WIND TURBINES
ENERGY FROM THE WIND

Look up at the Sun. About 4.5 billion years ago an atom cloud in space started to contract, the increase in temperature caused the atom nuclei to melt together to create heavier nuclei – and energy. The result was the Sun.

Earth and the other planets were created by matter moving so quickly that it could avoid being attracted to the large amount of matter that was gathering in the Sun. Now – billions of years later we can look up at the Sun 150 million km away and receive its rays of light.

EXERCISE 1. The average distance from the Earth to the Sun is 1.4960 · 10^{11} m. The speed of light is 2.9979 · 10^{8} m/s. Calculate the time in seconds it takes the light from the Sun to reach the Earth.

ENERGY CANNOT DISAPPEAR ENERGY CAN BE CONVERTED

The rays of the Sun are the source of all normal life on Earth. The rays contain energy for green plants on land and in the sea that are the basis of the food chains.

One fundamental principle is that energy cannot be created or disappear. This is called the Principle of Conservation of Energy. Energy can be converted from one form to another. Most of the energy in the rays of the Sun, that penetrate the Earth's atmosphere, is converted into heat. A not so obvious result is that some of the energy from the sunrays is converted into wind energy.

The sunrays create different temperatures in different locations around the world. Where it is warm the air expands, where it is cold the air contracts. Expanded air creates a low barometric pressure, contracted air creates a high barometric pressure. The pressure differences even out when the air moves – the wind blows. About 1-2% of the energy from the Sun is converted into wind energy.

Energy is measured in joule, or in short J. Some of the sunrays create e.g. 100 J, which are then converted. If 1 J is converted into wind energy then the remaining 99 J must be converted into another energy form according to the Principle of Conservation of Energy. This other energy form is mostly thermal energy.

Thermal energy is normally called heat. But physicists normally consider heat as thermal energy that moves from one place to another.

Wind is moving air molecules. Energy in motion is also called kinetic energy. Wind energy is therefore the kinetic energy of the air molecules.

EXERCISE 2. Nuclear energy (energy that comes when the atom nuclei melt together), energy from sunrays, thermal energy, wind energy and kinetic energy are all explained above. Come up with examples of other forms of energy. How do we use different energy forms in our daily lives? In everyday language we say that energy is used, but actually it is converted from one form to another.

EXERCISE 3. Find examples of energy conversions. Use e.g. some of the answers from the previous exercise.

FROM WIND ENERGY TO ELECTRIC ENERGY

A wind turbine converts wind energy to electric energy. Read about towers, rotors, nacelles, gears and generators on http://www.windpower.org in the Guided Tour section or in Wind With Miller.

EXERCISE 4. Write half a page on each of these wind turbine components. What is e.g. the maximum size of a tower?

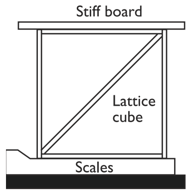
EXERCISE 5. Draw a wind turbine connected to the electrical grid and explain the conversion process from wind energy to electric energy by marking the different energy forms on the drawing. Rotational energy is one energy form. Which parts of the wind turbine is this type of energy related to?

EXERCISE 6. Find an old bicycle dynamo. Ask your teacher to disassemble it and discuss the different parts and their functions. A bicycle dynamo is actually a generator.

TEST THE STRENGTH OF THE TOWER

The tower must be strong enough to carry the nacelle and rotor and at the same time withstand powerful loads from the wind – in part the force of the wind directly against the tower and in part the force that is transferred from the rotor.

We can learn a lot about the loads on a real wind turbine tower by experimenting on tower components made of paper. The wind industry often use destructive material tests where stress on components is increased until they break in order to find the actual strength of each component.

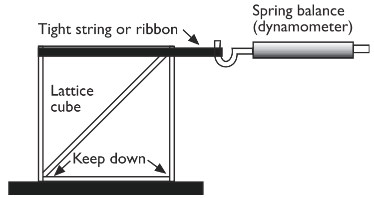


1) Build a lattice cube as described in the building instructions. Place the cube on a pair of scales with a stiff board on top. Place the palms of your hands on the board and slowly increase the pressure. Keep an eye on the weight displayed on the scales and note when the cube starts collapsing.

Our lattice cube started to collapse at: ______kg

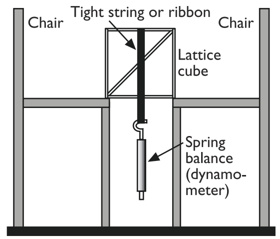
Can you compare this to the load on a real wind turbine tower?

2) Build another lattice cube or repair the one from the previous experiment. Place it on a hard surface. Two people press the bottom corners firmly against the surface. A third person places a string in a tight noose around the top corners. A spring balance (or a dynamo-meter) is used to pull slowly and horizontally at the noose.



Our lattice cube started to collapse at: ______kg

Can you compare this to the load on a real wind turbine tower?



3) Build yet an-other lattice cube or repair the one from the previous test. Two sides of the lattice cube are placed on e.g. two chairs and a noose made of string is placed around the cube. A spring balance (or a dynamo-meter) is used to slowly pull on the string.

Our lattice cube started to collapse at: ______kg

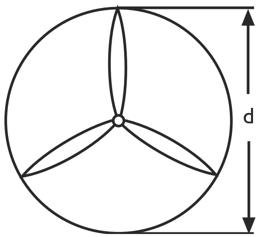
Can you compare this to the load on a real wind turbine tower?

What are the strongest and weakest points of the lattice tower? Why are lattice constructions so strong when the individual bars are weak?

Find the explanation on http://www.windpower.org/en/tour/wtrb/tower.htm.

ROTORS

Wind turbine rotors have increased in size over the years. The reason is that the bigger the surface swept by a rotor the more energy can be harvested from air molecules as there are more molecules that can deliver energy to the turbine. The energy that is available to the wind turbine is proportional to the swept area of the rotor.



A rotor covers a circular disc during one rotation and can thus harvest energy from the air molecules within this circular disc. The area A of a circular disc is given by the following formula:

$$A = \pi \cdot r^2 = \pi \cdot (½d)^2$$

where r is radius of the circular disc, d is the diameter and π is pi, $\pi = 3.1415...$

As an example take a wind turbine with a rotor diameter of 90 m and find the swept rotor area.

$$A = \pi \cdot (½d)^2 = \pi \cdot (½ \cdot 90\text{m})^2 = 6362\text{m}^2$$

This area is roughly equal to the size of a football (soccer) field.

EXERCISE 7. Find the swept rotor area of rotors with diameters of 30 m and 60 m.

60 m is twice as much as the rotor diameter of 30 m. How many times bigger is the area? How many percent are the areas of a normal football (soccer) field with a width of 65 m and a length of 102 m?

PARK EFFECT

This experiment should be carried out outdoors in a moderate wind (and no rain!).

Wind farms are installed both on land and at sea. When the wind turbine exploits the wind energy it also brakes the wind. A rule of thumb is to place wind turbines with a distance of at least 5 to 9 rotor diameters between them in the prevailing wind direction and a distance of at least 3 to 5 rotor diameters in the direction perpendicular to the prevailing wind direction.

Place a wind turbine in front of a fan. Place another wind turbine in different places behind the first wind turbine. Do the blades rotate slower when the wind turbines stand close together?

EXERCISE. What pros and cons can there be in installing wind farms as opposed to single wind turbines? You may read more about wind turbine siting on http://www.windpower.org.

FAST ROTATING AND SLOW ROTATING WIND TURBINES

An important factor for a wind turbine is the ratio of the blade tip speed and the wind speed. A wind turbine rotates slowly if the tip speed of the blades is approximately the same as the wind speed. The wind rose, known from American western movies, rotates slowly.

If the tip speed is several times faster than the wind speed the wind turbine rotates quickly. The classical Dutch windmills or the Mediterranean sail-type windmills have a tip speed of 4 times the wind speed and rotate quickly. Modern wind turbines also rotate quickly with tip speeds of 8-10 times the wind speed.

The British engineer John Smeaton (1724-1792) discovered a number of basic rules that apply to all wind turbines with a constant load. Smeaton's first rule is that the tip speed is (almost) proportional to the wind speed. In other words, tip speed is (almost) a constant figure times wind speed provided that the wind turbine pulls a constant load. Most modern wind turbines that produce alternating current rotate with an almost constant tip speed. This is because the generator is locked to the frequency of the grid.

Wind turbines cannot rotate with an infinitely high speed because of the friction in the bearings and because the blades will »stall«.

Read more about stall at http://www.windpower.org/en/tour/wtrb/stall.htm

If you know the rotor diameter d and therefore also the rotor radius $r = ½d$ as well as the time T for one rotation then you can calculate the tip speed as

$$v_t = \frac{2 \cdot \pi \cdot r}{T}$$

Speed is defined as distance divided by time so the formula shows that a blade tip travels one circle circumference $2 \cdot \pi \cdot r$ in a rotation time of T.

EXERCISE 8. Calculate the distance that a blade tip of a wind turbine with a rotor diameter of 90 m covers in one rotation.

Compare this to a carrousel. You may have noticed that the speed increases the further you move away from the centre. It is the same with a wind turbine. At a constant number of rounds pr. minute in wind turbine terminology known as rotational speed, the tip speed will increase with the size of the rotor. Large rotors will have a lower rotational speed than small rotors to end up with the same tip speed.

Smeaton noticed that when wind turbines are not pulling a load, large turbines have a lower rotational speed per minute than smaller wind turbines of the same type.

TIP SPEED

We will now test if the large rotor has a lower rotational speed than the small rotor when the wind turbine is not pulling a load.

This exercise requires a wind turbine where two rotors of the same type but with different diameters can be mounted. One further requirement is a fan. Two rigid rotors of different diameters – described in the building instructions – are needed. The other materials are mentioned below. The fan must be in a fixed position compared to the rotors.

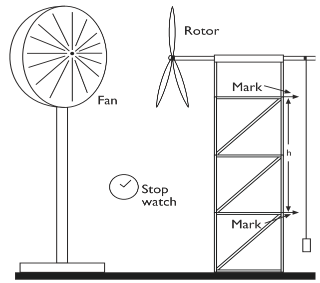
Find two obvious position markers on the wind turbine or fasten a couple of sticks or other visible markers. Tie string to the shaft. Fasten a cork or another light object at the other end of the string. When the cork reaches the shaft stop the rotor. If you let it swing around the shaft it may hurt someone. Use a stopwatch to time how long it takes the turbine to hoist the cork between the two position markers.

Small rotor: Hoisting the cork took ________s.

Large rotor: Hoisting the cork took ________s.

Did the large rotor rotate slower than the small one?

EXERCISE. Find the tip speed by performing a couple of extra measurements. Measure the



diameter d_{shaft} on the wind turbine shaft using e.g. a slide gauge. Calculate the circumference of the shaft as $2 \cdot \pi \cdot r_{shaft}$, where $r_{shaft} = ½d_{shaft}$. Measure the distance h between the two points. The number of rotations can be found as

$$n = \frac{h}{2 \cdot \pi \cdot r_{shaft}}$$

Note that n is not necessarily an integer. If the hoist time between the two markings is t the rotation time T can be found as

$$T = \frac{t}{n}$$

The tip speed can now be found by measuring the rotor diameter d. Do this for both the small and large rotor. Did you find the same tip speed?

EXERCISE. Large wind turbines rotate fewer rotations per minute than small wind turbines of the same type when the wind turbine does not carry a load. Explain this according to Smeaton's first basic rule.

WIND TURBINE POWER
In the newspapers, wind turbine sizes are mentioned as e.g. 750 kW or 1.2 MW. This is the same as when light bulbs are measured as 40 W or 60 W. W is the unit watt and this unit is used to measure power.

Power is a measure of how fast energy is converted or transferred. A light bulb of 60 W converts the electric energy from the grid to light energy and heat twice as fast as a 30 W light bulb. The connection between energy, power and time is as follows:

energy = power · time

JOULE AND WATT
If energy is measured in joule, J, and power in watt, W, then the units fit to the formula energy = power · time if time is measured in seconds, s. In 60 s a 30 W light bulb converts energy:

energy = power · time =
30 W · 60 s = 1800 J

Note that W · s = J. In the same time span a 60 W light bulb converts twice as much energy:

energy = 60 W · 60 s = 3600 J

EXERCISE 9. Calculate in joule the energy converted by a 60 W light bulb that burns for two hours. Calculate the time it takes a 60 W light bulb to convert 9000 J.

KILO AND MEGA
Figures with several digits are impractical. It is therefore practical to introduce abbreviations like k and M as in kW and MW. The abbreviations k and M stand for kilo and mega and signify one thousand and one million:

kilo: k = 1000 = 10^3
mega: M= 1000000 = 10^6

Modern wind turbines deliver electric energy to consumers through the electrical grid. A 750 kW wind turbine is a 750000 W wind turbine and a 1.2 MW wind turbine is a 1200000 W wind turbine. These numbers show the maximum power that the wind turbine can deliver to the electrical grid.

Now we understand the unit kWh that appears on the electrical bill. When the meter shows that 1 kWh of energy has been used, e.g. 1 kW power has been converted during one hour or 0.5 kW has been converted over 2 hours. The h in kWh is short for hour. Knowing that 1 hour is equal to 60 · 60 s = 3600 s we can calculate what 1 kWh is in J:

1 kWh = 1000 W · 3600 s
= 3.6 · 10^6 J = 3.6 MJ

Thus 1 kWh is 3.6 MJ.

GEARS
Most modern wind turbines are built so they rotate with an ideal and constant rotational speed. This speed is found by performing almost the same tests as the ones above. But the generator in a wind turbine typically needs a rotational speed of 25 rotations per second. Therefore a gear is placed between the rotor and the generator.

Does the increased rotational speed result in a larger amount of energy or power? No, the Principle of Conservation of Energy also applies here. Some of the energy will actually be transferred to the surroundings. The rotating gear parts rub against each other and some of the rotational energy is therefore converted into thermal energy in the gear parts and bearings. The aim is to convert as much of the energy into electrical energy as possible and try to reduce thermal energy in bearings and gear parts.

HEAVY LIFTS
Gears do not increase the energy or power output from the wind. But a gear can be used to lift heavy items. More energy is needed to lift heavier items. But the energy in the wind and therefore the power of the wind turbine has not increased. What the gear does is therefore increase the time used to lift the item because the formula:

energy = power · time

still applies. If the energy increases and the power is the same then the time must also increase.

Compare how heavy items your wind turbine can lift with and without a gear. You can also try the block and tackle method described in the building instructions.

POTENTIAL ENERGY
The energy in a weight that is elevated above the ground is called potential energy.

In the case of a wind turbine hoisting a weight, a part of the wind energy is hereby converted into potential energy in the weight. Potential energy is given as $m \cdot g \cdot h$, where m is the mass of the item, h is the distance that the item is elevated and g is a constant known as gravity acceleration that varies according to your location on Earth.

It is easy to understand the expression $m \cdot g \cdot h$. Potential energy is proportional to the mass m. If the mass is twice as big then the amount of energy is twice as big. Potential energy is also proportional to the elevated distance h. If the item or the weight is lifted twice the distance then the amount of potential energy is twice as large.

GRAVITATIONAL ACCELERATION
The value of g varies between 9.78 m/s^2 and 9.83 m/s^2 depending on the latitude of your location. You can find the value in a physics book or in an encyclopaedia. Note that the unit m/s^2 in this case equals the unit N/kg.

The value of the gravitational acceleration: g = ___________m/s^2.

EXAMPLE. In Denmark the gravitational acceleration is g = 9.82 m/s^2. If a mass of m = 0.200 kg is hoisted h = 0.20 m you get:

energy = $m \cdot g \cdot h$
= 0.200 kg · 9.82 m/s^2 · 0.2 m =
0.3928 J ≅ 0.39 J.

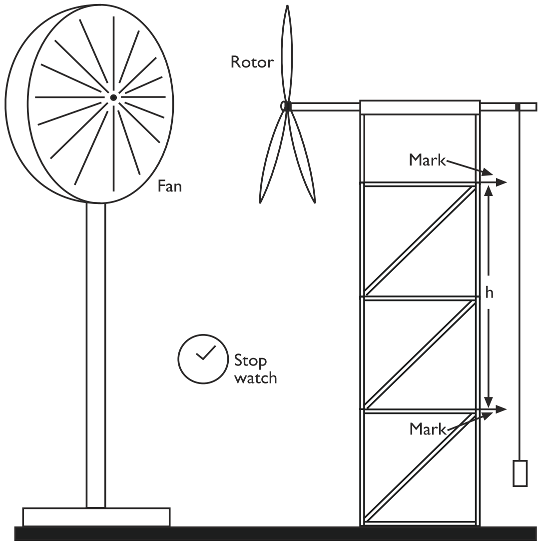
MEASURING POWER OUTPUT OF ROTORS

We will now compare the rotors by the power they can deliver. This can be done in the following way. The wind turbine delivers potential energy $m \cdot g \cdot h$ to the weight. Use a stop-watch for timing. The power can be found by using the general formula energy = power · time. This formula can be rewritten as:

$$\text{power} = \frac{\text{energy}}{\text{time}}$$

Try to guess which rotor delivers most power.

The fan setting must be the same for all the rotor tests. From experience we know that measuring the wind speed is not useful since the fan creates too much turbulence – i.e. small random gusts of wind.



MATERIALS

Wind turbine. Fan. Stopwatch. A pair of scales. String. One or several weights to create a load – preferably a light and a heavy weight. Two or several different rotors. Position markers.

THE EXPERIMENT

Start by creating the setup as shown. The fan must be positioned in the same place compared to the rotor in all the tests in order to ensure the same conditions for each rotor. Find a couple of natural position markers or attach a couple of sticks or other types of markings that are used to establish when the weight passes a certain height.

Choose a weight and find out how heavy it is by placing it on the scales. The mass is: m = _______kg

Measure the distance between the position markers: h = _______m.

The energy in J that is transferred to the weight is found by multiplying the values of m (in kg), h (in m) and g (in m/s^2): energy = $m \cdot g \cdot h$ = _____ J.

Now we only need to measure the time it takes for the weight to elevate the weight the distance h. Start timing when the weight passes the first position marking. Stop timing when it passes the second position marking. <u>When the weight reaches the shaft stop the rotor. If you let it swing around the shaft it may hurt someone.</u>

The timing result: time = _____s.

If you want, you can repeat the exercise and find the average time.

Find the power output of the wind turbine by inserting the energy in J and the time in s in the formula:

$$\text{power} = \frac{\text{energy}}{\text{time}} = \_\_\_\_\_\_\_\_\_\_ \text{ W}$$

EXERCISE. Calculate the power when you have the following numbers g = 9.82 m/s^2, m = 0.250 kg, h = 0.18 m and time = 17 s. Answer: power = 0.026 W.

Repeat the experiment with the extra rotors.

DISCUSSION

Did you guess which rotor delivered the most power? Try (if you can!) to explain why the power outputs from the rotors are different. You could have been right regardless of whether you guessed the large rotor or the small one. We will explain this in the experiment »Get maximum power output«. You need to repeat the test several times with different size weights to get a correct comparison of the different rotors. Try to pick a different weight and do the test again. Read about this in the experiment »Get maximum power output«.

GET MAXIMUM POWER OUTPUT

If a weight is too heavy then the wind turbine will not be able to elevate it and the turbine will not transfer any power to the weight. If, on the other hand, there is no load on the wind turbine, it will not transfer any power. In between these two extremes, the wind turbine must have a *maximum power output*.

We will try to find the load on the wind turbine that will result in maximum power output.

If you vary the mass of the weight m and at the same time measure the power like in the experiment »Measuring power output of rotors« then you can find the maximum power output. Plot the mass of the weight m in a coordinate system with the mass of the weight m on the primary axis (x axis) and the power output on the secondary axis (y axis). Connect the dots by drawing a line (in a soft curve) between them. Find the maximum power output and the corresponding mass. The resulting curve is called a mass-power characteristic.

Perform the test with different rotor types and compare the curves. Smeaton also did this type of experiment.

EXERCISE. According to Smeaton, the maximum power output of a wind turbine is proportional to the swept rotor area. If we have two rotors of the same type where the swept area of one rotor is twice as large as the other then we must also expect twice the maximum power output from the large rotor.

Test two rotors of the same type but with different diameters. Find the maximum power output of each rotor. Calculate the ratio of the two power outputs (divide one value by the other). Measure the diameters of the two rotors and calculate the ratio between the corresponding areas (divide one value by the other).

Were the two ratios the same as Smeaton found out?