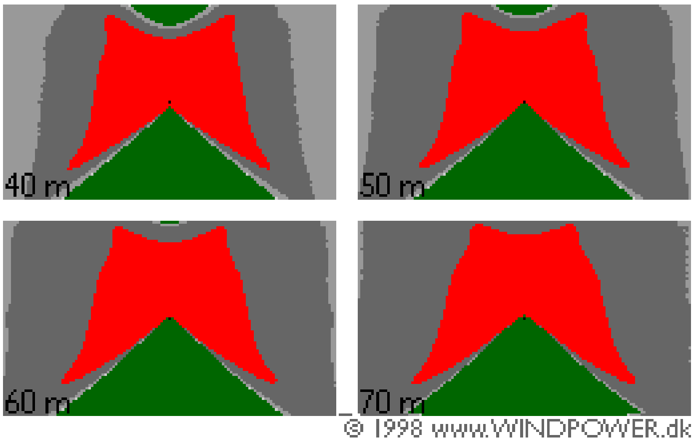
Shadow Size Grows with Rotor Diameter



The size of the rotor shadow and the number of shadow minutes per year in the vicinity of the turbine varies in proportion to the rotor area, as shown in the three pictures above. The red areas indicate the annual shadow patterns with more than 30 hours of shadow (worst case) from wind turbine rotors of 43, 53, and 63 m mounted on 50 m towers and computed for 55° latitude.

Hub Height of Minor Importance

The hub height of a wind turbine is of minor importance for the shadow from the rotor. The same shadow will be spread over a larger area, so in the vicinity of the turbine, say, up to 1,000 m, the number of minutes per year with shadows will actually decrease.



The four pictures show shadow casting during a year (worst case) from a wind turbine with a 43 m rotor diameter, placed with four different hub heights and computed for 55° latitude. The red areas represent areas with more than 30 hours of shadows.

If you are farther away from a wind turbine rotor than about 500-1000 metres, the rotor of a wind turbine will not appear to be chopping the light, but the turbine will be regarded as an object with the sun behind it. Therefore, it is generally not necessary to consider shadow casting at such distances.

Guide to the Wind Turbine Shadow Calculator

The calculator on the following page allows you to simulate shadows from a wind turbine on a plane, horizontal landscape any minute, hour, day, month, or year anywhere on the globe.

Warning:
Huge Plots Will Take Their Time - and lots of RAM

If you wish to compute shadows for a whole year, it may take your computer from 20 minutes to a couple of hours or more, depending on the speed of your browser and your machine, and how fine a map resolution and time resolution you choose. A fine map resolution (down to 3 pixels square) or a large plot area increases processing time and the required amount of RAM on your computer significantly.

Which Browser?

The shadow calculator is an extremely powerful, but computationally demanding programme.

If you use **Internet Explorer 4** for this calculator, be sure to enable Microsoft's Just-in-time compiler for JavaScript, since it is much faster. Internet Explorer will also give you the option of being able to read the number of minutes of shadow anywhere by moving the mouse cursor around the screen, if you select that option in your setup.

Netscape 4 will work, as well, and on some platforms it is occasionally (but rarely) faster than IE4.

Unfortunately Netscape up to version 4.05 for Macintosh appear to have a bug which means that they do not do "garbage collection" (cleanup after disused variables) properly. This means that the programme will run more and more slowly, until you quit your browser. Netscape has one advantage, however: You may let the programme run in the background while you do something else. (Version 4.06 seems to be safe, and faster than its predecessors).

Netscape 3 is quite fast, but it may very easily get a stack overflow and crash, if you use squares of much less than 25 pixels. Netscape 3 also stops and asks you if you want to continue every time you have completed 1 million iterations (i.e. repeated calculation steps). Since each month takes about 5 million iterations, you'll have to sit around and click "Yes" quite a few times. The solution is to upgrade, of course.

Colouring the Plot

The grey colours in your plot are selected automatically by the programme, so that the most shadow affected areas are shown in pure black, while the least affected areas are shown in white, regardless of whether you run the programme for 1 minute or a year. The unaffected areas remain green.

Screen Settings

If you have a screen with millions of colours, you will find that the grey shadows vary very smoothly across the screen. If you like to be able to see the different "bands" of shadow minute values, like we have done in our images on this web site, set your monitor to thousands of colours, or even 256 colours.

You Can Save Your Shadow Maps

If you have generated a shadow map which you want to look at later, or compare with another map, you may save the page (e.g. onto your desktop), just like any other web page in HTML format, if you use Internet Explorer 4. Just choose **Save** from your file menu, (and take care where you save it, and what you name it).

Read the Number of Minutes of Shadows in Each Cell

if you have an Internet Explorer 4 browser, and you leave this option on when you generate the map, you can do an exact readout (in the status line of your browser) of the number of minutes there may be shadows in each cell by moving the cursor around on the shadow map.

You May Recolour Your Result

The plot uses a number of standard colours which look logical on a colour screen. The colours, however, may not be optimal if you wish to print the result on a black and white printer. We have therefore included a facility which allows you to change the colour scheme without redoing the long calculations: You may use a particular colour in a "shadow zone" around the turbine. If you use a large high resolution map, it may take a few minutes for your programme to do the recolouring (IE 4 is slower than Netscape 4 for this).

Paint Your Shadow Zone

You may modify your plot to show you any zone with a certain minimum number of minutes of shadows in a certain colour. Be warned, however, that with a large high resolution map, it will take several minutes to complete that process.

Other Calculator Usage

Incidentally, this calculator is very practical for photographers who wish to know where the sun is before they go out to take a picture of their favourite motive in ideal lighting conditions. (We tested it when photographing wind turbines, of course). You may also use it if you wish to know how to place a terrace in your garden (regardless of whether you want shadow or sun).

Location

You may either specify your turbine location using the pop up menu which gives the longitude and latitude of a number of cities around the globe, or you may enter the longitude and latitude in degrees and minutes directly, together with your time zone.

Time Zone

The time zone is automatically included, if you use the pop up menu with city names. You may enter your time zone relative to GMT from the pop up menus, or you may enter the standard time zone meridian, i.e. the longitude relative to Greenwich which your local time system uses as a reference, which is generally a multiple of 15 degrees, corresponding to a one hour time difference. (India and a few other places have a time zone which is a multiple of 7.5 degrees, i.e. half an hour).

Time

You may enter date and time to see the sunrise and sunset times, plus the current direction of the light coming from the sun.

Wind Turbine

Enter the hub height and the rotor diameter. A typical hub height for a 600-750 kW wind turbine is 45 to 60 m, a typical rotor diameter is 43 to 48 m. (You may find typical hub heights and rotor diameters using the Wind Turbine Power Calculator turbine pop up menu).

If you wish to study shadows in areas which are lower than the base of the wind turbine, you can cheat, and increase the hub height of the turbine. Conversely, you can lower the hub height, if you wish to study areas which are higher than the base of the turbine.

If you enter, say 0.5 for the rotor diameter, you may use the programme to study the behaviour of a shadow from the top of a mast, or the corner of a building. (Or you can use it to build your own sundial).

Shadow Plot

You can specify the time range for which you like your shadow images computed. You can select a minute, an hour, a day, a month, or a year.

You may set the **plot area** to fit your screen size (and/or paper output). If you have enough RAM (and time) you may even specify a map larger than your screen. The default size prints well on A4 paper in landscape format.

The **resolution** parameter determines the area covered by each 3-25 pixel square. We recommend that you let each square represent less than half the rotor diameter to get a decent plot. Or, even more cleverly, you may set it to match your map resolution, and print your output on an acetate (overhead) foil as an overlay to a map of a prospective wind turbine location. (One printed pixel is 1/72 of an inch (1 inch = 2.54 cm)).

The **step length** in minutes determines how many rotor images the programme projects onto your ground surface. The default step length of 4 minutes corresponds to the sun azimuth changing on average 1 degree between each simulation. You may save processing time if you choose a longer step length. For a 1 month or 1 year simulation results are generally not affected much by using 8 minute steps - and it is 8 times faster than 1 minute steps. If the shadow image is not smooth, (or if it is asymmetrical in the East-West direction even if you are not running with a fixed rotor direction or a wind rose), your step length may be too large. If you double the step length, the programme assumes that the rotor shadow stays in the same place for twice as long, i.e. for each rotor image projected onto the ground, it adds the step length to a shadow counter for that particular area.

You may choose **rotor direction** as random (default), which means the rotor may be facing in any direction (random azimuth), you may choose

worst case, where the rotor always faces the sun.

You may choose a **fixed rotor azimuth angle** from -90 to 90 degrees. The angle is measured relative to South, and the solar angle is positive before noon, regardless of hemisphere. 0 means that the wind is coming form the South or North. Southeast/Northwest is 45 degrees in the Northern hemisphere, and -45 degrees in the Southern hemisphere. East/West is 90 or -90 degrees. To help you select the correct angle, you may use the pop up menu.

Finally, you may choose to enter a **wind rose** with a frequency distribution for your wind directions. Since a normal propeller type wind turbine is symmetrical about its rotor plane, you should add the percentages for North and South, and so forth in each of your directions. The programme accepts 8, 12 and 16 compass directions, which means that you specify 4, 6, or 8 percentages. The program checks that the sum is exactly 100, before it is willing to do the simulation. Please note that wind roses are specified with the North as 0 degrees, and that the degrees are given in a clockwise direction (retrograde direction).

You should specify the **fraction of daytime hours the turbine will be running.** 0.75 is a typical fraction. The basic result in terms of minutes of shadows is multiplied by this fraction.

You should specify the **fraction of daytime hours with bright sunshine**. The basic result in terms of minutes of shadows is multiplied by this fraction.

If you have accurate statistics on the number of bright sunshine hours per month, you may instead use that data in your calculations, by filling out **the sunshine table** at the bottom of the page. In that case the programme uses the table data for each month instead of the average. We have included sunshine data for 3 Danish locations (you select them from the pop up menu). If you have reliable monthly data available for your location, please e-mail us (giving the source) so that we may include it in the city pop up menu. Remember to check the box that says you want to use the table for your calculations. (A clever trick: If you wish to see the pattern of shadows during e.g. June, July, and August only, you may set the sunshine percentages for the three months only, and leave the rest of the months at zero, and then run a simulation for a year, using the sunshine table).

You may set a **maximum distance from the wind turbine** for the shadow plot, since it is usually not relevant to look at distances above 7 to 10 rotor diameters or 1,000 m at the most.

Finally, you may choose to have your output displayed with **mouse-sensitive shadow readout** (for I.E. 4 browsers), which means that you may read the number of minutes of shadow in each cell on the map in your browser's status line by placing the mouse cursor on a particular cell. Using this mechanism increases RAM demand.

Sunrise

In this programme the sunrise time is defined as the moment a straight line to the centre of the sun passes the horizon in the upwards direction on the date you have entered in your data. In your local newspaper, you may find that the sunrise is defined as being some minutes earlier, when the upper edge of the sun reaches the horizon. In addition, the refraction (bending of the light) in the atmosphere means that you can actually see the sun before it reaches the horizon. The sunrise is in local time, or daylight saving time, if the Daylight saving time box is checked.

Noon
The solar noon is when the sun reaches it highest point in the sky, i.e. the solar altitude is at its maximum. Noon is in local time, or daylight saving time, if the Daylight saving time box is checked.

Sunset
In this programme sunset time is defined as the moment a straight line to the centre of the sun passes the horizon in the downwards direction on the date you have entered in your data. In your local newspaper, you may find that the sunset is defined as being some minutes later, when the upper edge of the sun reaches the horizon. In addition, the refraction (bending of the light) in the atmosphere means that you can actually see the sun after it goes below the horizon. The sunset is in local time, or daylight saving time, if the Daylight saving time box is checked.

Declination
The declination is the angle between the earth's equatorial plane, and the earth-sun line. As the earth rotates, it spins around its axis which points to the North Star. This axis is inclined 23.45 relative to the plane in which it orbits the sun. The angle between the equatorial plane and the earth-sun line thus varies between +/-23.45 during the year, being approximately zero on the 21/3 and 23/9 (Equinox), and reaching its extreme values on 21/6 and 21/12 (Solstice). (Its precise value varies a bit from year to year since a year is 365.25 days long).

Sunrise/Sunset Duration
This is the number of minutes and seconds it takes for the solar disc to move the 0.531 between the bottom and the top of the sun at sunrise or sunset. At the equator the sunrise and sunset last little more than two minutes. As you move towards the polar regions, the duration increases significantly, particularly in winter, as you may verify by altering the latitude.

Solar Azimuth
The solar azimuth is the angle in the horizontal plane between the South and the sun at the moment in time you have entered in your data. The angle is positive before noon, negative after noon (regardless of hemisphere).

Solar Altitude
The solar altitude is the angle between the horizontal plane and the sun.

Direction form the Sun (Sun Vector)
If you are standing in the centre of the turbine with your back towards the South, and you move x units of length to the right (East), y ahead (North), and z up (or rather -z down), then a straight line from your new position to the centre of the turbine will be pointing directly to the sun. The values for x, y, and z are given in the three boxes.

Updated 26 September 2000

Wind Turbine Shadow Calculator

Calculator

This calculator requires a Netscape 3.01 or IE 4 or later browser to work. If you are using Navigator 3.01 or later or Internet Explorer 4 or later, and you see this message, you need to enable JavaScript. In Netscape, choose Options | Network Preferences, choose the Languages tab, and click Enable JavaScript. Then click reload on your browser. In Internet Explorer, choose Edit | Preferences | Java, and enable Java, select the Microsoft virtual machine, and enable the "Just in time compiler". Then click reload on your browser. Do not operate the form until this page and its programme have loaded completely. Otherwise the program will complain about missing data, and you will have to click **Reload**. This calculator lets you experiment with your local conditions to determine the shape and size of the local area which may be affected by shade (light flicker) from a wind turbine. For an actual project you will probably want professional wind project software which will help you with a lot of other aspects as well. (See the Links section).

After changing data, use the tab key, click the Calculate button, or click anywhere on the page outside the field you have updated to get the results in the right column. To get a plot image, click on the Plot button. Click on the question marks for help. (If a plot windows disappears, it is probably hidden behind this window).

Location

? Select: Copenhagen *) or type

55 41 ' latitude (•) North ( ) South

12 35 ' longitude (•) East ( ) West

Time Zone

? 15 time zone meridian (•) East ( ) West

or **GMT** + 1 : 00

Time

? day 21 month 6

time (0:00-23:59) 14 : 00 [ ] Daylight saving time

Wind Turbine

? 50 m hub height, 43 m rotor diameter

Results this Day

? Sunrise [ ] : [ ]

? Noon [ ] : [ ]

? Sunset [ ] : [ ]

? Declination [ ]

Sunrise/sunset duration

? [ ] min. [ ] sec.

Results this Minute

? Solar azimuth [ ]

? Solar altitude [ ]

Direction from the sun

[ ] [ ] [ ]

(East, North, Up coordinates)

Shadow Plot

? this... ○ minute ○ hour ◉ day ○ month ○ year, step [4] minute(s)

Plot area height [450] width [720] pixels, resolution = [15] m per [15] pixels

Rotor direction (azimuth) ◉ random ○ worst case (Darrieus)

○ facing azimuth [-45] = [SW/NE] ○ use wind rose table below

Turbine running [75] % of the daytime. Max. distance [1000] m

Sunshine [40] % of the time **OR** check here ☐ to use monthly sunshine hours from table below.

☐ Include mouse sensitive shadow duration readout (only useful if used with an I.E. 4 browser)

*)= Cities marked with an asterisk in the city popup menu include sunshine and wind rose data for the tables below.

Bright Sunshine Table

Month	Daytime Hours	Bright Sunshine Hours	Bright Sunshine per cent
January		0	0
February		0	0
March		0	0
April		0	0
May		0	0
June		0	0
July		0	0
August		0	0
September		0	0
October		0	0
November		0	0
December		0	0
Year Total		0	0

Wind Rose Table

using [12] directions

wind rose sector (not azimuth)	%
N-S 180/0 °	0
SSW-NNE 330/15(°	0
ESE-WNW 300/12(°	0
E-W 270/90 °	0
ENE/WSW 240/60 °	0
NNE-SSW 210/30 °	0
not used °	0
not used °	0

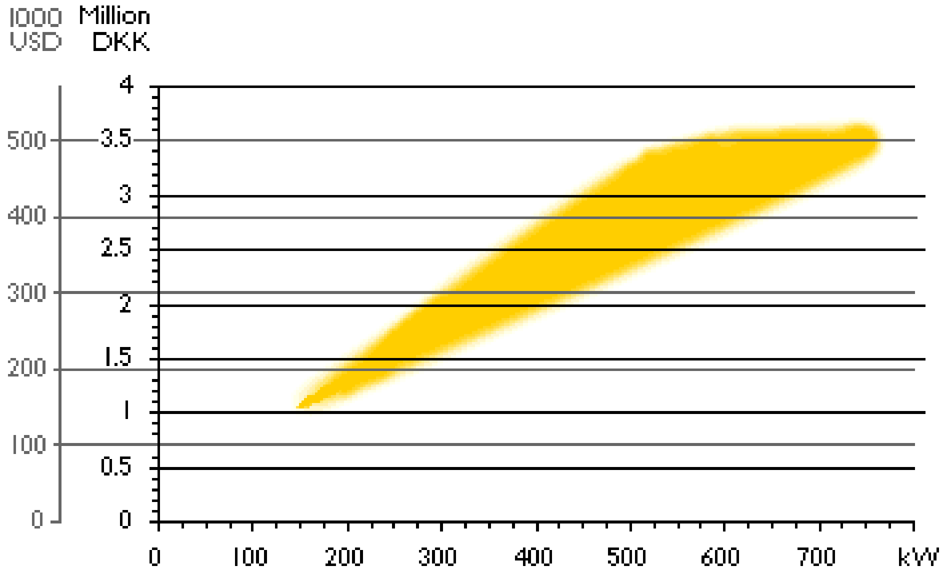
Total ... ... [0]

Total must be 100%

Daytime hours are computed automatically by this programme.
Source for bright sunshine hours:

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 rater 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 500 - 750 kW. This is where you are likely to find a machine which is optimised for any particular wind climate.

Typical 600 kW Machines on the Market Today

Even if prices are very similar in the range from 500 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 450 kW machine, if it is located in a low wind area. The working horse today is typically a 600 kilowatt machine with a tower height of some 40 to 50 metres and a rotor diameter of around 43 metres.

We use a typical Danish 600 kW turbine as an example below (approximate amounts in US dollars, prices vary with tower heights, rotor diameter, and local specifications):

	Currency * USD
600 kW wind turbine, typically	400 000 - 500 000
Installation costs, typically	100 000 - 150 000
Total	500 000 - 650 000

*) Prices, costs, and exchange rates were reasonably accurate on 13 February 1998. The price range goes from the cheapest turbine model without any options to a special low wind model on a tall tower with a large rotor diameter. Freight costs are not included. Currency conversion requires a Netscape 3.0 browser.

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, yet. We'll return to that in a couple of pages. Energy production is measured in kilowatt hours. If this sounds confusing, take a look at the Reference Manual of this web site).

For single turbines or small clusters of turbines the costs will usually be somewhat higher. On the next page we will discuss installation costs further.

Installation Costs for Wind Turbines

Novar Wind Farm, Scotland, under construction in a moor, July 1997. Photograph by Steffen Damborg

Installation costs include **foundations**, normally made of armed 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.

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 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 (see the section on Wind Turbines in the Electrical Grid). 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 5000 Danish wind turbines installed in Denmark since 1975 show that newer generations of turbines have relatively lower repair and maintenance costs that 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 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.

Project Lifetime, Design Lifetime

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.

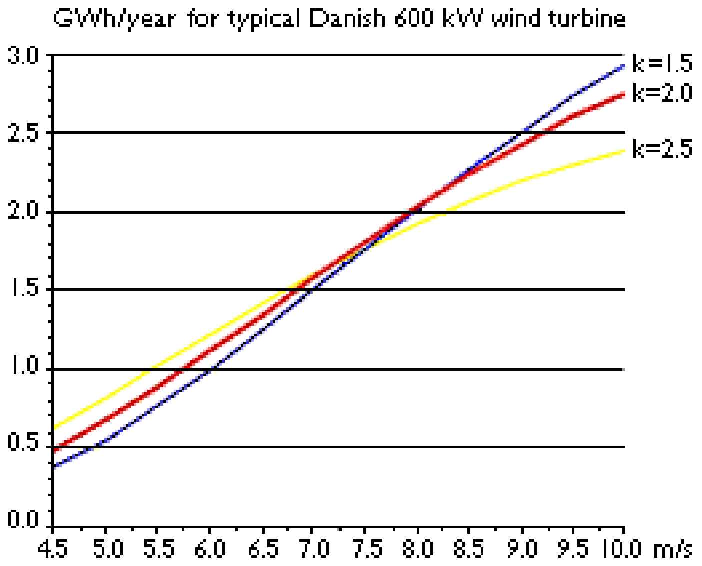
The actual lifetime of a wind turbine depends both on the quality of the turbine and the local climatic conditions, e.g. the amount of turbulence at the site, as explained in the page on turbine design and fatigue loads.

Offshore turbines may e.g. last longer, due to low turbulence at sea. This may in turn lower costs, as shown in the graph on the page on the Economics of Offshore Wind Turbines.

Updated 6 August 2000
http://www.windpower.org/tour/econ/oandm.htm

Income from Wind Turbines

Energy Output from a Wind Turbine



If you have read the page on Annual energy output from a wind turbine, this graph will already be familiar to you.

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). We will be working with the red curve (k=2) in our example.

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.

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Updated 6 August 2000

Wind Energy and Electrical Tariffs

This page is relevant for private investors in wind energy, but not for power companies, which of course know everything about their own tariff system.

Electrical Energy Tariffs

Electricity companies are generally more interested in buying electricity during the periods of peak load (maximum consumption) on the electrical grid, because this way they may save using the electricity from the less efficient generating units. According to a study on the social costs and benefits of wind energy by the Danish AKF institute (see the Links page), wind electricity may be some 30 to 40 per cent more valuable to the grid, than if it were produced completely randomly.

In some areas, power companies apply variable electricity tariffs depending on the time of day, when they buy electrical energy from private wind turbine owners.

Normally, wind turbine owners receive less than the normal consumer price of electricity, since that price usually includes payment for the power company's operation and maintenance of the electrical grid, plus its profits.

Environmental Credit

Many governments and power companies around the world wish to promote the use of renewable energy sources. Therefore, they offer a certain environmental premium to wind energy, e.g. in the form of refund of electricity taxes etc. on top of normal rates paid for electricity delivered to the grid.

Capacity Credit

To understand the concept of capacity credit, let us look at its opposite, **power** tariffs: Large electricity customers are usually charged both for the amount of energy (kWh) they use, and for the maximum amount of power (kW) they draw from the grid, i.e. customers who want to draw a lot of energy very quickly have to pay more. The reason they have to pay more is, that it obliges the power company to have a higher total generating capacity (more power plant) available.

Power companies have to consider adding generating capacity whenever they give new consumers access to the grid. But with a modest number of wind turbines in the grid, wind turbines are almost like "negative consumers", as explained in the section on Wind turbines in the electrical grid: They postpone the need to install other new generating capacity.

Many power companies therefore pay a certain amount per year to the wind turbine owner as a capacity credit. The exact level of the capacity credit varies. In some countries it is paid on the basis of a number of measurements of power output during the year. In other areas, some other formula is used. Finally, in a number of areas no capacity credit is given, as it is assumed to be part of the energy tariff. In any case, the capacity credit is usually a fairly modest amount per year.

Reactive Power Charges

Most wind turbines are equipped with so called asynchronous generators, also called induction generators, cf. the section on electrical parts of a wind turbine. These generators require current from the electrical grid to create a magnetic field inside the generator in order to work. As a result of this, the alternating current in the electrical grid near the turbine will be affected (phase-shifted). This may at certain times decrease (though in some cases increase) the efficiency of electricity transmission in the nearby grid, due to reactive power consumption.

In most places around the world, the power companies require that wind turbines be equipped with switchable electric capacitor banks which partly compensate for this phenomenon. (For technical reasons they do not want full compensation). If the turbine does not live up to the power company specifications, the owner may have to pay extra charges.

Normally, this is not a problem which concerns wind turbine owners, since the experienced manufacturers routinely will deliver according to local power company specifications.

Updated 26 September 2000
http://www.windpower.org/econ/tariffs.htm

Basic Economics of Investment

Social Return from Investment in Wind Energy

On the next two pages, we look at the economics of an investment in wind energy from the point of view of society as a whole, as economists typically do. If you do not like economics, or if you know everything about it in advance, skip this page.

We do not account for environmental benefits, we shall do that later. We do not look at financing or taxation. These items vary enormously from one country to the other, but they do not make any nation richer or poorer: They only serve to redistribute income.

What society gets in return for investment in wind energy is pollution-free electricity; let us find out how much that costs.

Private Investors' Guide

If you are a private investor in wind energy you can still use our calculations - pre tax, that is: Generally speaking, investments which have a high rate of return before tax will have an even higher rate of return after taxes.

This is a surprise to most people.

The reason is, however, that depreciation regulations for all sorts of business tend to be very favourable in most countries. With rapid tax depreciation you get a higher return on your investment, because you are allowed to deduct the loss of value of your asset faster than it actually loses it value. This is nothing special for wind turbines. It is true for all sorts of business investment.

Once again, do note, that our calculations in real terms omit financing and taxes. As a prudent investor, you would probably want to plan your cash flow to make sure you can pay your debts. This you obviously have to calculate in **money** terms, i.e. in nominal terms.

Working with Investments

With any investment, you pay something now to get something else later. We assume that a dollar in your pocket today is more valuable to you than a dollar tomorrow. The reason why we say that, is that you could invest that dollar somewhere or put it into a bank account and earn interest on it.

To tell the difference between today's and tomorrow's dollars, we therefore use the **interest rate**. If we do that, 1 dollar a year from now is worth 1/(1+**r**) to you today. **r** is the interest rate, for example 5 per cent per year.

Thus 1 dollar a year from now is worth 1/1.05 = 0.9523 dollars today. 1 dollar 2 years from now is worth 1/(1.05*1.05) = 0.9070 and so forth...

But what about inflation? To deal with that we shall simply only work with dollars which have the same purchasing power as a dollar does today. Economists call that working with **real** values, instead of nominal ones.

Work in Real Values, not Nominal Values

An investment in a wind turbine gives you a **real** return, i.e. **electricity**, and not just a financial (cash) return. This is important, because if you expect some general inflation of prices during the next 20 years, you may expect electricity prices to follow the same trend.

Likewise, we would expect operation and maintenance costs to follow roughly the same price trend as electricity. If we expect all prices to move in parallel (with the same growth rates) over the next 20 years, then we can do our calculations quite simply: We do not need to adjust or calculations for inflation, we simply do all of our calculations in the price level of our base year, i.e. the year of our investment.

In other words, when we work with **real** values, we work with money which represent a **fixed** amount of purchasing power.

Use the *Real* Rate of Interest, not the Nominal Rate

Since we are studying the **real** rate of return (profitability) of wind energy, we have to use the **real** rate of interest, i.e. the interest rate minus the expected rate of inflation. (If both rates are high, say, above 10 per cent, you cannot really subtract the percentages, you should divide like this (1+r)/(1+i) but let's not make this into a course in economics).

Typical real rates of interest for calculation purposes these days are in the vicinity of 5 per cent per annum or so. You may say that in countries like Western Europe you could even go down to 3 per cent. Some people have a very high demand for profitability, so they might wish to use a higher real rate of interest, say, 7 per cent. Using the bank rate of interest is nonsense, unless you then do **nominal** calculations, i.e. add price changes everywhere, including to the price of electricity.

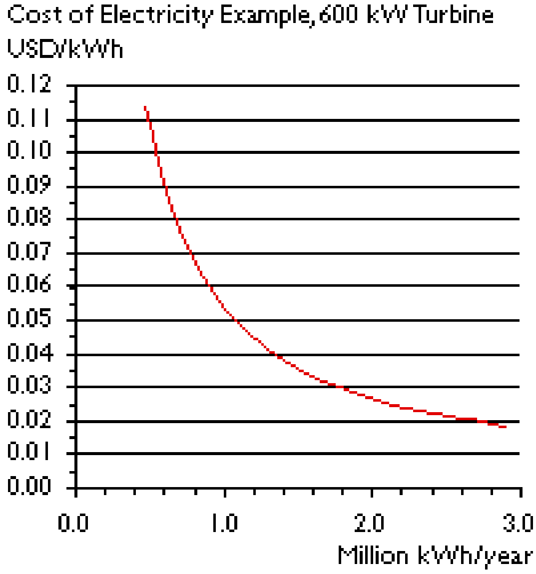
Wind Energy Economics

There is no Such Thing as a Single Price for Wind Energy

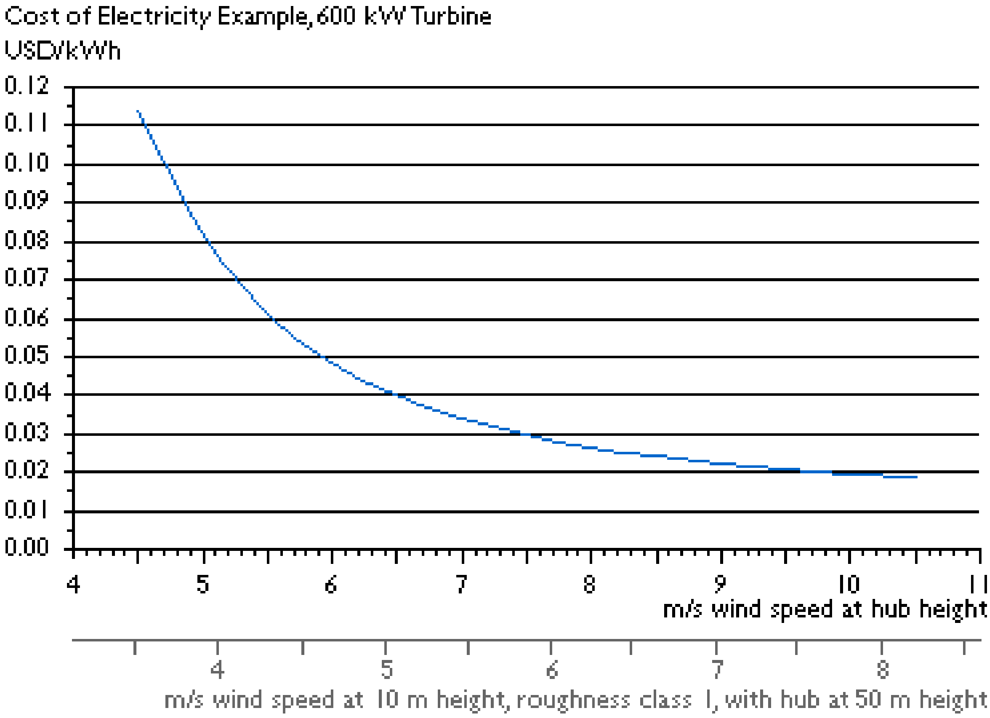
As we learned from the page on energy output, annual electricity production will vary enormously depending on the amount of wind on your turbine site. Therefore, there is not a single price for wind energy, but a range of prices, depending on wind speeds.

The graph to the right shows how the cost of electricity produced by a typical Danish 600 kW wind turbine varies with annual production. (We used the example built into the Wind Energy Economics Calculator to find the points for the graph).

The relationship is really very simple: If you produce twice as much energy per year, you pay half the cost per kilowatt hour. (If you believe that maintenance costs increase with turbine use, the graph might not be exactly true, but close to true).



If we use the graph above, plus the example from the page on income from wind turbines we find the relationship between wind speeds and costs per kWh below. Remember, that everything on this page is based on our examples, so you cannot use the graph to predict costs for any particular project. As an example, if your real rate of interest is 6 per cent per annum, rather than 5, costs are approximately 7.5 per cent higher than shown in the graph. When you use the Wind Energy Economics Calculator in a moment, you can use your own data to compute the cost of electricity.



The example is for a 600 kW wind turbine with project lifetime of 20 years; investment = 585,000 USD including installation; operation & maintenance cost = 6750 USD/year; 5% p.a. real rate of interest; annual turbine energy output taken from power density calculator using a Rayleigh wind distribution (shape factor = 2).

You should note that wind speeds at 50 metre hub height will be some 28 to 35 per cent higher* than at 10 metre height, which is usually used for meteorological observations, cf. the wind speed calculator page. Look at the grey axis at the bottom of the graph to see how wind speeds at 10 metre height may translate into higher wind speeds. A wind speed of e.g. 6.25 m/s at 10 metre height in roughness class 1 will translate into 8 m/s at 50 metre hub height.

* For roughness classes between 1 and 2.

Guide to the Wind Energy Economics Calculator

This page is a guide to the Wind Energy Economics Calculator on the next page. It may may sense for you to look at the calculator first, and then click on the question marks to jump back here and get the full explanation of how it works.

Built-in Examples

To kick start you to get working right away we have included some data examples for wind turbines, which you may select from the pop up menu. The offshore example is taken from the Danish power companies' report on offshore wind turbines. Details may be found in our report on the energy balance of wind turbines, which you may download from the publications section.

Project Lifetime

Danish wind turbines have a design lifetime of 20 years. With offshore wind conditions (low turbulence) it is likely that the the turbines will last longer, probably 25 to 30 years.

Since offshore foundations are designed to last 50 years, it may be interesting to calculate two generations of turbines on the same set of foundations, possibly with a repair overhaul after 25 years.

Read more on the page on Operation and Maintenance.

Wind Turbine Price

Prices may vary due to transportation costs, different tower heights, different rotor diameters etc. You can use the example prices, or you can type a price of your own directly in the box to the right.

Read more on the page What does a Wind Turbine Cost?

Installation Cost

Costs may vary with the location, particularly with costs for road construction and grid connection. 30% of turbine cost is a fair average for Denmark.

Read more on the page on Installation Costs.

Income from Electricity Sales

This optional data item is interesting for individuals who want to invest in a wind turbine. You may also include capacity credit, if any. Specify the number of kilowatt hours you found using the Power Density Calculator, and the tariff (payment) per kilowatt hour. You may also enter an amount directly in the box to the far right in the form.The data is not needed to compute the cost of electricity.

Read more on the page on Income from Wind Turbines, and the page on

Electricity Tariffs.

Operation and Maintenance

You may include either a fixed amount per year (by typing directly into the box to the right) or a percentage of the cost of the turbine. Costs could include a service contract with the manufacturer. You may specify a fixed cost per kilowatt hour instead, if you wish.

Read more on the page on Operation and Maintenance.

Net Present Value

Here you specify the **real** rate of interest to tell the programme how to evaluate future income and expenditure.

The Net Present Value of your project is the value of all payments, discounted back to the beginning of the investment. If the figure is **positive**, your project has a real rate of return which is **larger** than your real rate of interest. If the value is negative, the project has a lower rate of return.

To compute the real rate of return, the programme takes the first payment listed at the bottom of the calculator (number 01) and divides it by (1+the real rate of interest). It then divides the next payment (number 02) by (1+the real rate of interest) to the second power, and so forth, and adds it all up together with the initial investment (number 00).

Real Rate of Return

The real rate of return tells you the real rate of interest which makes the net present value of your project exactly zero. In other words, the real rate of return tells you how much real interest you earn on your investment. (The programme does not use your real rate of interest for anything, it computes one for you).

Computing that rate is a bit tricky, since it requires that the programme makes a guess to find the answer that makes the net present value zero. If it guesses to high, the net present value becomes negative. If it guesses too low, it becomes positive. But the programme uses a very clever, blazingly fast technique called Newton-Rapson iteration which means that the guesses improve dramatically each time. After 5 guesses it has found your answer with 5 digit precision.

Electricity Cost per kWh

The cost is calculated by finding the sum of the total investment and the discounted value of operation and maintenance costs in all years. We then divide the result by the sum of the **discounted value** of all future electricity production, i.e. we divide each year's electricity production by (1+i) to the n th power, where n is the period number (01 to 50. If you have specified an income from electricity sales, that amount is not used, or more accurately, it is subtracted from all non-zero amounts specified in the list of payments in period 01 to 50.

Payments

The payments in these boxes are the results of your specifications above, and they are used to calculate the net present value and the real rate of return. The boxes are also used to calculate the cost of electricity after subtracting any income from electricity sales from all non zero boxes in period 01 to 50.

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www.WINDPOWER.org
Danish Wind Turbine Manufacturers Association

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Calculator

Wind Energy Economics Calculator

This very handy calculator requires a Netscape 3.0 or later browser to work, but you may read the example in any case. If you are using Navigator 3.0 or later and you see this message, you need to enable JavaScript. Choose Options | Network Preferences, choose the Languages tab, and click Enable JavaScript. Then click reload on your browser. Do not operate the form until this page and its programme have loaded completely. **Note**: Prices and costs are examples only. They may not reflect current market conditions or local site or installation conditions.

You may experiment by changing the figures in the example below. You can fill in any box, except the result boxes marked with an asterisk (*). After changing data, use the tab key, click the Calculate button, or click anywhere on the page outside the field you have updated to see the results. Click on the question marks for help.

Investment with [20] years expected lifetime [USD] ?

[600 kW example] wind turbine price [450000] ?

[30 %] installation costs+ [135000] ?

Total investment * [585000]

Current Income and Expenditure per Year

Income [1500000] kWh @ [0.05] per kWh = [75000] ?

(•) Use [1.5] % of turbine price for operation & maintenance ?

( ) Use [ ] per kWh (in present day prices) - [6750]

( ) Specify total cost (in present day prices) to the right

Total Net Income per Year * [68250]

Net Present Value @ [5] % p.a. **real** interest rate * [ ] ?

Real Rate of Return *** [per cent per annum] * [ ] ?

Electricity Cost per kWh** Present value per kWh * [ ] ?

[ ]

Payments, (Used for Net Present Value and Real Rate of Return) **

00 -585000 Investment (expenditure, therefore always a minus sign)

01	68250	02	68250	03	68250	04	68250	05	68250
06	68250	07	68250	08	68250	09	68250	10	68250
11	68250	12	68250	13	68250	14	68250	15	68250
16	68250	17	68250	18	68250	19	68250	20	68250
21	0	22	0	23	0	24	0	25	0
26	0	27	0	28	0	29	0	30	0
31	0	32	0	33	0	34	0	35	0
36	0	37	0	38	0	39	0	40	0
41	0	42	0	43	0	44	0	45	0
46	0	47	0	48	0	49	0	50	0

* = Boxes marked with an asterisk cannot be changed directly by the user.
** = These boxes is filled out by the programme, but you may change the amounts if you wish. The calculation of electricity cost per kWh uses the same payments as above, but the programme subtracts the electricity sales income from all non zero payment values in the table, year 01 to year 50. If you want to be sure what you are doing when computing the electricity cost per kWh, you should set the income from electricity sales to zero.
*** = To compute the real rate of return you must have entered both expenditures and income from electricity sales.

?

Guided Tour

Updated 6 August 2000
http://www.windpower.org/tour/econ/econ.htm

Economics of Offshore Wind Energy

New Danish Reports on Offshore Wind Energy

In 1997 the Danish electrical power companies and the Danish Energy agency finalised plans for large scale investment in offshore wind energy in Danish waters.

The plans imply that some 4 100 MW of wind power are to be installed offshore before the year 2030. Wind would by then cover some 50 per cent of Danish electricity consumption (out of a total of 31 TWh/year).

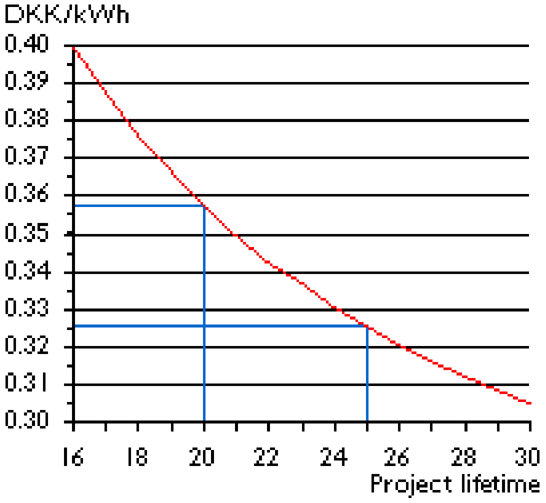
Improving Economics of Offshore Wind Energy

On the previous page, the calculator already includes an example showing the expected average cost of offshore wind energy in Denmark, using presently available technology.

The most important reason why offshore wind energy is becoming economic is that the cost of foundations has decreased dramatically. The estimated total investment required to install 1 MW of wind power offshore in Denmark is around 12 million DKK today, (equivalent to 4 million DEM, or 1.7 million USD). This includes grid connection etc.

Since there is substantially more wind at sea than on land, however, we arrive at an average cost of electricity of some 0.36 DKK/kWh = 0.05 USD/kWh = 0.09 DEM/kWh. (5% real discount rate, 20 year project lifetime, 0.08 DKK/kWh = 0.01 USD/kWh = 0.02 DEM in operation and maintenance cost).

Accounting for Longer Project Lifetime



It would appear, however that turbines at sea would have a longer technical lifetime, due to lower turbulence.

If we assume a project lifetime of, say, 25 years instead of 20, this makes costs 9 per cent lower, at some 0.325 DKK/kWh.

The cost sensitivity to project lifetime is plotted in the accompanying graph, which was made using the calculator on the previous page.

Danish power companies, however, seem to be optimising the projects with a view to a project lifetime of 50 years. This can be seen from the fact that they plan to require 50 year design lifetime for both foundations, towers, nacelle shells, and main shafts in the turbines.

If we assume that the turbines have a lifetime of 50 years, and add an overhaul (refurbishment) after 25 years, costing some 25 per cent of the initial investment (this figure is purely a numerical example), we get a cost of electricity of 0.283 DKK/kWh, which is similar to average onshore locations in Denmark.

Updated 26 September 2000
http://www.windpower.org/tour/econ/offshore.htm

Employment in the Wind Industry

30,000 Jobs Worldwide in 1995

The wind industry in 1995 employed some 30,000 people worldwide. This estimate is based on a study from the Danish Wind Turbine Manufacturers Association, which was published in 1995.

The study accounts for both **direct** and **indirect** employment. By indirect employment we mean the people who are employed manufacturing **components** for wind turbines, and the people who are involved in **installing** wind turbines worldwide.

9,000 Jobs in Denmark

The Danish wind industry had some 8 500 people employed in 1995. It may be interesting to see how they are divided between different components:

Component	Employment
Turbine assembly	3 600
Rotor blades	2 000
Electronic controllers	700
Brakes, hydraulics etc.	200
Towers	1 500
Installation of turbines	300
Other	300
Total	8 300

In reality wind turbine production creates about 50 per cent more jobs, since Danish manufacturers import many components, e.g. gearboxes, generators, hubs etc. from abroad. In addition, jobs are created through the installation of wind turbines in other countries.

How was the Study done?

You may think we went out and asked the wind turbine manufacturers to get the figures. Well, we did, but only to check our calculations. The point is, that you are likely to end up with the wrong answer, if you rely on asking people about something as complex as job creation throughout the economy. You may see remarkably large errors in other estimates made as naive back-of-an-envelope calculations elsewhere on the Web. (Out of courtesy, we won't include the link, here).

Actually, we started very differently using a so called **input-output model**, which is what most economists in government service, or central statistical bureaus would do. In an input output model we actually follow the flow of deliveries from each sector of the economy to other sectors of the economy. In our case, we have a 117 by 177 table of deliveries between the sectors, and the statisticians have double checked that they sum up to the total production in the economy. With this table on may follow sub-sub-contracting all the way back in the economy in an infinite number of links. (Using a mathematical technique called matrix inversion):

Home

How to get Hold of the Study

You may download the employment study (44K) in Adobe Acrobat pdf-format for printing in the original layout on your own printer. To download to a PC: Click the **Download** button using the **right** mouse button. To download to a Macintosh, hold the mouse button down, and select **Save this Link as...**

Download

Guided Tour

Wind Energy Pictures

To get the best quality, set your monitor to thousands of colours or better when viewing these pictures.

The Wind Energy Pioneer - Poul la Cour

To get the best quality, set your monitor to thousands of colours or better when viewing these pictures.

Askov Folk High School still exists.
Presently a non-profit association is trying to collect funds to preserve Poul la Cour's original windmill

Poul la Cour

Poul la Cour (1846-1908) who was originally trained as a meteorologist was the pioneer of modern electricity generating wind turbines.

La Cour was one of the pioneers of modern aerodynamics, and built his own wind tunnel for experiments.

The picture shows Poul la Cour and his wife Christine at Askov. (49K JPEG)

La Cour was concerned with the storage of energy, and used the electricity from his wind turbines for electrolysis in order to produce hydrogen for the gas light in his school.

One basic drawback of this scheme was the fact that he had to replace the windows of several school buildings several times, as the hydrogen exploded due to small amounts of oxygen in the hydrogen(!)

Class of 1904

La Cour gave several courses for wind electricians each year at Askov Folk High School. This picture shows the group graduating in 1904. (124K, JPEG)

La Cour's Wind Turbines

Two of his test wind turbines in 1897 at Askov Folk High School, Askov, Denmark. 89K, JPEG

La Cour founded the Society of Wind Electricians which in 1905, one year after it was formed, had 356 members.

The Journal of Wind Electricity

The world's first **Journal of Wind Electricity** was also published by Poul la Cour.

In 1918 some 120 local utilities in Denmark had a wind turbine, typically of a size from 20 to 35 kW for a total of some 3 megawatt installed power.

These turbines covered about 3 per cent of Danish electricity consumption at the time. The Danish interest in wind power waned in subsequent years, however, until a supply crisis set in during World War II.

Updated 30 April 2001

http://www.windpower.org/pictures/lacour.htm

The Wind Energy Pioneers - 1940-1950

To get the best quality, set your monitor to thousands of colours or better when viewing these pictures.

The F.L. Smidth Turbines

During World War II the Danish engineering company **F.L. Smidth** (now a cement machinery maker) built a number of two- and three-bladed wind turbines.

Yes, Danish wind turbine manufacturers **have** actually made two-bladed wind turbines, although the so-called "Danish concept" is a three bladed machine.

All of these machines (like their predecessors) generated DC (direct current).

(43 K, JPEG)

(Photograph © F.L.Smidth & Co. A/S)

This three-bladed F.L. Smidth machine from the island of Bogø, built in 1942, looks more like a "Danish" machine. It was part of a wind-diesel system which ran the electricity supply on the island. (22K, JPEG)

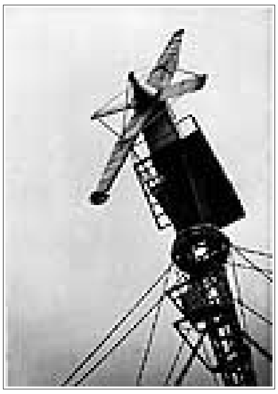
Today, we would probably argue about how the concrete tower looks, but this machine actually played an important role in the 1950s wind energy study programme in Denmark.

In 1951 the DC generator was replaced with a 35 kW asynchronous AC (alternating current) generator, thus becoming the second wind turbine to generate AC.

(Photograph © F.L.Smidth & Co. A/S)

The Wind Energy Pioneers: The Gedser Wind Turbine

Johannes Juul and the Vester Egesborg Turbines



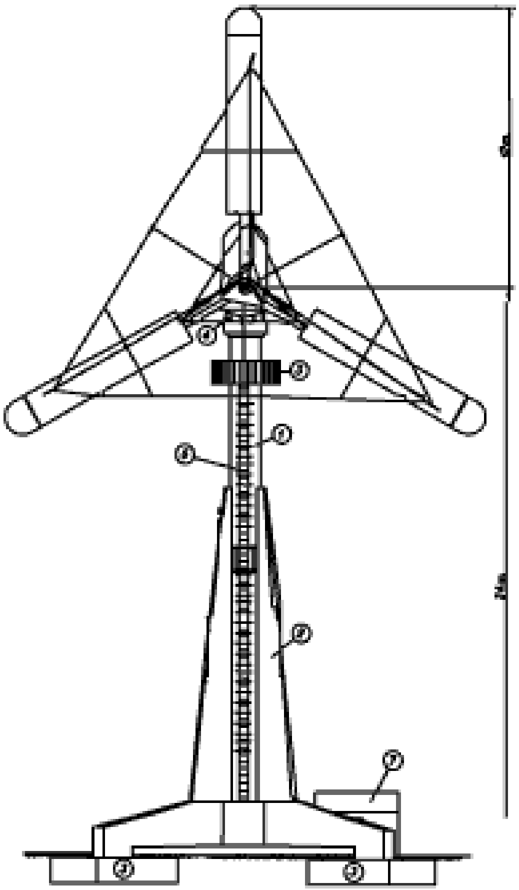
The engineer Johannes Juul was one of the first students of Poul La Cour in his courses for "Wind Electricians" in 1904.

In the 1950s J. Juul became a pioneer in developing the world's first alternating current (AC) wind turbines at Vester Egesborg, Denmark. (57K JPEG)

Gedser is a good, windy area located at the southern tip of the island of Falster in Denmark.

The concrete tower of the Gedser turbine is still there after 50 years, although it is now equipped with a modern Danish wind turbine nacelle

The Gedser Wind Turbine



The innovative 200 kW Gedser wind turbine (35K JPEG) was built in 1956-57 by J. Juul for the electricity company SEAS at Gedser coast in the Southern part of Denmark.

The three-bladed upwind turbine with electromechanical yawing and an asynchronous generator was a pioneering design for modern wind turbines, although its rotor with guy wires looks a bit old fashioned today.

The turbine was stall controlled, and J. Juul invented the emergency aerodynamic tip brakes which were released by the centrifugal force in case of over speed. Basically the same system is used today on modern stall controlled turbines.

The turbine, which for many years was the world's largest, was incredibly durable. It ran for 11 years without maintenance.

The Gedser wind turbine was refurbished in 1975 at the request of NASA which wanted measurement results from the turbine for the new U.S. wind energy programme.

The machine ran for a few years with test measurements after which it was dismantled. The nacelle and rotor of the turbine are now on display the Electricity Museum at Bjerringbro, Denmark. (Photographs © the Electricity Museum, Bjerringbro).

The Nibe Turbines

After the first oil crisis in 1973, interest in wind energy rekindled in several countries. In Denmark, the power companies immediately aimed at making large turbines, just like their counterparts in Germany, Sweden, the UK, and the USA.

In 1979 they built two 630 kW wind turbines, one pitch controlled, and one stall controlled. In many ways they suffered the same fate as their even larger colleagues abroad: The turbines became extremely expensive, and the high energy price subsequently became a key argument against wind energy.

Pictures

Wind Turbines From the 1980s

The Riisager Turbine

A carpenter, Christian Riisager, however, built a small 22 kW wind turbine (39K, JPEG) in his own back yard using the Gedser Wind Turbine design as a point of departure. He used inexpensive standard components (e.g. an electric motor as generator, and car parts for gear and mechanical brake) wherever possible.

Riisager's turbine became a success with many private households around Denmark, and his success gave the present day Danish wind turbine manufacturers their inspiration to start designing their own wind turbines from around 1980.

(Photograph © 1996 Copyright The Electricity Museum, Bjerringbro, Denmark).

Competing Turbine Designs

Some designs, including the Riisager design were partly based on solid experience from the classical Gedser wind turbine, or classical slow moving multi-bladed American "wind roses", others were more revolutionary including vertical axis Darrieus machines, machines using flaps for power control, or hydraulics for the transmission system, etc. etc. Most machines were very small by today's standards, usually 5 to 11 kW.

Picture from the secret testing grounds of Vestas Wind Systems in 1979: The engineer L on Bjervig next to his 12 kW 7.3 m rotor diameter Darrieus "biplane" machine.
Picture © BTM Consult 1979.

The Tvind 2 MW Machine

One important exception to the rule of small machines was the **Tvind 2 MW machine**, a fairly revolutionary machine, (in a political sense, too, having been built by idealist volunteers, practising gender quotas and other politically correct activities, including waving Chairman Mao's little red book.) The machine is a downwind machine with 54 m rotor diameter running at variable speed with a synchronous generator, and indirect grid connection using power electronics. The machine is still running nicely. (Photograph © 1998 Soren Krohn)

Early Danish wind turbine development was thus a far cry from simultaneous government sponsored research programmes on very large machines in Germany, USA, Sweden, the UK, or Canada.

In the end, improved versions of the classical, three-bladed upwind design from the Gedser wind turbine appeared as the commercial winner of this wild competition, but admittedly not without a number of wreckages, mechanical, and financial.

Risoe National Laboratory

Risoe National Laboratory was really born to become the Danish answer to Los Alamos, i.e. the national centre for nuclear research. Today it is far better known for its work on wind energy.

Risoe National Laboratory's Department of Wind Energy and Atmospheric Physics has a staff of some 100 people working on basic research into *aeroelastics*, i.e. the interaction between aerodynamics and structural dynamics, on *wind turbine technology*, and wind resource assessment. It also has a separate, small, commercial activity dealing with type approval of wind turbines.

Risoe was originally founded with this last purpose in mind, when the Danish Government instituted a support programme for the erection of wind turbines in Denmark. In order to protect the buyers of wind turbines (and their surroundings) the Government required that all supported wind turbines be type approved for safety. The strict safety regulations (including requirements for dual braking systems) indirectly helped developing safer and more reliable wind turbines. (The support programme was abandoned in 1989).

Bonus 30 kW

The Bonus 30 kW machine (21K, JPEG)

manufactured from 1980 is an example of one of the early models from present day manufacturers.

Like most other Danish manufacturers, the company was originally a manufacturer of agricultural machinery.

The basic design in these machines was developed much further in subsequent generations of wind turbines.

(Photograph copyright Bonus Energy A/S).

Updated 15 December 2000

http://www.windpower.org/pictures/eighties.htm

The Great California Wind Rush

Nordtank 55 kW

The 55 kW generation of wind turbines which were developed in 1980 - 1981 became the industrial and technological breakthrough for modern wind turbines.

The cost per kilowatt hour (kWh) of electricity dropped by about 50 per cent with the appearance of this generation of wind turbines. The wind industry became much more professionalised, and the parallel development of the European Wind Atlas Method by Risoe National Laboratory was extremely important in lowering kWh costs.

The picture shows a particularly imaginative way of siting these Nordtank 55 kW wind turbines (43K, JPEG), on a harbour pier at the town of Ebeltoft, Denmark. Red tipped rotor blades have disappeared completely from the market since then, after it was discovered that birds do not fly into the rotors anyway.

(Photograph copyright © 1981 NEG Micon A/S)

The Great California Wind Rush

Literally thousands of these machines were delivered to the wind programme in California in the early eighties. The Micon 55 kW (69K, JPEG) is one example of such a machine, delivered to one huge park of more than 1000 machines in Palm Springs, California.

Having started series manufacturing of wind turbines about 5 years earlier, Danish manufacturers had much more of a track record than companies from other countries. About half of the wind turbines placed in California are of Danish origin.

The market for wind energy in the United States disappeared overnight with the disappearance of the Californian support schemes around 1985.

Since then, only a tiny trickle of new installations have been commissioned, although the market seems to have been picking up, lately. Germany is now the world's main market, and the country with the largest wind power installation.
(Photograph copyright NEG Micon A/S).

Modern Wind Turbines

To get the best quality, set your monitor to thousands of colours or better when viewing these pictures.

Aved re Holme, Denmark

The picture shows the Aved re Wind Farm, just 5 kilometres from the city centre of Copenhagen, Denmark. The 12 Bonus 300 kW wind turbines, (and one 1,000 kW power company test wind turbine) are located next to a 250 MW coal-fired power plant.
(Photograph © 1997 Copyright S ren Krohn) (39K, JPEG)

Denmark's Largest Wind Farm: Middelgrunden

Denmark currently has some 2,000 megawatts of wind power, and 6,000 wind turbines in operation. 80 per cent of the turbines are owned by individuals or local wind turbine co-operatives.

The largest wind farm in Denmark is Middelgrunden, which is also the largest offshore wind farm in the world. It consists of 20 Bonus 2 MW wind turbines - a total power of 40 MW.

The largest land based wind farm in Denmark is Syltholm on the island of Lolland, consisting of 35 NEG Micon 750 kW wind turbines - a total power of 26,25 MW.
(Photograph © 2000 Soren Krohn) (52 K, JPEG)

Updated 5 January 2001
http://www.windpower.org/pictures/modern.htm

Offshore Wind Turbines

To get the best quality, set your monitor to thousands of colours or better when viewing these pictures.

The world's first offshore wind farm is located North of the island of Lolland in the Southern part of Denmark

Vindeby

The Vindeby wind farm (32K, JPEG) in the Baltic Sea off the coast of Denmark was built in 1991 by the utility company SEAS.

The wind farm consists of 11 Bonus 450 kW stall controlled wind turbines, and is located between 1.5 and 3 kilometres North of the coast of the island of Lolland near the village of Vindeby.

The turbines were modified to allow room for high voltage transformers inside the turbine towers, and entrance doors are located at a higher level than normally. These same modifications were carried over to the subsequent Tun Knob project.

Two anemometer masts were placed at the site to study wind conditions, and turbulence, in particular. A number of interesting results on offshore wind conditions have been obtained through these studies which were carried out by Ris National Laboratory.

The park has been performing flawlessly.

Electricity production is about 20 per cent higher than on comparable land sites, although production is somewhat diminished by the wind shade from the island of Lolland to the South.

(Photograph copyright Bonus Energy A/S)

Tun Knob

The world's second offshore wind farm is located between the Jutland peninsula and the small island of Tun in Denmark

The Tun Knob offshore wind farm (36K, JPEG) in the Kattegat Sea off the Coast of Denmark was built in 1995 by the utility company Midtkraft. The picture shows the construction work with a floating crane.

The Wind farm consists of 10 Vestas 500 kW pitch controlled wind turbines.

The turbines were modified for the marine environment, each turbine being equipped with an electrical crane to be able to replace major parts such as generators without the need for a floating crane.

In addition, the gearboxes were modified to allow a 10 per cent higher rotational speed than on the onshore version of the turbine. This will give an additional electricity production of some 5 per cent. This modification could be carried out because noise emissions are not a concern with a wind park located 3 kilometres offshore from the island of Tun , and 6 kilometres off the coast of the mainland Jutland peninsula.

The park has been performing extremely well, and production results have been substantially higher than expected, cf. the page on offshore wind conditions.

The Future of Offshore Wind Energy

Offshore wind energy is an extremely promising application of wind power, particularly in countries with high population density, and thus difficulties in finding suitable sites on land. Construction costs are much higher at sea, but energy production is also much higher.

The Danish electricity companies have announced major plans for installation of up to 4 000 megawatts of wind energy offshore in the years after the year 2000. The 4 000 MW of wind power is expected to produce some 13.5 TWh of electricity per year, equivalent to 40 per cent of Danish electricity consumption.

Megawatt-Sized Wind Turbines

To get the best quality, set your monitor to thousands of colours or better when viewing these pictures.

Nordtank 1500

The prototype of the NEG Micon 1500 kW Turbine (35K JPEG) was commissioned in September 1995.

The original model had a 60 metre rotor diameter and two 750 kW generators operating in parallel.

The most recent version is a 1,500/750 kW model (with two 750 kW generators) with a 64 metre rotor diameter.

The photograph was taken at the Tjaereborg site in the Western part of Denmark near the city of Esbjerg.

(Photograph © 1995 NEG Micon A/S 1996)

The Tjaereborg test site for megawatt turbines is located in Western Denmark near the city of Esbjerg

Vestas 1.5 MW

The prototype of the Vestas 1500 kW Turbine (51K JPEG) was commissioned in 1996.

The original model had a 63 metre rotor diameter and a 1,500 kW generator.

The most recent version has a 68 metre rotor diameter and a dual 1650/300 kW generator.

The picture shows the nacelle being hoisted by a crane.

In the background to the left you may see the ELSAM 2 MW test turbine (on a concrete tower), and the NEG Micon 1500 kW a bit farther in the background. At the far left you can catch a glimpse of a Bonus 750 kW turbine (the most recent version is a 1 MW turbine).

(Photograph © 1996 Vestas Wind Systems A/S 1996)

The Future for Megawatt-Sized Turbines

600 and 750 kW machines continue to be the "working horses" of the industry at present, but the megawatt-market took off in 1998.

Megawatt-sized machines will be ideal for offshore applications, and for areas where space for siting is scarce, so that a megawatt machine will exploit the local wind resources better.

Multi-Megawatt Wind Turbines

To get the best quality, set your monitor to thousands of colours or better when viewing these pictures.

NEG Micon 2 MW

The prototype of the NEG Micon 2 MW turbine (1024 x 768 pixels, 132K JPEG) was commissioned in August 1999. It has a 72 m (236 ft.) rotor diameter. In this case (Hagesholm, Denmark) it is mounted on a 68 m tower. In the background you see the foundations for two sister machines.The turbine is intended for offshore applications.

From the outside it resembles the 1500 kW NEG Micon machine so much, that you'd have to see the turbine in its stopped state (with the blades pitched out of the wind) in order to notice the difference: The rotor blades are pitchable, since the machine has active stall power control, whereas its 1500 kW cousin has passive stall power control.

(Aerial photograph © 1999 Soren Krohn)

Bonus 2 MW

The prototype of the Bonus 2 MW turbine (88 K) was commissioned in the fall of 1998. It has a 72 m (236 ft.) rotor diameter. In this case (Wilhelmshaven, Germany) it is mounted on a 60 m tower. The turbine is intended for offshore applications, and has Combi Stall power control (Bonus trademark for active stall power control). The machine resembles the Bonus 1 MW and 1.3 MW machines considerably.
(Aerial photograph © 1999 Soren Krohn)

Nordex 2,5 MW

The prototype of the Nordex 2,5 MW turbine (132 K) was commissioned in the spring of 2000. The rotor diameter of the wind turbine is 80 m. The image shows the prototype at Grevenbroich, Germany, which has a 80 m tower. The turbine has pitch power control. It is the world's largest commercial wind turbine.
(Photo © 2000 Nordex)

Updated 9 February 2000
http://www.windpower.org/pictures/multimeg.htm

Wind Energy Reference Manual

Wind Energy Reference Manual
Part 1:
Wind Energy Concepts

Unit Abbreviations

m = metre = 3.28 ft.
s = second
h = hour
W = Watt
HP = horsepower
J = Joule
cal = calorie
toe = tonnes of oil equivalent
Hz= Hertz (cycles per second)

10^{-12} = p pico = 1/1000,000,000,000
10^{-9} = n nano = 1/1000,000,000
10^{-6} = µ micro = 1/1000,000
10^{-3} = m milli = 1/1000
10^{3} = k kilo = 1,000 = thousands
10^{6} = M mega = 1,000,000 = millions
10^{9} = G giga = 1,000,000,000
10^{12} = T tera = 1,000,000,000,000
10^{15} = P peta = 1,000,000,000,000,000

Wind Speeds

1 m/s = 3.6 km/h = 2.187 mph = 1.944 knots
1 knot = 1 nautical mile per hour = 0.5144 m/s = 1.852 km/h = 1.125 mph

Wind Speed Scale

Wind Speed at 10 m height m/s	knots	Beaufort Scale (outdated)	Wind
0.0-0.4	0.0-0.9	0	Calm
0.4-1.8	0.9-3.5	1	Light
1.8-3.6	3.5-7.0	2	
3.6-5.8	7-11	3	
5.8-8.5	11-17	4	Moderate
8.5-11	17-22	5	Fresh
11-14	22-28	6	Strong
14-17	28-34	7	
17-21	34-41	8	Gale
21-25	41-48	9	
25-29	48-56	10	Strong Gale
29-34	56-65	11	
>34	>65	12	Hurricane

Roughness Classes and Roughness Lengths

The roughness class is defined in the European Wind Atlas on the basis of the roughness length in metres z_0, i.e. the height above ground level where the wind speed is theoretically zero. ln is the natural logarithm function.

```
if (length <= 0.03)
class = 1.699823015 + ln(length)/ln(150)
if (length > 0.03)
class = 3.912489289 + ln(length)/ln(3.3333333)
```

You may use the calculator below and enter either the roughness length or the roughness class.

This calculator requires a Netscape 3, IE 4, or later browser to work. If you are using Navigator 3, IE 4, or later and you see this message, you need to enable JavaScript. In Netscape, choose Edit | Preferences | Advanced, and click Enable JavaScript. Then click reload on your browser. In Internet Explorer, choose Edit | Preferences | Web Browser | Java and click Enable Java. Then click reload on your browser. Do not use the calculator until this page and its programme have loaded completely.

Roughness Class Calculator

Calculator

Roughness length in m

= Roughness class

Roughness Classes and Roughness Length Table

Rough-ness Class	Roughness Length m	Energy Index (per cent)	Landscape Type
0	0.0002	100	Water surface
0.5	0.0024	73	Completely open terrain with a smooth surface, e.g.concrete runways in airports, mowed grass, etc.
1	0.03	52	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills
1.5	0.055	45	Agricultural land with some houses and 8 metre tall sheltering hedgerows with a distance of approx. 1250 metres
2	0.1	39	Agricultural land with some houses and 8 metre tall sheltering hedgerows with a distance of approx. 500 metres
2.5	0.2	31	Agricultural land with many houses, shrubs and plants, or 8 metre tall sheltering hedgerows with a distance of approx. 250 metres
3	0.4	24	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain
3.5	0.8	18	Larger cities with tall buildings
4	1.6	13	Very large cities with tall buildings and skycrapers

Definitions according to the European Wind Atlas, WAsP.
For practical examples, see the Guided Tour section on Wind Speed Calculation.

Density of Air at Standard Atmospheric Pressure

Temperature ° Celsius	Temperature ° Farenheit	Density, i.e. mass of dry air kg/m3	Max. water content kg/m3
-25	-13	1.423	
-20	-4	1.395	
-15	5	1.368	
-10	14	1.342	
-5	23	1.317	
0	32	1.292	0.005
5	41	1.269	0.007
10	50	1.247	0.009
15	**59**	**1.225** *)	0.013
20	68	1.204	0.017
25	77	1.184	0.023
30	86	1.165	0.030
35	95	1.146	0.039
40	104	1.127	0.051

*) The density of dry air at standard atmospheric pressure at sea level at 15° C is used as a standard in the wind industry.

Power of the Wind **)

m/s	W/m2	m/s	W/m2	m/s	W/m2
0	0	8	313.6	16	2508.8
1	0.6	9	446.5	17	3009.2
2	4.9	10	612.5	18	3572.1
3	16.5	11	815.2	19	4201.1
4	39.2	12	1058.4	20	4900.0
5	76.2	13	1345.7	21	5672.4
6	132.3	14	1680.7	22	6521.9
7	210.1	15	2067.2	23	7452.3

**) For air density of 1.225 kg/m^3, corresponding to dry air at standard atmospheric pressure at sea level at 15° C.

The formula for the power per m^2 in Watts = $0.5 * 1.225 * v^3$, where v is the wind speed in m/s.

Warning: Although the power of the wind at a wind speed of e.g. 7 m/s is 210 W/m^2, you should note, that the average power of the wind at a site with an average wind speed of 7 m/s typically is about **twice** as large. To understand this, you should read the pages in the Guided Tour beginning with the Weibull Dustribution and ending with the Power Density Function.

Updated 15 December 2000
http://www.windpower.org/stat/unitsw.htm

Wind Energy Reference Manual Part 2: Energy and Power Definitions

Energy

Physicists define the word **energy** as the amount of **work** a physical system is capable of performing. Energy, according to the definition of physicists, can neither be created nor consumed or destroyed.

Energy, however may be **converted** or transferred to different forms: The **kinetic** energy of moving air molecules may be converted to **rotational** energy by the rotor of a wind turbine, which in turn may be converted to **electrical** energy by the wind turbine generator. With each conversion of energy, part of the energy from the source is converted into **heat** energy.

When we loosely use the expression **energy loss** (which is impossible by the definition above), we mean that part of the energy from the source cannot be used directly in the next link of the energy conversion system, because it is converted into heat. E.g. rotors, gearboxes or generators are never 100 per cent efficient, because of heat losses due to friction in the bearings, or friction between air molecules.

Most of us have the sensible notion, however, that as we e.g. burn fossil fuels, somehow, loosely speaking, the global potential for future energy conversion becomes smaller. That is absolutely true.

Physicists, however, use a different terminology: They say that the amount of **entropy** in the universe has increased. By that they mean that our ability to perform **useful work** converting energy decreases each time we let energy end up as **heat** which is dissipiated into the universe. Useful work is called **exergy** by physicists.

Since the vast majority of wind turbines produce electricity, we usually measure their performance in terms of the **amount of electrical energy** they are able to convert from the kinetic energy of the wind. We usually measure that energy in terms of **kilowatt hours (kWh)** or megawatt hours MWh during a certain period of time, e.g. an hour or a year.

People who want to show that they are very clever, and show that they understand that energy cannot be created, but only converted into different forms, call wind turbines **Wind Energy Converters (WECs)**. The rest of us may still call them wind turbines.

Note Energy is **not** measured in kilowatts, but in **kilowatt hours** (kWh). Mixing up the two units is a very common mistake, so you might want to read the next section on power to understand the difference.

Energy Units

1 J (joule) = 1 Ws = 4.1868 cal

1 GJ (gigajoule) = 10^9 J

1 TJ (terajoule) = 10^{12} J

1 PJ (petajoule) = 10^{15} J

1 kWh (kilowatt hour) = 3,600,000 Joule

1 toe (tonne oil equivalent)

= 7.4 barrels of crude oil in primary energy

= 7.8 barrels in total final consumption
= 1270 m^3 of natural gas
= 2.3 metric tonnes of coal
1 Mtoe (million tonne oil equivalent) = 41.868 PJ

Power
Electrical power is usually measured in watt (W), kilowatt (kW), megawatt (MW), etc. Power is **energy transfer per unit of time**.

Power may be measured at any point in time, whereas **energy** has to be measured during a certain period, e.g. a second, an hour, or a year. (Read the section on energy, if you have not done so yet).

If a wind turbine has a **rated power** or **nameplate power** of 600 kW, that tells you that the wind turbine will produce 600 kilowatt hours (kWh) of **energy** per hour of operation, when running at its maximum performance (i.e. at high winds above, say, 15 metres per second (m/s)).

If a country like Denmark has, say 1000 MW of wind **power** installed, that does not tell you how much **energy** the turbines produce. Wind turbines will usually be running, say, 75 per cent of the hours of the year, but they will only be running at **rated power** during a limited number of hours of the year.

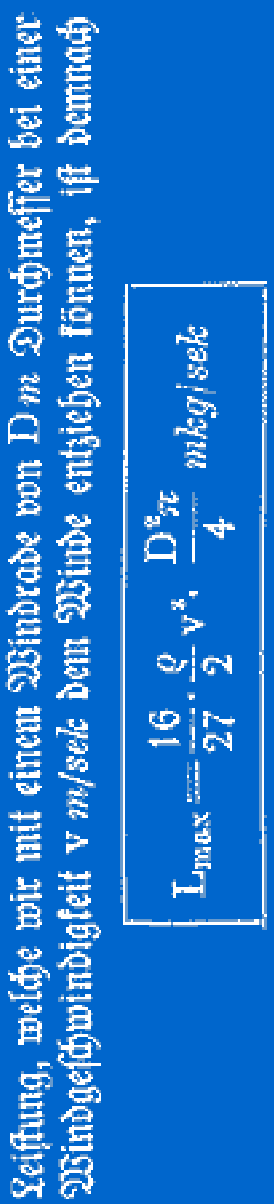
In order to find out how much **energy** the wind turbines produce you have to know the distribution of wind speeds for each turbine. In Denmark's case, the average wind turbines will return 2,300 hours of full load operation per year. To get total energy production you multiply the 1000 MW of installed **power** with 2,300 hours of operation = 2,300,000 MWh = 2.3 TWh of energy. (Or 2,300,000,000 kWh).

In other areas, like Wales, Scotland, or Western Ireland you are likely to have something like 3,000 hours of full load operation or more. In Germany the figure is closer to 2,000 hours of full load operation.

The **power** of automobile engines are often rated in **horsepower** (HP) rather than kilowatt (kW). The word "horsepower" may give you an intuitive idea that **power** defines how much "muscle" a generator or motor has, whereas **energy** tells you how much "work" a generator or motor performs during a certain period of time.

Power Units
1 kW = 1.359 HP

Updated 26 September 2000
http://www.windpower.org/stat/unitsene.htm

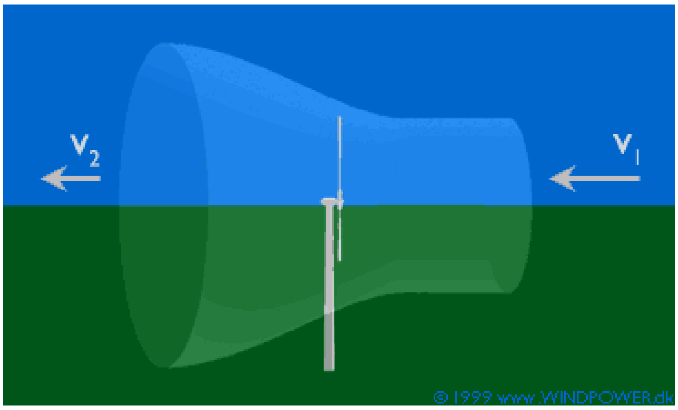


The original formulation of Betz' law in German.

Proof of Betz' Law

This page gives a proof of Betz' law. Before reading this page you should have read the pages in the Guided Tour on how the wind turbine deflects the wind and Betz' Law. If you do not follow the argument in detail, just glance through the rest of this page, which uses Betz' own reasoning from his book Wind-Energie from 1926 to explain the law.

Proof of Betz' Theorem



Let us make the reasonable assumption that the average wind speed through the rotor area is the average of the undisturbed wind speed before the wind turbine, v_1, and the wind speed after the passage through the rotor plane, v_2, i.e. $(v_1+v_2)/2$. (Betz offers a proof of this).

The mass of the air streaming through the rotor during one second is

$$m = \rho F (v_1+v_2)/2$$

where m is the mass per second, ρ is the density of air, F is the swept rotor area and $[(v_1+v_2)/2]$ is the average wind speed through the rotor area. The power extracted from the wind by the rotor is equal to the mass times the drop in the wind speed squared (according to Newton's second law):

$$P = (1/2)\, m\, (v_1^2 - v_2^2)$$

Substituting m into this expression from the first equation we get the following expression for the power extracted from the wind:

$$P = (\rho/4)\, (v_1^2 - v_2^2)\, (v_1+v_2)\, F$$

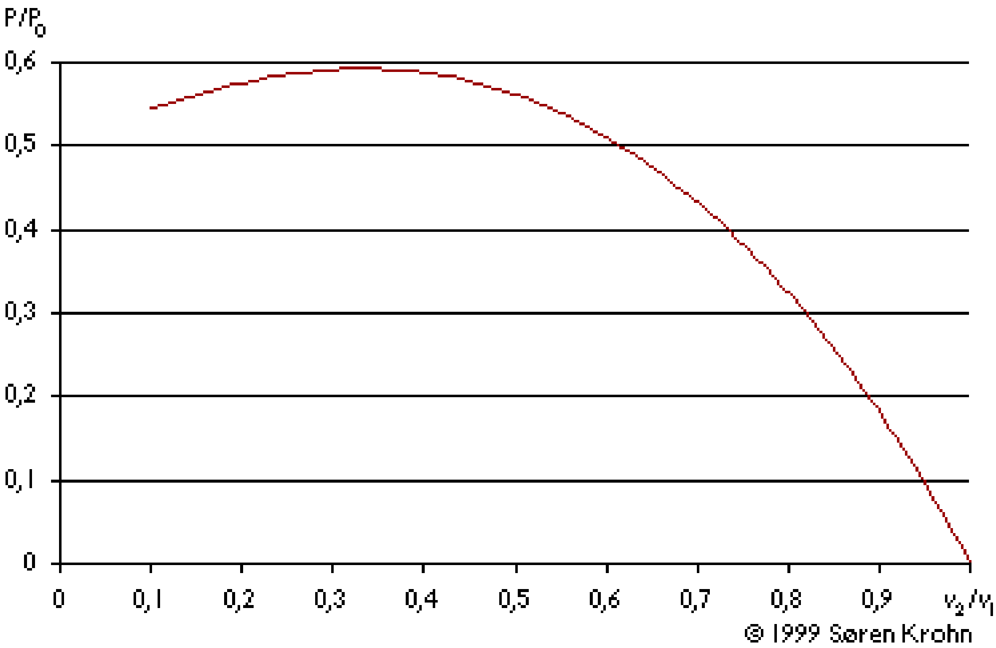
Now, let us compare our result with the total power in the undisturbed wind streaming through exactly the same area F, with no rotor blocking the wind. We call this power P_0:

$$P_0 = (\rho/2)\, v_1^3\, F$$

The ratio between the power we extract from the wind and the power in the undisturbed wind is then:

$$(P/P_0) = (1/2)\, (1 - (v_2 / v_1)^2)\, (1 + (v_2 / v_1))$$

We may plot P/P_0 as a function of v_2/v_1:



We can see that the function reaches its maximum for $v_2/v_1 = 1/3$, and that the maximum value for the power extracted from the wind is 0,59 or 16/27 of the total power in the wind.

Click here to go back the Guided Tour page on Betz' Law.

Wind Energy Reference Manual
Part 3:
Acoustics

dB(A) Sound Levels in decibels and Sound Power in W/m^2

Level dB(A)	Power W/m^2	Level dB(A)	Power W/m^2	Level dB(A)	Power W/m^2
0	$1.000*10^{-12}$	55	$3.162*10^{-7}$	83	$1.995*10^{-4}$
10	$1.000*10^{-11}$	56	$3.981*10^{-7}$	84	$2.512*10^{-4}$
20	$1.000*10^{-10}$	57	$5.012*10^{-7}$	85	$3.162*10^{-4}$
30	$1.000*10^{-9}$	58	$6.310*10^{-7}$	86	$3.981*10^{-4}$
31	$1.259*10^{-9}$	59	$7.943*10^{-7}$	87	$5.012*10^{-4}$
32	$1.585*10^{-9}$	60	$1.000*10^{-6}$	88	$6.310*10^{-4}$
33	$1.995*10^{-9}$	61	$1.259*10^{-6}$	89	$7.943*10^{-4}$
34	$2.512*10^{-9}$	62	$1.585*10^{-6}$	90	$1.000*10^{-3}$
35	$3.162*10^{-9}$	63	$1.995*10^{-6}$	91	$1.259*10^{-3}$
36	$3.981*10^{-9}$	64	$2.512*10^{-6}$	92	$1.585*10^{-3}$
37	$5.012*10^{-9}$	65	$3.162*10^{-6}$	93	$1.995*10^{-3}$
38	$6.310*10^{-9}$	66	$3.981*10^{-6}$	94	$2.512*10^{-3}$
39	$7.943*10^{-9}$	67	$5.012*10^{-6}$	95	$3.162*10^{-3}$
40	$1.000*10^{-8}$	68	$6.310*10^{-6}$	96	$3.981*10^{-3}$
41	$1.259*10^{-8}$	69	$7.943*10^{-6}$	97	$5.012*10^{-3}$
42	$1.585*10^{-8}$	70	$1.000*10^{-5}$	98	$6.310*10^{-3}$
43	$1.995*10^{-8}$	71	$1.259*10^{-5}$	99	$7.943*10^{-3}$
44	$2.512*10^{-8}$	72	$1.585*10^{-5}$	100	$1.000*10^{-2}$
45	$3.162*10^{-8}$	73	$1.995*10^{-5}$	101	$1.259*10^{-2}$
46	$3.981*10^{-8}$	74	$2.512*10^{-5}$	102	$1.585*10^{-2}$
47	$5.012*10^{-8}$	75	$3.162*10^{-5}$	103	$1.995*10^{-2}$
48	$6.310*10^{-8}$	76	$3.981*10^{-5}$	104	$2.512*10^{-2}$
49	$7.943*10^{-8}$	77	$5.012*10^{-5}$	105	$3.162*10^{-2}$
50	$1.000*10^{-7}$	78	$6.310*10^{-5}$	106	$3.981*10^{-2}$
51	$1.259*10^{-7}$	79	$7.943*10^{-5}$	107	$5.012*10^{-2}$
52	$1.585*10^{-7}$	80	$1.000*10^{-4}$	108	$6.310*10^{-2}$
53	$1.995*10^{-7}$	81	$1.259*10^{-4}$	109	$7.943*10^{-2}$
54	$2.512*10^{-7}$	82	$1.585*10^{-4}$	110	$1.000*10^{-1}$

To understand the table above, read the pages starting with Sound from Wind Turbines in the Guided Tour. If you wish to know about designing wind turbines for quiet operation, read the pages on turbine design in the Guided Tour.

The subjective sound **loudness** is perceived to double every time the dB(A) level increases by 10.

By definition the sound **level** in dB = 10 * $\log_{10}$(power in W/m^2) + 120, where $\log_{10}$ is the logarithm function with base 10. [If you only have access to the the natural log function, ln, then you can always use the relation $\log_{10}(x) = \ln(x) / \ln(10)$]

If you solve the equation for the power, you get:

The sound **power** in $W/m^2 = 10^{0.1*(dB-120)}$

Sound Level by Distance from Source

Distance m	Sound Level Change dB(A)	Distance m	Sound Level Change dB(A)	Distance m	Sound Level Change dB(A)
9	-30	100	-52	317	-62
16	-35	112	-53	355	-63
28	-40	126	-54	398	-64
40	-43	141	-55	447	-65
50	-45	159	-56	502	-66
56	-46	178	-57	563	-67
63	-47	200	-58	632	-68
71	-49	224	-59	709	-69
80	-50	251	-60	795	-70
89	-51	282	-61	892	-71

How to use the table above:

If a wind turbine has a source noise level of 100 dB(A), it will have a noise level of 45 dB(A) 141 m away. [100 - 55 dB(A) = 45 dB(A)].

The sound level decreases by approximately 6 dB(A) [= $10*\log_{10}(2)$] every time you double the distance to the source of the sound. The table assumes that sound reflection and absorption (if any) cancel one another out.

How to derive the table above:

The surface of a sphere = 4 pi r^2, where pi = 3.14159265, and r is the radius of the sphere. If we have a sound emission with a power of x W/m^2 hitting a sphere with a certain radius, then we'll have the same power hitting four times as large an area, if we double the radius.

Adding Sound Levels from Two Sources

dB	41	42	43	44	45	46	47	48	49	50
41	44.0	44.5	45.1	45.8	46.5	47.2	48.0	48.8	49.6	50.5
42	44.5	45.0	45.5	46.1	46.8	47.5	48.2	49.0	49.8	50.6
43	45.1	45.5	46.0	46.5	47.1	47.8	48.5	49.2	50.0	50.8
44	45.8	46.1	46.5	47.0	47.5	48.1	48.8	49.5	50.2	51.0
45	46.5	46.8	47.1	47.5	48.0	48.5	49.1	49.8	50.5	51.2
46	47.2	47.5	47.8	48.1	48.5	49.0	49.5	50.1	50.8	51.5
47	48.0	48.2	48.5	48.8	49.1	49.5	50.0	50.5	51.1	51.8
48	48.8	49.0	49.2	49.5	49.8	50.1	50.5	51.0	51.5	52.1
49	49.6	49.8	50.0	50.2	50.5	50.8	51.1	51.5	52.0	52.5
50	50.5	50.6	50.8	51.0	51.2	51.5	51.8	52.1	52.5	53.0

Example: A turbine located at 200 m distance with a source level of 100 dB(A) will give a listener a sound level of 42 dB(A), as we learned in the table before this one. Another turbine 160 m away with the same source level will give a sound level of 44 dB(A) on the same spot. The total sound level experienced from the two turbines will be 46.1 dB(A), according to the table above.

Two identical sound levels added up will give a sound level +3 dB(A) higher. Four turbines will give a sound level 6 dB(A) higher. 10 turbines will give a level 10 dB(A) higher.

How to add sound levels in general

For each one of the sound levels at the spot where the listener is located, you look up the sound power in W/m^2 in the first of the three sound tables. Then you add the power of the sounds, to get the total no. of W/m^2. Then use the formula dB = $10 * \log_{10}$(power in W/m^2) + 120, to get the dB(A) sound level.

Guided Tour

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Wind Energy Reference Manual
Part 4: Electricity

Voltage

In order to make a current flow through a cable you need to have a voltage difference between the two ends of the cable - just like if you want to make air move through a pipe, you need to have different pressure at the two ends of the pipe.

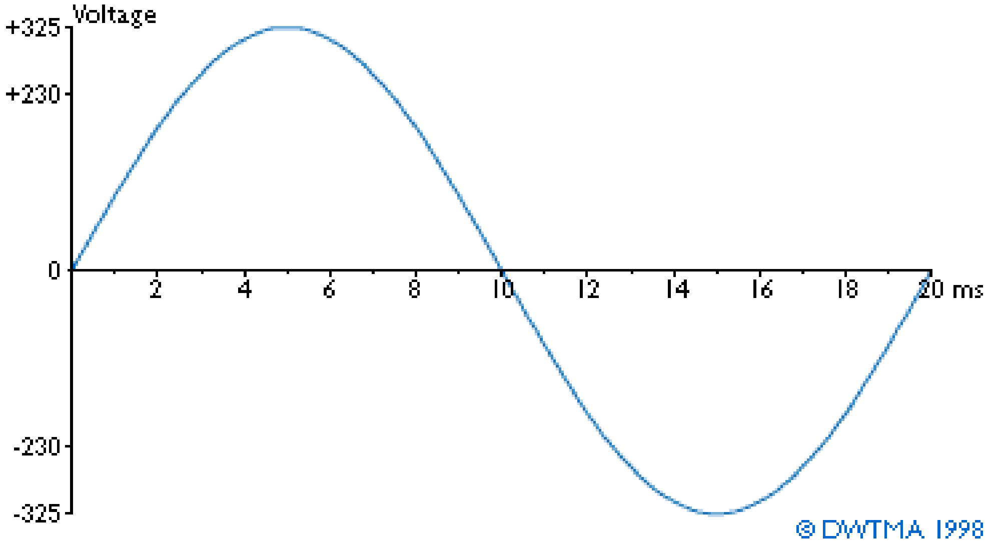
If you have a large voltage difference, you may move larger amounts of energy through the wire every second, i.e. you may move larger amounts of power. (Remember that power = energy per unit of time, cf. the page on Energy and Power Definitions).

Alternating Current

The electricity that comes out of a battery is **direct current** (DC), i.e. the electrons flow in one direction only. Most electrical grids in the world are **alternating current** (AC) grids, however.

One reason for using alternating current is that it is fairly cheap to transform the current up and down to different voltages, and when you want to transport the current over longer distances you have much lower energy losses when you use a high voltage. Another reason is that it is difficult and expensive to build circuit breakers (switches) for high DC voltages which do not produce huge sparks.

Grid Frequency



With an alternating current in the electrical grid, the current changes direction very rapidly, as illustrated on the graph above: Ordinary household current in most of the world is 230 Volts alternating current with 50 cycles per second = 50 Hz ("Hertz" named after the German Physicist H.R. Hertz (1857-1894)). The number of cycles per second is also called the **frequency** of the grid. In America household current is 130 volts with 60 cycles per second (60 Hz).

In a 50 Hz system a full cycle lasts 20 milliseconds (ms), i.e. 0.020 seconds. During that time the voltage actually takes a full cycle between +325 Volts and -325 Volts. The reason why we call this a 230 volt system is that the electrical energy per second (the power) on average is equivalent to what you would get out of a 230 volt DC system.

As you can see in the graph, the voltage has a nice, smooth variation. This type of wave shape is called a **sinusoidal curve**, because you can derive it from the mathematical formula

voltage = vmax * sin(360 * t * f),

where **vmax** is the maximum voltage (amplitude), **t** is the time measured in seconds, and **f** is the frequency in Hertz, in our case **f** = 50. **360** is the number of degrees around a circle. (If you prefer measuring angles in radians, then replace 360 by 2*pi).

Phase

Since the voltage in an alternating current system keeps oscillating up and down you cannot connect a generator safely to the grid, unless the current from the generator oscillates with exactly the same frequency, and is exactly "in step" with the grid, i.e. that the timing of the voltage cycles from the generator coincides exactly with those of the grid. Being "in step" with the grid is normally called being **in phase** with the grid.

If the currents are not in phase, there will be a huge power surge which will result in huge sparks, and ultimately damage to the circuit breaker (the switch), and/or the generator.

In other words, connecting two live AC lines is a bit like jumping onto a moving seesaw. If you do not have exactly the same speed and direction as the seesaw, both you and the people on the seesaw are likely to get hurt.

The page on Power Quality Issues explains how wind turbines manage to connect safely to the grid.

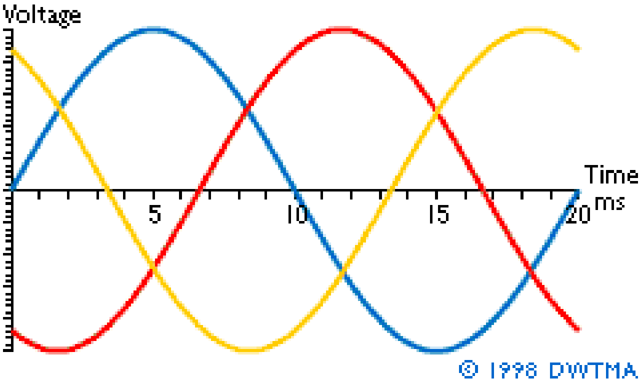
Alternating Current and Electromagnetism

To learn about electromagnetism, turn to the next pages.

3 Phase Alternating Current

The power of alternating current (AC) fluctuates. For domestic use for e.g. light bulbs this is not a major problem, since the wire in the light bulb will stay warm for the brief interval while the power drops. Neon lights (and your computer screen) will blink, in fact, but faster than the human eye is able to perceive. For the operation of motors etc. it is useful, however, to have a current with constant power.

Voltage Variation for Three Phase Alternating Current



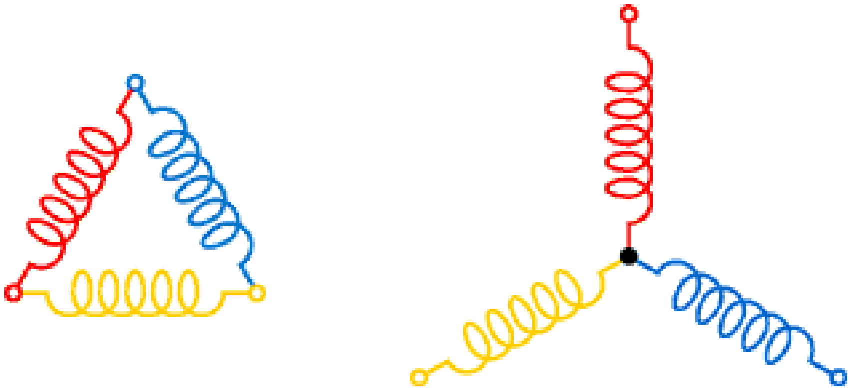
It is indeed possible to obtain constant power from an AC system by having three separate power lines with alternating current which run in parallel, and where the current phase is shifted one third of the cycle, i.e. the red curve above is running one third of a cycle behind the blue curve, and the yellow curve is running two thirds of a cycle behind the blue curve.

As we learned on the previous page, a full cycle lasts 20 milliseconds (ms) in a 50 Hz grid. Each of the three phases then lag behind the previous one by 20/3 = 6 2/3 ms.

Wherever you look along the horizontal axis in the graph above, you will find that the sum of the three voltages is always zero, and that the difference in voltage between any two phases fluctuates as an alternating current.

On the next page you will see how we connect a generator to a three phase grid.

Connecting to 3 Phase Alternating Current



On the page on synchronous generators we mention that each of the electromagnets in the stator is connected to its own phase. You may wonder how that can be done, because in a three phase system we usually have only three conductors (wires). The answer is given in the pictures above:

Delta Connection

If we call the three phase conductors L1, L2 and L3, then you connect the first magnet to L1 and L2, the second one to L2 and L3, and the third one to L3 and L1.

This type of connection is called a **delta connection**, because you may arrange the conductors in a delta shape (a triangle). There will be a voltage difference between each pair of phases which in itself is an alternating current. The voltage difference between each pair of phases will be larger than the voltage we defined on the previous page, in fact it will always be 1.732 times that voltage (1.732 is the square root of 3).

Star Connection

There is another way you may connect to a three phase grid, however:

You may also connect one end of each of the three magnet coils to its own phase, and then connect the other end to a common junction for all three phases. This may look surprising, but consider that the sum of the three phases is always zero, and you'll realise that this is indeed possible.

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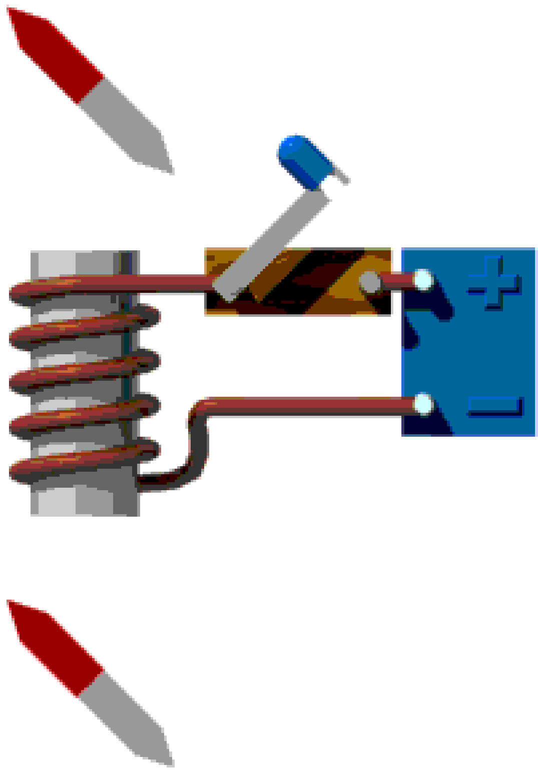
Electromagnetism



Electromagnetism was discovered by accident in 1821 by the Danish Physicist H.C. Ørsted. Electromagnetism is used both in the conversion of mechanical energy to electrical energy (in generators) and in the opposite direction in electric motors.

In the picture to the left we have set up an electric circuit with a coil of insulated copper wire, winding around an "iron" (magnetic steel) core.

Click the switch in the picture to the left to turn on the (direct) current, and watch what happens.

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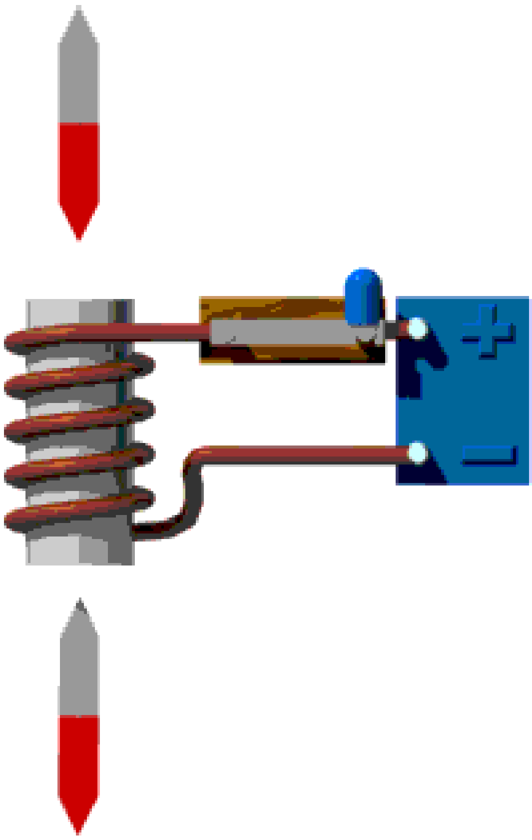
http://www.windpower.org/stat/emag/index.htm

Electromagnetism



The current magnetises the iron core and creates a pair of magnetic **poles**, one North, and the other South. The two compass needles consequently point in opposite directions. (You may repeat the experiment by clicking on the switch again).

This magnetic field would be created whether we had the iron core in the middle or not. But the iron core makes the magnetic field much more powerful.

The iron core may be shaped e.g. like a horse shoe, or a **C**, which is a design used in generators.

Generators usually have several North - South **pole pairs**.

For now, let's see how electromagnetism can work "in reverse" on the next page on induction.

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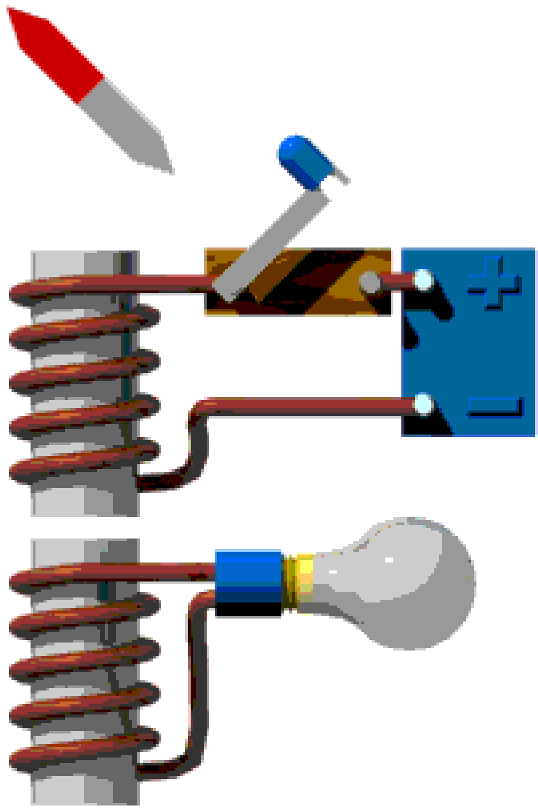
http://www.windpower.org/stat/emag/emagn.htm

Induction



To the left we have set up another experiment, that looks almost like the one on the previous page. In the upper part we have a battery, a switch, and an electromagnet.

Below the electromagnet we have set up another iron core with an insulated copper coil around it. We have then connected a light bulb to the lower coil.

Now, once again, flick the switch, and watch what happens.

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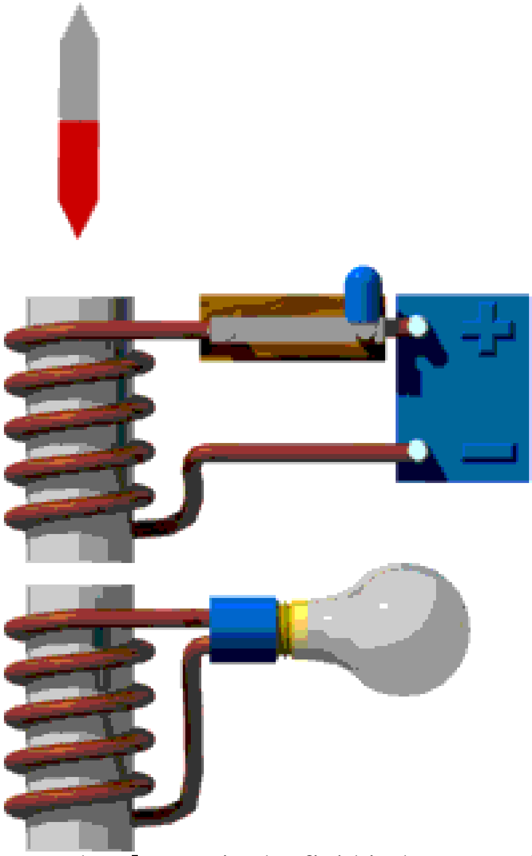
http://www.windpower.org/stat/emag/induct1.htm

Induction



As you can see, the light bulb flashes the moment you connect the switch to the battery.

The explanation is, that the magnetic field coming from the upper electromagnet flows through the lower iron core.

The **change** in that magnetic field, in turn induces an electric current in the lower coil.

You should note that the current in the lower coil ceases once the magnetic field has stabilised.

If you switch off the current, you get another flash, because the magnetic field disappears. The **change** in the field induces another current in the lower core, and makes the light bulb flash again.

In order to apply your knowledge of electromagnetism and induction, you may now return to the page on wind turbine generators.

Updated 26 September 2000
http://www.windpower.org/stat/emag/induct2.htm

Wind Energy Reference Manual Part 5: Environment and Fuels

Energy Content of Fuels *)

	GJ per tonne
North Sea Crude Oil	42.7
LPG (Liquefied petroleum gas: Propane, Butane)	46.0
Petrol (Gasoline)	43.8
JP1 (Jet aircraft fuel)	43.5
Diesel / Light Fuel oil	42.7
Heavy Fuel Oil	40.4
Orimulsion	28.0
Natural Gas	39.3 per 1000 Nm^3
Steam Coal	24.5
Other Coal	26.5
Straw	14.5
Wood chips	14.7
Household Waste 1995	10.0
Household Waste 1996	9.4

CO_2-Emissions *)

	kg CO_2 per GJ	kg CO_2 per kg fuel
Petrol (Gasoline)	73.0	3.20
Diesel / Light Fuel oil	74.0	3.16
Heavy Fuel Oil	78.0	3.15
Orimulsion	76.0	2.13
Natural Gas (methane)	56.9	2.74
Coal	95.0	2.33 (steam coal) 2.52 (other)

*) Conversion factors provided by the Danish Energy Agency

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This is a list of useful publications for readers who wish to find the relevant physics or mathematical formulae etc.

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Wind Energy Glossary

NEW feature: Type the first letter of the word to scroll to that letter.
Then click on a term to go to the page which explains it. In some cases we send you to the top of the page with the explanation, rather than the to word itself, in order to give you a better idea of each concept.

A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

English	German	Spanish	French	Danish
Aerodynamics	Aerodynamik	aerodinámica*	aérodynamique*	aerodynamik
active stall power control	aktive Stall-regelung	regulación* activa por pérdida aerodinámica	régulation active par décrochage aérodynamique	aktiv stallregulering
alternating current (AC)	Wechselstrom	corriente* alterna (CA)	courant alternatif	vekselstrøm
anemometer	Anemometer	anemómetro	anémomètre	anemometer
asynchronous generator	Asynchrongenerator	generador asíncrono	générateur asynchrone	asynkron generator
availability factor	Verfügbarkeitsfaktor	factor de disponibilidad	facteur de disponibilité	rådighedsfaktor
azimuth angle	Azimuth	ángulo azimutal	(angle d') azimut	azitmutvinkel
Betz' law	Betz'sches Gesetz	ley* de Betz	loi* de Betz	Betz' lov
birds	Vögel	aves*	oiseaux (avifaune)	fugle
bolt assembly	Verschrauben	unión* con pernos	assemblage par boulons	boltsamling
Cage rotor	Käfigläufer, Kurzschlußläufer	rotor de jaula de ardilla	induit à cage d'écureuil	kortslutningsrotor
capacity credit	Leistungsvergütung	crédito de capacidad	crédit de capacité	effektbetaling
capacity factor	Kapazitätsfaktor	factor de carga	facteur de capacité	kapacitetsfaktor
computational fluid dynamics (CFD)	Computational Fluid Dynamics (CFD)	dinámica* de fluidos computacional (CFD)	dynamique* des fluides numérique	computational fluid dynamics (CFD)
cooling system	Kühlung	sistema de refrigeración	système de refroidissement	kølesystem
Coriolis force	Corioliskraft	fuerza* de Coriolis	force* de Coriolis	Corioliskraft
corrosion (offshore)	Korrosion (Offshore)	corrosión* (en agua de mar)	corrosion* (en mer)	korrosion (offshore)
cost of electricity	Stromkosten	coste de la electricidad	coût d'électricité	omkostninger til elproduktion
cut in wind speed	Einschaltwind-geschwindigkeit	velocidad* de conexión	vitesse* de démarrage	starthastighed
cut out wind speed	Abschaltwind-geschwindigkeit	velocidad* de corte	vitesse* de coupure	stophastighed

Danish concept	Dänisches Konzept	concepto danés	conception* danoise	dansk koncept
dB (A), decibel (A) scale	dB(A)-Skala	dB(A), escala* de decibelios A	dB (A), échelle* des décibel (A)	dB (A), decibel (A) skala
delta connection	Dreieckschaltung	conexión* triángulo	connexion*(ou couplage) en triangle	deltaforbindelse
density of air	Luftdichte	densidad* de aire	densité* d'air	massefylde, vægtfylde
direct grid connection	direkte Netzanbindung	conexión* directa a red	raccordement direct au réseau	direkte nettilslutning
downwind (machine)	Leeläufer	máquina* con rotor a sotavento	(éolienne*) sous le vent	bagløber
drag	Luftwiderstand	resistencia* aerodinámica	trainée*	drag, luftmodstand
Economics	Wirtschaftlichkeit	economía*	économie*	økonomi
economies of scale	Kostenvorteile bei größeren Anlagen	economías* de escala	économies* d'échelle	stordriftsfordele
efficiency	Wirkungsgrad	eficiencia*	efficacité*	effektivitet
electromagnetism	Elektromagnetismus	electromagnetismo	électromagnétisme	elektromagnetisme
energy	Energie	energía*	énergie*	energi
energy balance	Energiebilanz	balance de energía	bilan énergétique	energibalance
extreme load	Extremlast	carga* extrema	charge extrême	ekstremlast
Fatigue load	Materialermüdung	carga* de fatiga	charge de fatigue	udmattelseslast
flange	Flansche	brida*	bride*	flange
flicker	kurzzeitige Spannungs-schwankungen	flicker	flicker	flicker
foundation	Fundament	cimentación*	fondation	fundament
Gearbox	Getriebe	multiplicador, caja* multiplicadora)	multiplicateur	gearkasse
Gedser wind turbine	Gedser-Windkraftanlage	el aerogenerador de Gedser	l'éolienne* de Gedser	Gedsermøllen
generator	Generator	generador	générateur (ou génératrice*)	generator
geostrophic wind	geostrophischer Wind	viento geostrófico	vent géostrophique	geostrofisk vind
global winds	globale Winde	vientos globales	vents globaux	globale vinde
gravity foundation (offshore)	Schwerkraft-Fundament (Offshore)	cimentación* (marina) por gravedad	fondation* de caissons (d'acier ou de béton)(offshore)	gravitationsfundament (offshore)
grid frequency	Netzfrequenz	frecuencia* de red	fréquence* du réseau	netfrekvens
(electrical) grid	(elektrisches) Netz	red* (eléctrica)	réseau (électrique)	(el) net
gust	Bö	ráfaga*	rafale*	vindstød, vindbyge
guy (wire)	Abspannung	viento	hauban	bardun

Horizontal axis wind turbine (HAWT)	Horizontalachser, -läufer	aerogenerador de eje horizontal	éolienne* à axe horizontal	horisontalakslet vindmølle
hub	Nabe	buje	moyeu	nav
hub height	Nabenhöhe	altura* de buje	hauteur du moyeu	navhøjde
hydraulics system	Hydrauliksystem	sistema hidraúlico	système hydraulique	hydrauliksystem
Hz (Hertz)	Hz (Hertz)	Hz (hercio)	Hz (Hertz)	Hz (Hertz)
Indirect grid connection	indirekte Netzanbindung	conexión indirecta a red*	raccordement indirect au réseau	indirekte nettilslutning
induction	Induktion	inducción*	induction*	indution
induction generator	Induktionsgenerator	generador de inducción	générateur à induction	asynkrongenerator
installation costs	Installationskosten	costes de instalación	coûts d'installation	installationsomkostninger
inverter	Wechselrichter	inversor	onduleur	vekselretter
islanding	Inselbildung	islanding (o funcionamiento en isla)	opération* insulaire	ødrift
J				
Killed steel	beruhichter Stall	acero calmado	acier calmé	beroliget stål
Lattice tower	Gitterturm	torre* de celosía	mât en trellis	gittertårn
(design) lifetime	Lebensdauer	vida* (de diseño)	durée de vie*	(design) levetid
lift	Auftrieb	sustentación* ("lift")	poussée* aérodynamique	opdrift, lift
Manufacturers	Hersteller	fabricantes	fabricants	fabrikanter
masking noise	Hintergrundgeräusche	ruido enmascarador	effet de masque	maskerende lyd
mono pile foundation (offshore)	Fundament mit einem Pfeiler (Offshore)	cimentación* (marina) monopilote	monopilot d'acier (fondation offshore)	enkeltspælsfundament (offshore)
mountain wind	Bergwind	viento de montaña	vent de montagne	bjergvind
Nacelle	Gondel	góndola*	nacelle*	nacelle
noise	Schall, Lärm	ruido	bruit	støj
Obstacle	Hindernis	obstáculo	obstacle	lægiver
occupational safety	Betriebssicherheit	seguridad* en el trabajo	sécurité* du travail	arbejdssikkerhed
offshore wind energy	Offshore-Windenergie	energía* eólica marina	énergie* éolienne offshore	offshore vindkraft

operation and maintenance costs	Betriebs- und Wartungskosten	costes* de operación y mantenimiento	coûts d'exploitation et d'entretien	drifts- og vedligeholdelses-omkostninger
Park effect	Parkeffekt	efecto del parque	effet de parc	parkvirkning
pitch control	Pitchregelung	regulación* por cambio del ángulo de paso	contrôle à calage variable	pitchregulering
pole changing generator	Generator mit Polumschaltung	generador con número de polos variable	génératrice* à pôles commutables	polomkobbelbar generator
(magnetic) pole	(magnetischer) Pol	polo (magnético)	pôle (magnétique)	(magnet) pol
porosity	Porosität	porosidad*	porosité*	porøsitet
power coefficient(rotor) power coefficient	Leistungsbeiwert (des Rotors)	coeficiente de potencia (del rotor)	coefficient de puissance (du rotor)	(rotorens) effektkoefficient
power curve	Leistungskurve	curva* de potencia	courbe* de puissance	effektkurve
power density	Leistungsdichte	densidad* de potencia	densité* de puissance	effekttæthed
power of the wind	Leistung des Windes	potencia* del viento	puissance* du vent	vindens effekt
power quality	Leistungsqualität	calidad* de potencia	qualité* du courant électrique	spændingskvalitet
(electrical) power	(elektrische) Leistung	potencia* (eléctrica)	puissance* (électrique)	(elektrisk) effekt
Q				
Rated power, nameplate power	Nennleistung	potencia* nominal	puissance* nominale	mærkeeffekt
Rayleigh distribution rectifier	Rayleigh-Verteilung	distribución* de Rayleigh	distribution* de Rayleigh	Rayleighfordeling
rectifier	Gleichrichter	rectificador	redresseur	ensretter
renewable energy	erneuerbare Energie	energía* renovable	énergie* renouvelable	vedvarende energi
rotor area(swept) rotor area	Rotorfläche	área* del rotor (de barrido del rotor)	surface* balayée par le rotor (ou le l'hélice)	(bestrøget) rotorareal
rotor blade	Rotorblatt	pala*	pale*	rotorblad, vinge
rotor (of a generator)	Rotor (des Generators)	rotor (del generador)	rotor (d'une génératrice)	rotor (på generator)
rotor (of a wind turbine)	Rotor (der Windkraftanlage)	rotor (de una turbina eólica)	hélice*, rotor (d'une éolienne)	rotor (på vindmølle)
roughness class	Rauhigkeitsklasse	clase* de rugosidad	classe* de rugosité	ruhedsklasse
roughness length	Rauhigkeitslänge	longitud* de rugosidad (o parámetro de aspereza)	longueur* de rugosité	ruhedslængde

roughness rose	Rauhigkeitsrose	rosa* de las rugosidades	rose* des rugosités	ruhedsrose
safety	Sicherheit	seguridad*	sécurité*	sikkerhed
Scale parameter (Weibull distribution)	Skalierungsparameter (Weibull-Verteilung)	parámetro de escala (distribución de Weibull)	paramètre d'échelle (distribution de Weibull)	skalaparameter (Weilbullfordeling)
sea bird	Seevogel	ave marina	oiseau de mer	søfugl
sea breeze	Seebrise	brisa* marina	brise de mer *	søbrise
shadow casting	Schattenwurf	distribución* de las sombras	projection* d'ombres	skyggekastning
shape parameter (Weilbull distribution)	Formparameter (Weibull-Verteilung)	parámetro de forma (distribución de Weibulll)	paramètre de forme (distribution de Weibull)	formfaktor (Weilbullfordeling)
shelter effect	Windschatten eines Hindernisses	efecto de resguardo	effet d'obstacle	lævirkning
sinusoidal	sinusförmig	sinusoidal	sinusoïdal	sinusformet
site, siting	Standort, Standortwahl	emplazamiento	site, choix de site	plads, placering
(generator) slip	(Generator-) Schlupf	deslizamiento (del generador)	glissement (d'un générateur)	(generator) slip
soft start	"weiches" Einschalten	arranque suave	démarrage souple	blød indkobling
sound	Schall	sonido	son	lyd
speed up effect	Beschleunigungseffekt	efecto acelerador	effet de survitesse	speed up effekt
stall	Strömungsabriß, Stall	pérdida* de sustentación ("stall")	décrochage aérodynamique ("stall")	stall
stall control	Stallregelung, Regelung durch Strömungsabriß	regulación* por pérdida aerodinámica ("stall control")	régulation* par décrochage aérodynamique	stallregulering
star connection	Sternschaltung	conexión* estrella	connexion* (ou couplage) en étoile	stjerneforbindelse
stator	Stator	estator	stator	stator
stream tube	Stromröhre	tubo de corriente	tube de courant	strømrør
structural dynamics	Strukturdynamik	dinámica* estructural	dynamique des structures (dynami-que structurale)	strukturdynamik
synchronous generator	Synchrongenerator	generador síncrono	générateur (ou génératrice*) synchrone	synkrongenerator
synchronous speed	Synchrondrehzahl	velocidad* de sincronismo	vitesse* synchrone	synkron hastighed
Three phase alternating current	Dreiphasen-Wechselstrom	corriente* alterna trifásica	courant alternatif triphasé	trefaset vekselstrøm
thyristor	Thyristor	tiristor	thyristor	thyristor
tower	Turm	torre*	tour*	tårn

tripod foundation (offshore)	Dreibein-Fundament (Offshore)	cimentación* (marina) en trípode	fondation* à trois pieds (le trépied) (offshore)	tripod fundament (offshore)
tubular tower	Rohrturm	torre* tubular	tour tubulaire	rørtårn
turbulence	Turbulenz	turbulencia*	turbulence*	turbulens
(rotor blade) twist	Verwindung (des Rotorblatts)	torsión, alabeo (de la pala)	torsion* de la pale	twist, vridning
Upwind (machine)	Luvläufer	(máquina*) con rotor a barlovento	éolienne* face au vent	forløber
Variable (rotational)	variable (Drehzahl)	velocidad* (de giro) variable	vitesse* (de rotation) variable	variabel (omløbs)hastighed
vertical axis wind turbine (VAWT)	Vertikalachser, -läufer	aerogenerador de eje vertical	éolienne* à axe vertical	vertikalakslet vindmølle
vortex generator	Vortexgenerator	generador de torbellinos	génératrice* de vortex	vortex generator
Wake effect	Nachlauf-Effekt	efecto de la estela	effet de sillage	kølvandseffekt, wake effekt, slipstrøm
weak grid	schwaches Netz	red* débil	réseau faible	svagt net
Weilbull distribution	Weibull-Verteilung	distribución* de Weibull	distribution* de Weibull	Weilbullfordeling
wind energy	Windenergie	energía* eólica	énergie* éolienne	vindenergi
wind map	Windkarte	mapa eólico	carte* des vents	vindkort
wind power	Windkraft	potencia* eólica	puissance* éolienne	vindkraft
wind rose	Windrose	rosa* de los vientos	rose* des vents	vindrose
wind shade	Windschatten	abrigo (o sombra) del viento	abri, effet d'abri	lævirkning
wind shear	Windscherung	cizallamiento (o cortadura) del viento	cisaillement du vent	vindgradient, wind shear
wind turbine	Windkraftanlage	aerogenerador, turbina* eólica, aeroturbina*	éolienne*, aérogénérateur	vindmølle, vindkraftanlæg
wind vane	Windfahne	Windfahne	girouette*	vindfane
X				
Yaw	Windnachführung	orientación*	orientation*	krøjning
yaw mechanism	Windnachführ-mechanismus	mecanismo de orientación	dispositif d'orientation	krøjemekanisme
Z				

* = femenino   * = féminin

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About this Web Site

Unless otherwise mentioned, the material on this site was written, edited, designed, programmed, and presented by Søren Krohn.

The material in this web site was created on Apple Macintosh Power PC 8500 computers, Apple Macintosh Power PC G3 and G4 computers and Apple Macintosh Power Book notebook computers. Web pages were generated using the amazingly simple Adobe PageMill programme, admittedly with some manual HTML doctoring here and there. Wind With Miller was layouted with Adobe GoLive. Our link errors were caught using Adobe SiteMill. Tricky multi-file searches for word modifications were done with BBEdit. 2D graphics and extrusion profiles were drawn in Macromedia FreeHand. 3D graphics and motion pictures were designed using Infini-D. Image optimisation for the web was done with Adobe Photoshop and lately Adobe ImageReady. The excellent freeware GifBuilder was used to create compact cartoons, and lately some cartoons were processed in Adobe ImageReady. Downloadable web site versions were compressed using Stuffit de Luxe. QuickTime movies were shot with Canon XL1 and XM1 digital video cameras, edited with Adobe Premiere and Apple FinalCut Pro, and compressed with MediaCleaner Pro and Sorenson Video Pro. QuickTimeVR panoramas wer edited in Apple QuickTime VR Authoring Studio. Printed publications were lay-outed in Adobe PageMaker and Adobe InDesign and converted to pdf-format with Adobe Acrobat Distiller. For bulk mailing of update notices we use eMerge, while we update our mailing list using FileMaker Pro. All of these programmes except GifBuilder and eMerge are available for both Mac and Windows platforms.