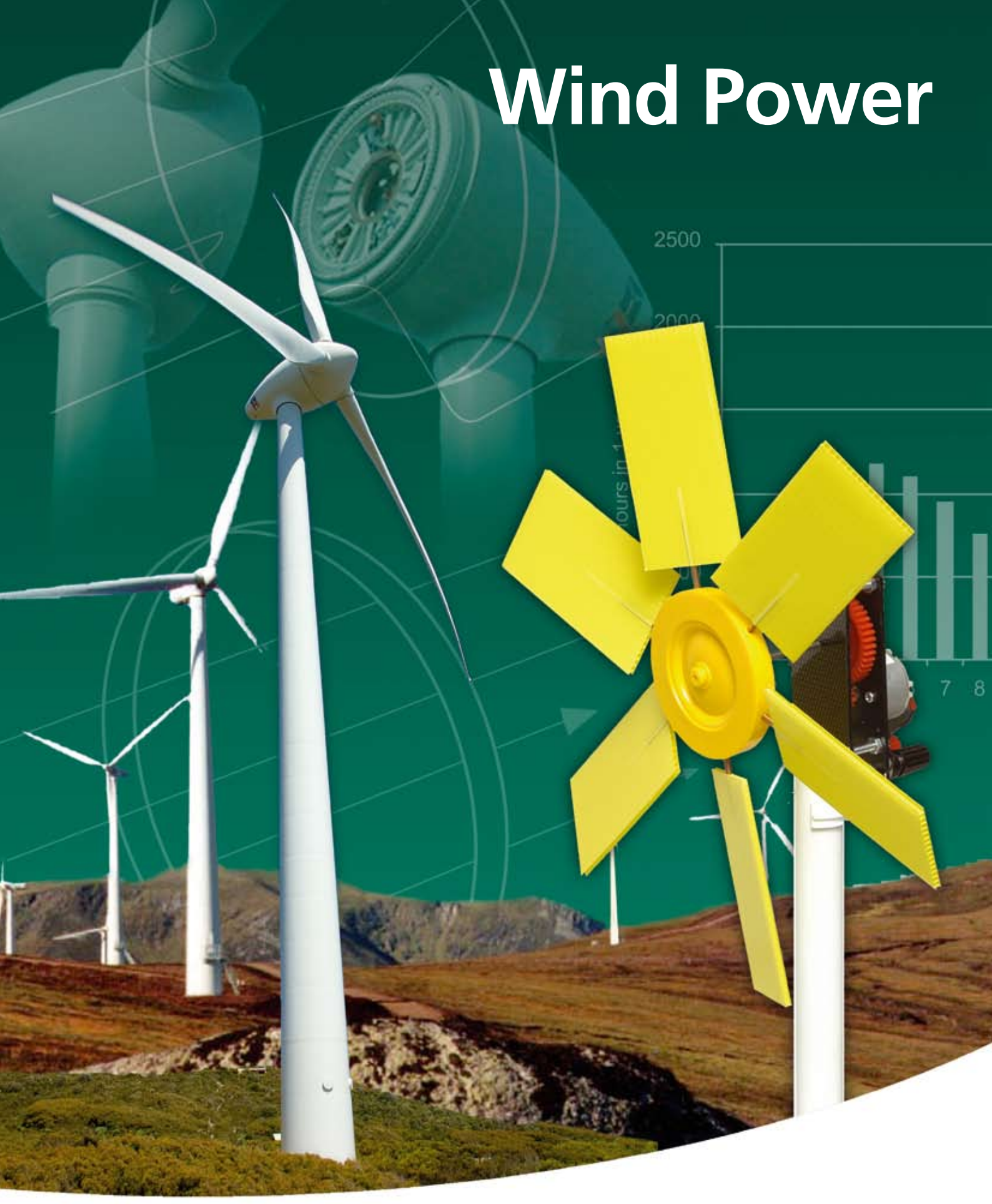
Wind Power



Innovations in practical work

www.sep.org.uk

Science Enhancement Programme

WIND POWER

The Science Enhancement Programme is a part of Gatsby Technical Education Projects. It is developing curriculum resources to support effective learning in science, and providing courses and professional development opportunities for science teachers. This booklet is part of the series 'Innovations in practical work', exploring ways in which low-cost and novel resources can be used in secondary science.

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HEALTH AND SAFETY

For practical activities, the Science Enhancement Programme has tried to ensure that the experiments are healthy and safe to use in schools and colleges, and that any recognised hazards have been indicated together with appropriate control measures (safety precautions). It is assumed that these experiments will be undertaken in suitable laboratories or work areas and that good laboratory practices will be observed. Teachers should consult their employers' risk assessments for each practical before use, and consider whether any modification is necessary for the particular circumstances of their own class/school. If necessary, CLEAPSS members can obtain further advice by contacting the Helpline on 01895 251496 or e-mail science@cleapss.org.uk.

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INTRODUCTION

Energy from the wind

How will we use the planet's energy resources over the coming decades? This is one of the most important questions facing us at this time. Many people believe that the use of wind power has a vital contribution to make. To make informed choices, one of the things we need to know is what a wind turbine is and what it does. SEP has developed a model wind turbine to support practical activities and to help to explain the science behind wind power.

Understanding how a wind turbine works involves students in using some challenging concepts, such as energy and power, the conservation of energy and the efficiency of energy transfers; the activities provide a helpful context for students to practice the use of these concepts.

Practical activities

There is a range of possible activities that can be done with the SEP wind turbine. The emphasis of the materials in this booklet is on KS4, but some of the activities can be adapted for use at KS3. In addition, SEP has developed a 'mini-turbine' that can be used for introductory work on wind power. To complement the practical activities, there are also some computer-based activities (data analysis, modelling and website research) that can be run alongside the practical work.

What's in this booklet?

This booklet provides a source of ideas and information about wind power, as well as suggesting classroom activities and materials that can be used in existing schemes of work. The booklet includes the following:

- *Using wind turbines in the classroom* This gives an 'illustrated overview' of the SEP mini-turbine and the SEP wind turbine, and provides some ideas and suggestions for how they could be used in the classroom.
- *Student activities* Teachers' notes and student resources for a range of activities on wind power and wind turbines for KS4.
- *Background science* Further information for teachers who wish to know more about the science of wind power, the design of wind turbines and their cost-effectiveness.

At the back of the booklet, there are references to useful websites, and information on how to obtain the practical resources. In addition, you can find further resources on the SEP website, including PowerPoint slides and Word worksheets that you can adapt for your own use.

Visit www.sep.org.uk/practical to download resources and to find further information.

CURRICULUM LINKS

For each of the GCSE science specifications starting in 2006, this table shows summary extracts of statements that are particularly relevant to the materials in this booklet.

GCSE Specification	Extracts related to wind power
AQA Unit Physics 1a: Energy and electricity	To compare and contrast the particular advantages and disadvantages of using different energy sources to generate electricity (13.4). Energy from renewable energy sources can be used to drive turbines directly. Renewable energy sources used in this way include wind (13.4). The advantages and disadvantages of using fossil fuels, nuclear fuels and renewable energy sources to generate electricity (13.4).
AQA Applied Science (Double) Unit 2 Science for the needs of society	Know that nuclear fuels and renewable energy resources (wind, solar, hydro-electric, wave, tidal) may be used as alternatives to fossil fuels (11.3). Appreciate the problems of using nuclear fuels (problems of radioactive emissions, disposal of waste) and of using renewable sources (unreliability and possible effects on the environment) (11.3).
Edexcel Topic 10: You're in charge	Evaluate whether renewable energies such as solar power and wind power can meet the UK's future electricity needs, and evaluate their economic, environmental and social impact (P1 a 10.1).
OCR Gateway Module P2: Living for the future	Describe ways that the Sun's energy can be harnessed using convection currents (wind) to drive turbines. Survey the distribution of wind turbines in the UK. Describe the advantages and disadvantages of wind turbines.
OCR Twenty First Century Science Module P3: Radioactive materials	Recall two examples to show that we can use renewable energy sources instead of fuels to generate electricity (P3.3, 5)
WJEC Science Physics 1	Be aware of the planning processes involved in the development of power stations based upon renewable resources, e.g. wind and wave farms (1a). Use data to explore the cost-effectiveness of introducing domestic solar and wind energy equipment, including fuel-cost savings and payback time (3e).

Some of the materials in this booklet could be adapted for use at KS3. The following table shows relevant learning objectives of the QCA KS3 scheme of work.

QCA Scheme of work	Learning objectives
Unit 7I Energy resources	• that renewable energy resources include wind, waves, running water, sunlight, biomass and some geothermal sources • how a device works using a renewable energy resource • that renewable energy resources can be used to generate electricity.
Unit 9I Energy and electricity	• that electricity can be made to flow by causing movement in an electrical generator • that fossil fuels, nuclear fuels and renewable energy sources can be used to drive electrical generators.

USING WIND TURBINES IN THE CLASSROOM: IDEAS AND SUGGESTIONS

More and more wind turbines are being built in the UK. Most of these will be sited off-shore, but some will be on land, and these have provoked some controversy. Though opinion polls suggest that many people support wind power in principle, there is more opposition in those places where there are plans to erect wind turbines. However, some surveys also suggest that people who have first-hand experience of living near wind turbines tend to be more favourable. Some people believe that wind power can contribute a large proportion of the UK's energy supply, while others are more sceptical. Knowing more about the science of wind power and how wind turbines work can help students to understand and take part in these debates.

This section gives an 'illustrated overview' of how practical work can be undertaken with model wind turbines in the classroom. In the margin, references are given to student activities – these resources and the accompanying teachers' notes can be found later in this booklet.

HOW DOES A WIND TURBINE WORK?

There have been many different kinds of design of wind turbines over the years, but most modern turbines now all have a very similar appearance. They almost always have three blades mounted on a horizontal axis, and typically the rotor diameter is between 30 and 80 metres. Depending on the blade length and the nature of the terrain, the height of the tower is typically between 40 and 80 metres.

This wind turbine at Carland Cross in Cornwall illustrates the typical design of a modern turbine.



Most of the work done on site when erecting a wind turbine is in the preparation of the foundations. These need to be dug deeply in order to support the forces on the tower, and this can take several months to complete. It then only takes a matter of days to transport and assemble the rest of the turbine. The base of the tower contains the transformer, which connects the turbine to the National Grid. After erecting the tower, the nacelle is lifted into place. This contains the generator and the control equipment. Finally the hub and the rotor blades are lifted into place and attached to the nacelle.

These photographs show two of the stages in the construction of a wind turbine at Ford Dagenham. The base of the tower contains the transformer. On top of the tower is the nacelle, which is connected to the hub and the rotor blades.





Classroom activities

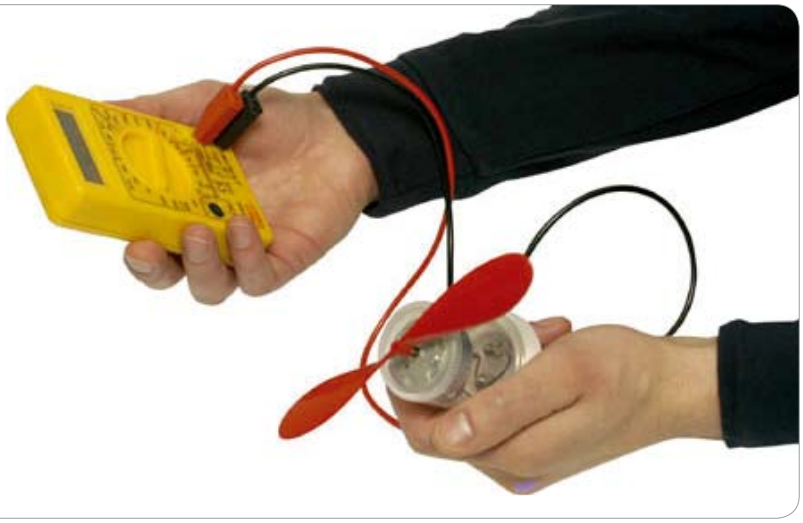
The basic principle of a wind turbine is very simple. The movement of the wind makes the rotor blades turn round; this makes the generator turn which produces an electric current. The SEP mini-turbine can be used to introduce students to this simple idea. It consists of a small electric motor attached to a toy propeller and connected to a pair of terminal posts. Note that the propeller blade is mounted 'back-to-front', since in this position it works better as a turbine blade (the reason for this is discussed later on page 18).

See Activity A1
How does a wind turbine work? (page 29)



The SEP mini-turbine allows students to do simple experiments on wind power.

To demonstrate how the turbine can generate an electrical current, it can be connected to an LED or to an electric motor. To get an indication of the size of the output, students can connect the turbine to a voltmeter or digital multimeter – the faster the turbine turns, the higher the voltage reading. Turning the blades by giving them a flick shows this.

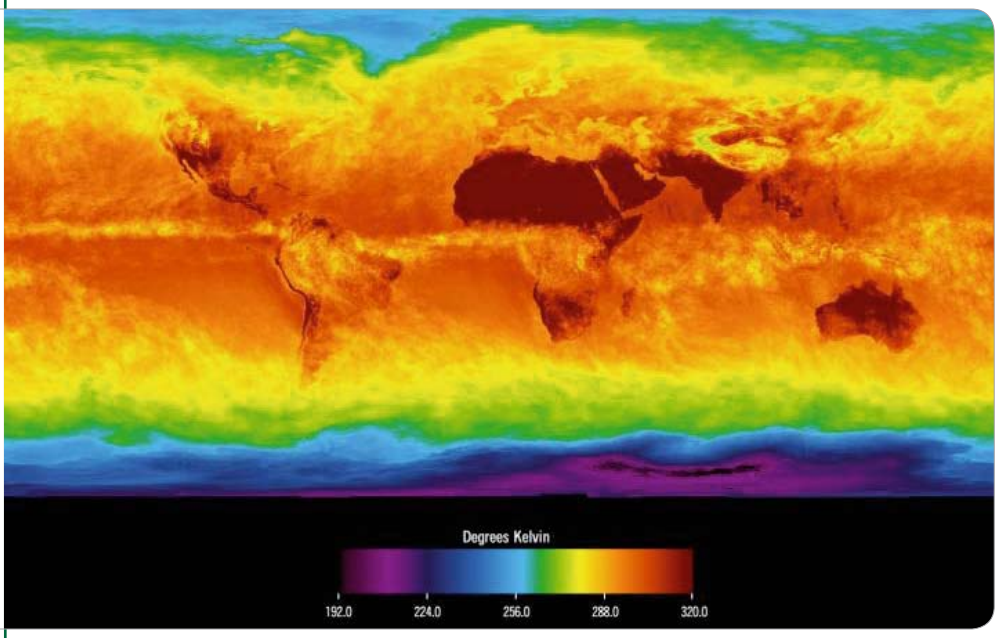


A digital multimeter can be used to obtain voltage measurements on the output of the turbine.

Note that although a voltmeter gives an indication of the performance of the turbine, it does not measure its energy output. Energy is only transferred when the turbine is connected to a load (e.g. an LED or motor). This slows down the turbine, and if the load is too large, the turbine may not turn at all. Since a voltmeter has a very high resistance, only a very small current flows, and it does not have much effect on the speed of the turbine.

WINDS AND WIND TURBINES

Wind power is a renewable energy resource, and it is useful to remind students of the reason for this. The source of the energy in wind is the Sun. Because of the curvature of the Earth, there is a temperature gradient between the equator and the poles. Energy flows from the hot equator to the cold poles, and it is the system of winds that provides the global mechanism for doing this.



Winds are caused by convection currents that arise from the temperature differences on Earth. This satellite image represents the average temperatures during April 2003 obtained using infrared sensors.

Doing experiments with turbines outdoors using real wind is a very worthwhile activity, though for more reproducible results in the laboratory, desk fans will be needed. These can be obtained quite cheaply; a convenient size is 12″ diameter and it will be useful to have three different speed settings.



Though less impressive than global weather systems, a desk fan provides a more reliable source of air currents.

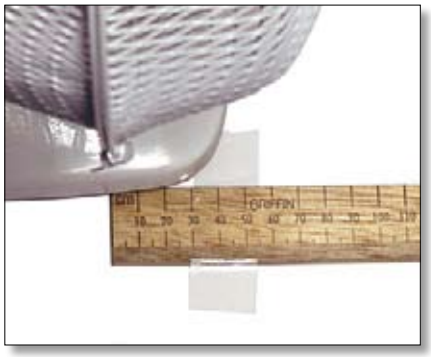
See Activity A1
How does a wind turbine work?
(page 29)

Classroom activities

Using a desk fan and the mini-turbine connected to a voltmeter, students can look at the effects of different wind speeds and angles on output. To measure distances from the fan, it is best to tape a metre rule to the bench so it does not get knocked out of position. Using the settings on the fan, students can vary the speed of the wind.

The distance of the turbine should be measured from the centre of the fan blades.

'Wind speed' can be controlled using the settings on the fan.





Students should find that the higher the fan speed, the higher the output voltage – although the result may not be very surprising, it is worth getting direct experience of the turbine's behaviour. In fact, theory predicts that the energy output of a turbine rises greatly with wind speed, being proportional to (wind speed)^3, i.e. if the speed is doubled then the wind has eight times the energy. (The significance of this is discussed in the Background science section on page 45).

The best angle for the turbine is facing the fan directly; if the angle of the turbine is changed, the output voltage decreases gradually at first and then sharply. Modern wind turbines usually have wind sensors mounted on the nacelle, so that when the wind changes direction, an electric motor inside the turbine makes it turn to face the wind.

The mini-turbine can also be used in a clamp stand for more accurate work.



Holding the mini-turbine in the hand is useful for exploratory work as it is easy to change the distance and the angle of the turbine. For a more quantitative approach, the mini-turbine could be held in a clamp stand, which allows distances and angles to be measured more accurately.

Sometimes a location has just a single wind turbine; often a number of wind turbines are grouped together in a wind farm. They need to be positioned so that they are able to extract the maximum energy from the wind allowing for different wind directions. By using a number of desk fans and mini-turbines a wind farm could be modelled, though it can be difficult to interpret the behaviour in such an experiment because of the complex nature of the air turbulence.



A group of wind turbines is called a wind farm – this example is the Novar Wind Farm in Scotland.

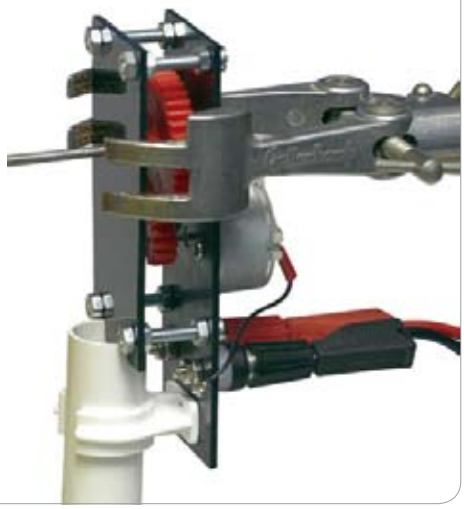
GETTING THE MOST ENERGY FROM THE WIND

Wind turbines are designed to extract energy efficiently from the wind. The SEP wind turbine was developed to enable students to explore how turbine output is affected by design. It allows a range of different factors to be investigated such as the size, shape, angle and number of blades. As before, the performance of the turbine can be measured by connecting it directly to a voltmeter or digital multimeter (though again note that this does not measure its energy output).



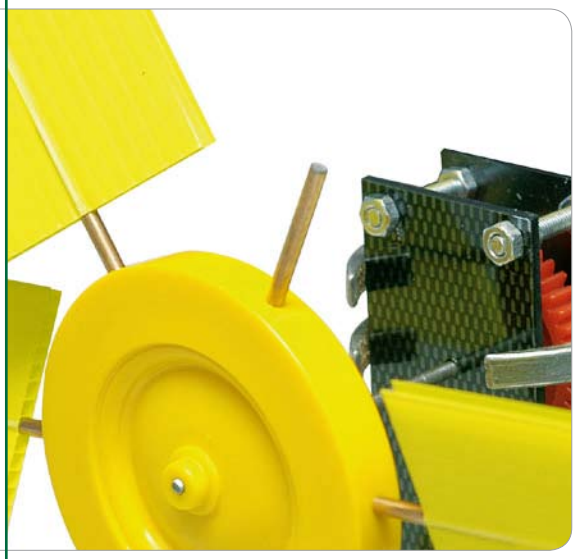
The SEP wind turbine set up ready for use. For reliable results, it needs to be positioned directly in front of and level with the fan.

The turbine should be clamped securely allowing the gears to turn freely.



The turbine contains the same motor as the mini-turbine, but it uses a gearing mechanism, so that the motor turns over three times faster than the rotor blades. To ensure that the turbine does not get out of alignment it must be securely clamped near the bottom of the pole and at the top of the gearbox.

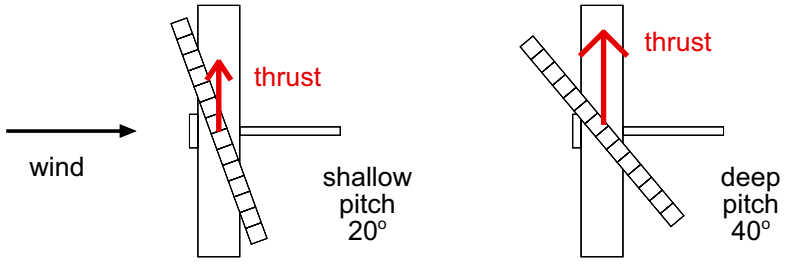
The turbine blades are attached to the hub using metal posts.



The blades are made of corriflute. The turbine kit includes some blades already cut to size, but it is also possible to cut new blades of different shapes and sizes. The blades can be attached and removed simply by pushing on and off the posts on the turbine hub.

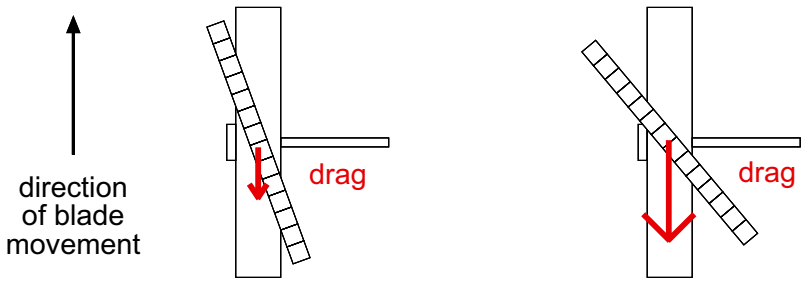
A good place to start is to investigate how the angle or pitch of the blades affects the output of the turbine. Students often predict that blades with a deep pitch should work better than those that are flatter to the direction of the wind. Experiments confirm that with the blades set at a shallow pitch (e.g. 20°), it takes quite a long time for the turbine to get started; with a deeper pitch (e.g. 40°) the turbine starts to rotate more quickly. The reason for this is that with a deep pitch, the air pushing against the blade produces a larger turning force (called 'thrust') than with a shallow pitch.

A blade with a deeper pitch produces a greater thrust.



However, what can surprise students is the effect of pitch on the maximum speed of the turbine. With a shallower pitch, the turbine turns faster and produces a greater voltage. The reason for this is that once the blades start to move, a new force acts on them. This force is caused by the moving blade pushing against the air, and is called 'drag'. The faster the blade moves, the greater the drag. Eventually, the drag becomes equal to the thrust and there is no overall force. The turbine has reached its maximum speed. Since there is less drag on the shallow pitch blade, which 'cuts through' the air more easily, it can reach a higher speed than the deep pitch blade.

There is less drag on a blade with a shallower pitch.

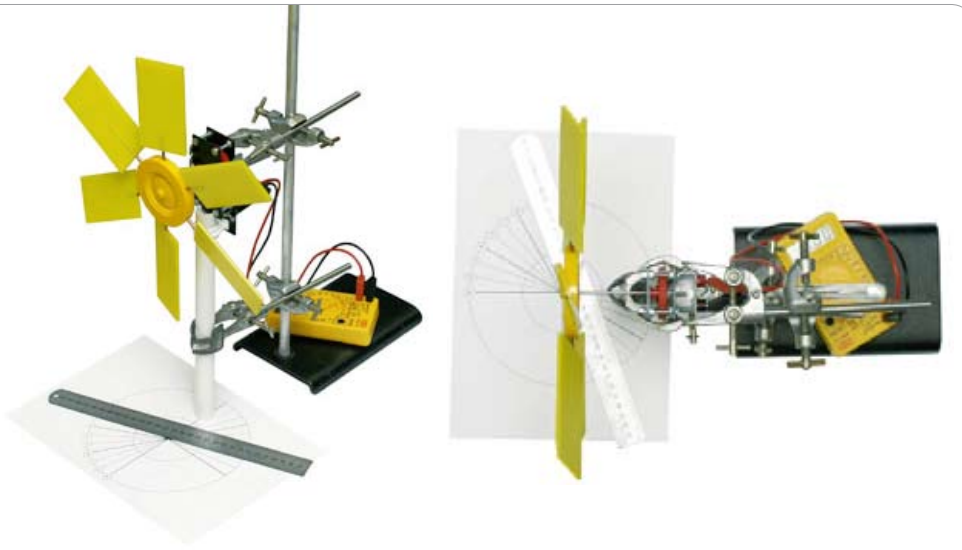


Classroom activities

In any experiments that students do using the SEP wind turbine, they will need to know how to set the pitch of the blades. Investigating the effect of blade pitch on output is therefore a convenient place to start. The simplest way for students to measure the pitch is to use the template designed for this purpose (see page 42). Because they need to look down from some distance above the wind turbine, it is better to lift the clamp stand and turbine off the bench and put it on the floor. It can be placed over the template, and by looking down from above, the blade pitch can be set.

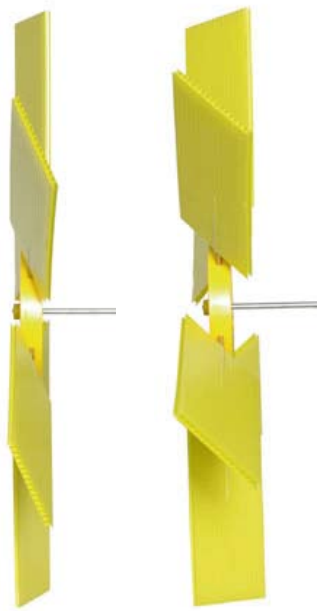
See Activity A2
Getting the most energy from the wind (page 31)

The blade pitch can be set by placing the turbine arrangement over a template and then looking down from above while adjusting the pitch.



Notice that a ruler has been laid on the template along the angle being used to set the blades. This is helpful as the alignment between the blade and the ruler can be seen more easily.

On the left, the turbine blades have been set at a 20° pitch, and on the right, at 40°.



Using pitches of 20° and 40° is sufficient for students to make a comparison, but if time allows, they could look at a wider range of angles. At a pitch of 0° the turbine will not turn. As the pitch increases, the output will increase until an optimum pitch is reached. Using the highest fan setting and with the turbine at a distance of 40 cm, this is typically between 10° and 20°. Increasing the pitch further results in a decreasing output. Since this experiment uses a desk fan, the turbine may still turn even when the blades are set at 90° due to the twisting air stream from the fan. This would not happen with a real wind. To show the rotation of the air, stick three pieces of audiotape about 80 cm long around the centre of the fan at 120° to each other. You can see the pieces of tape flap around in a spiral formation.

Sticking some lengths of audiotape to the desk fan is a good way of demonstrating the turbulence in the air flow.



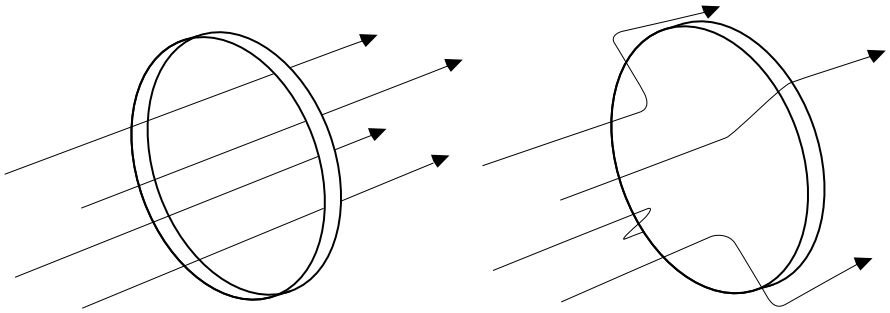
See Activity A5
Analysing fluctuations in turbine output (page 34)

Because of the turbulence in the air from the fan, the output from the turbine is quite variable. To obtain a voltage measurement, the simplest way is to record the maximum reading over a 20 second period. More detailed analysis of the output can be done by datalogging the voltage or by using the secondary data provided with the student activities. These results show a periodic fluctuation in the output voltage. Again, this arises as a consequence of the use of a desk fan and would not occur in a real wind. The pattern shown in the output is related to the regular variation in turbulence caused by the rotation of the fan.

WHAT HAPPENS TO THE WIND BEHIND THE TURBINE?

When a stream of moving air hits the turbine blades, energy is transferred from the air to the blades. As a result, the air slows down. Is it possible to stop the air completely and transfer all of the energy to the turbine? Unfortunately, the answer is no. It the air stopped completely when it hit the turbine, further air would be prevented from passing.

One way of thinking about this is to imagine two extreme cases. Both would make poor turbines. The first is a hollow ring. Wind passes through this unaffected, and no energy is extracted. The efficiency is 0%. Now imagine a solid disc. The forward movement of the wind is stopped completely. But because the wind cannot pass through the disc, it has to flow around the outside. Although the air is now moving more slowly, none of the energy lost from the air has been used to do work. The efficiency of this turbine is also 0%.



Two extreme cases, showing 'zero efficiency turbines' - no energy is extracted from wind if it passes through a hollow ring or if it hits a solid disc.

So, for a turbine to extract energy from the wind, a balance needs to be struck between letting the wind through the area swept out by the turbine blades and making it pass around the outside. The proportion of energy that can be extracted has, in fact, a maximum theoretical limit of 59%. For a real wind turbine, the average efficiency would be much less, typically around 15 - 25%. Manufacturers of wind turbines are not too concerned about maximising the efficiency of the turbine or approaching the theoretical limit. What is more important for them is to minimise the cost of generating electricity. Building a highly efficient turbine but at great expense is not cost-effective. So, the optimum design for a turbine is one that balances efficiency and construction cost.

See Activity A2
Getting the most energy from the wind (page 31)

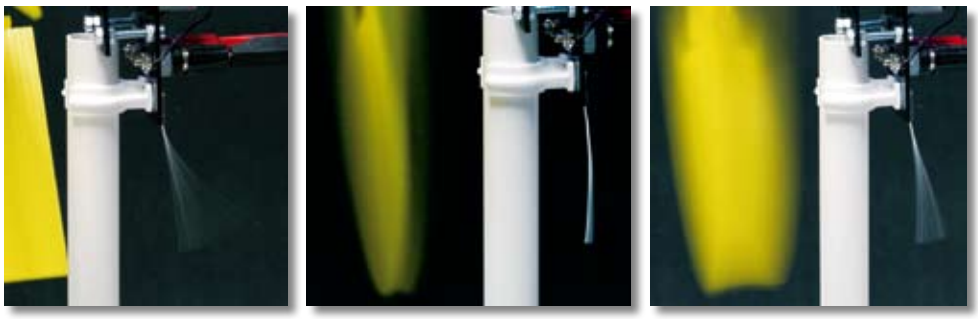
Classroom activities

Students can observe how the air slows down behind the turbine blades by sticking a small strip of paper onto the case of the wind turbine. The speed of the air is indicated by how vigorously the strip of paper flaps backwards and forwards.



A strip of paper at the rear of the turbine can be used to detect changes in wind speed.

Holding the turbine hub to keep it still and twisting the blades to 90° produces the maximum air flow. The air flow is noticeably less when the blades are set at 20° and the turbine is rotating at maximum speed. With the blades set at 40°, the turbine starts up more quickly, but the maximum speed is lower. Less energy is extracted from the moving air, and the effect can be seen in the way the strip of paper moves.



The strip flaps a lot when the blades are not rotating (left). With a pitch of 20° (middle) more energy is extracted from the wind than with a pitch of 40° (right).

CHOOSING THE NUMBER OF BLADES

Most modern wind turbines have three blades and are based on a Danish design that was first constructed in the 1950s. However, designs for windmills and wind turbines have used many other different numbers and shapes of blades. So why are three blades now so commonly used? We might expect that by using more blades we could extract more energy from the wind. However, as in the earlier section on blade pitch, the effects of changing the number of blades can seem counter-intuitive for students.

Think back to the two extreme examples of wind turbines on page 11. Using too few blades is a bit like the hollow ring; the efficiency is low because too much air is passing through. But using too many blades is a bit like the solid disc, so increasing the number of blades can actually reduce the efficiency. The use of three blades on a modern wind turbine is a good compromise. A turbine with more blades would not extract more energy from the wind, and would be more expensive to make. Using two blades would be cheaper, but to extract as much energy from the wind as three blades they need to turn faster and this makes the turbine noisier. The engineering required is also more complex, and relatively few have been built.

A wind pump has a very different job to do than a wind turbine designed to generate electricity. Its design reflects this difference. By using more blades at a deeper pitch, it is able to work even in low wind speeds. Thus, it is able to pump water in wide range of conditions all year round.

A wind pump has more blades than a modern wind turbine because it does a different job.

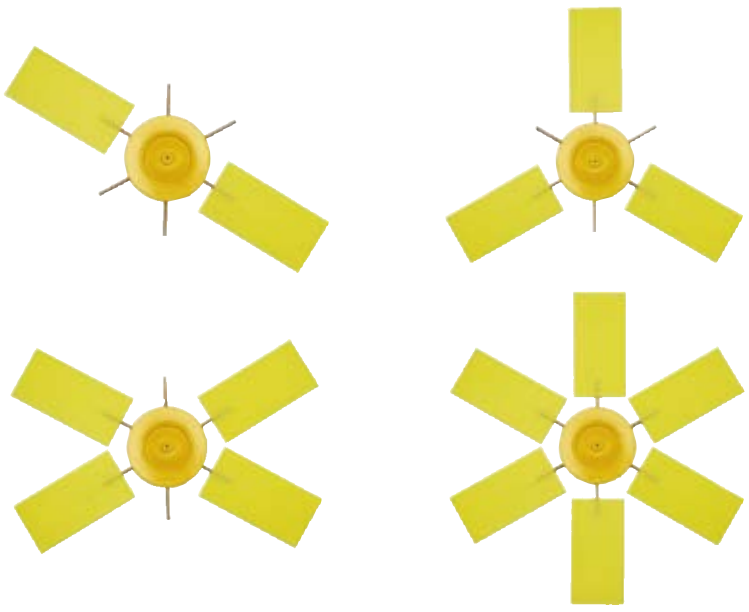


Classroom activities

Students can use the SEP wind turbine to investigate the effect of changing the number of blades, and get an insight into why three blades are considered the optimum number in real wind turbines. They will need to use the template for measuring blade pitch in order to keep the pitch the same (e.g. at 20º) as they vary the number of blades.

See Activity A3
How many blades?
(page 32)

The arrangement of posts on the turbine hub allows comparisons to be made between 2, 3, 4 and 6 blades.



Using the equipment and conditions as detailed in the student activities, they may well find that using three blades produces the maximum output voltage. Even if they do not get so convenient a result as this, what should be apparent is that increasing the number of blades beyond three does not have a great effect on the output. They should be aware that the optimum design will be a balance between maximising the output and minimising the construction costs.



Though this arrangement will not work, real turbines have been designed using one blade by using a counterweight.

Students can be asked to predict what would happen if they used just one turbine blade. Though this is an unbalanced arrangement and would not turn, they could be asked to suggest how a one-bladed turbine could be made to work.

One-bladed turbines using a counterweight do in fact exist. Using only one blade gives a cost reduction, but like the two-bladed turbine it adds to the engineering complexity. Similarly, it needs to rotate faster and is noisier than the three-bladed turbine, and the design has been used only rarely.

CHOOSING THE SHAPE OF BLADES

An old-fashioned windmill looks very different from a modern wind turbine. One reason is that it does a different job. Another is the strength of the materials that were available to construct them. The materials used for a traditional windmill place a limit on the length of the blades. If the blades were made longer, they would not be able to withstand the forces involved. The blades are wide and are designed to rotate relatively slowly. By using new materials such as carbon fibre, modern turbine blades are made to be flexible, and they are much stronger for their weight than those previously available. They can be made longer than traditional windmill blades, sweeping out a larger area as they rotate and thus can extract more energy. By being able to design the turbine so that it rotates more quickly than a windmill, the blades can be made narrower, leading to a reduction in the costs of the materials.





Two examples of windmill designs – the 19th century Rayleigh Windmill in Rochford, Essex (left) and a traditional Greek windmill (right).

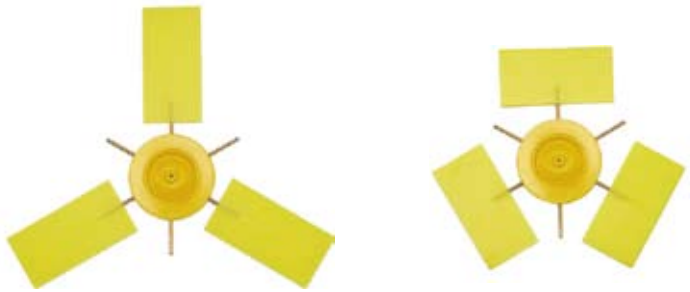
On a turbine with blades of a fixed pitch, most of the thrust is produced by the region of the blade that is furthest from the hub. On a traditional Greek windmill, the cloth sails are positioned on the outer edge in order to generate the most force.

Classroom activities

See Activity A4
How does blade shape affect output? (page 33)

A simple activity that students can do is to look at the performance of two types of blade with the same area but different shapes. The longer blades sweep out a larger area than the wider blades, and so the wind that passes through this area has more energy. The longer blades therefore produce a larger output voltage than the wider blades.

Comparing the performance of blades with the same area but different shapes.



ARE WIND TURBINES COST-EFFECTIVE?

The cost-effectiveness of a wind turbine will depend on the expense of constructing and maintaining it, and on the price at which the generated electricity can be sold. Advances in technology have made wind turbines that are more efficient and more reliable, and combined with the recent large increases in the costs of fossil fuels, wind power has become financially more competitive.

In addition to the design of the turbine itself, another factor that will influence the power output will be its location. A good site would be one where the average wind speed is greater than 6 m s^{-1} at 45 metres above ground level. But wind turbines cannot be put up just anywhere. In addition, there must be no inhabited dwellings within 500 metres, and there must be enough clear ground around the turbine so that it would fall in clear space if it collapsed. The environmental impact of the proposed turbine must be assessed and, depending on the size, either the local council or central government must approve the planning application.

Classroom activities

Students can use a spreadsheet model to look at the power output of wind turbines, the costs of building them, and the length of time it takes for a positive cash flow to be generated. This model can be downloaded from the SEP website, and it is discussed in more detail in the Background science section on page 45.

See Activity A6
Energy and costs (page 35)

They can also do research to identify potential locations for wind turbines. Using the Internet to obtain information from maps and data on wind speeds enables students to make estimates of possible power outputs. They can look at actual case studies, and consider the potential for wind power in the area where they live.

See Activity A7
Locating a wind farm (page 36)

FURTHER INVESTIGATIONS INTO TURBINE DESIGN

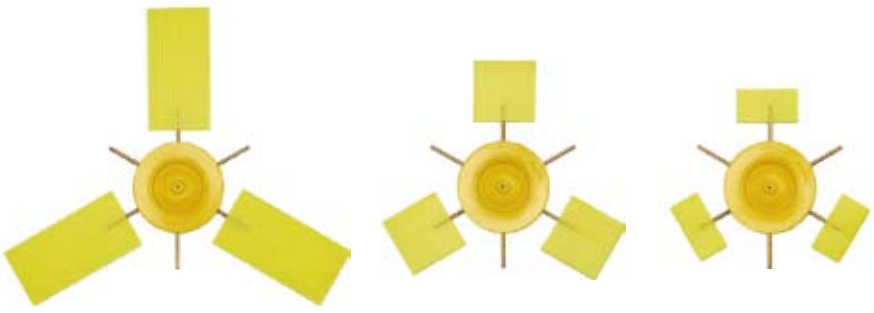
Each of the activities described so far have required students to look at the effect of changing a particular variable and have specified the conditions under which this should be done. The reason for this has been to focus on the conceptual explanations for each of the effects. These activities could be made more open-ended, with students being asking to identify variables and to plan their own investigation, so that the emphasis of the practical work would be more on the enquiry skills. However, if students begin with the more directed activities in order to gain an understanding of the science of the turbines, there are still plenty of opportunities for applying this knowledge in further investigations.

Classroom activities

To minimise the cost of constructing a wind turbine, as little material as possible should be used. If the area of a turbine blade does not affect the output of the turbine very much, then a great deal of money can be saved by putting up turbines with smaller blades. Students can look at the effects of the size of the blade on the performance of the turbine, and use the knowledge they have gained in earlier activities to interpret the behaviour. By varying the length they should find that longer blades produce a larger output (though the size of the desk fan will place a restriction on this because of the diameter of the air stream produced).

See Activity X1
Investigating the effects of blade size (page 37)

Students can explore the effects of blade length on output.



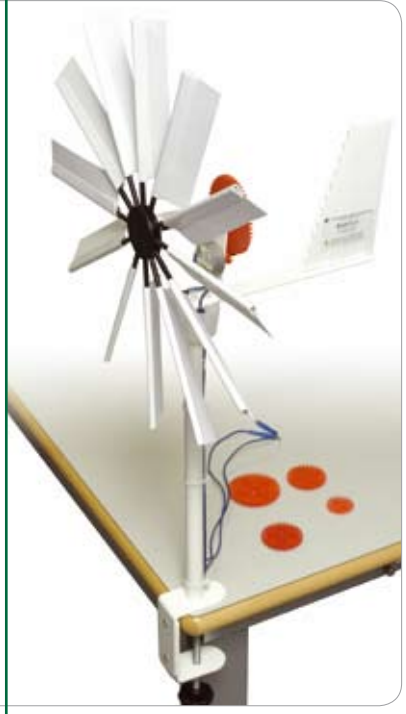
By varying the width they should find that up to a point, wider blades produce a larger output. Beyond this, having wider blades is counter-productive and reduces the output.

Students can also explore how the output is affected by blade width.



By bringing together what they have found out about blade length and blade width, they can try to design the optimum shape for the blades using a given area of corriflute.

The NEF wind turbine uses more blades and variable gearing.



The SEP wind turbine has been designed to be sufficiently cheap that multiple sets could be purchased by a school to maximise the hands-on experience of students.

The NEF wind turbine kit is more expensive, but it does allow further investigations to be undertaken. In particular, it has a set of different sized gears, which can be used in various combinations to simulate different turbine types. By connecting the turbine to different loads, the most effecting gearing for each load can be explored. In addition, the hub wheel allows up to 12 blades to be used so investigations into blade number can be extended, and since the blades are made from cardboard, students can cut out their own blade shapes easily. Designs for blades could be made and printed out using a computer.

See Activity X2
Does the best pitch work in all wind speeds? (page 38)

Another more open ended-investigation is to look at whether there is an optimum pitch that works across all wind speeds. In fact, at low wind speeds the pitch that produces the maximum power output is deeper than that for high wind speeds.

In order to get the best performance in a range of wind conditions, real wind turbines have variable pitch blades. A computer-controlled system monitors the wind and the turbine, and can rotate the blades so that their pitch is matched to the wind speed. This includes shutting the turbine down in strong winds to prevent it being damaged: when the blades are turned to face the wind directly, the turbine stops rotating.

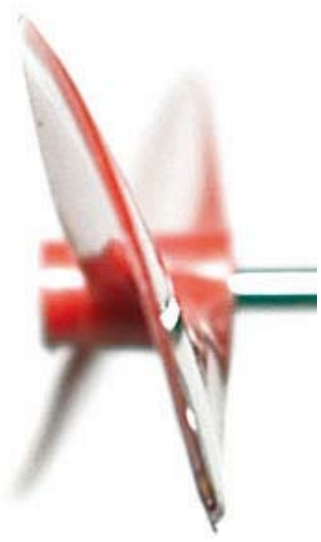
LOOKING AT THE DESIGN OF REAL BLADES

The SEP wind turbine has blades made out of corriflute, and which are therefore flat. Because of this, the pitch of each blade is the same from the hub to the tip. A real blade is curved from front to back, and the shape of the curve varies along its length. Turbine blades are designed using the same aerodynamic principles that are used in the design of aircraft wings.



This blade is being lifted into place during the construction of a wind turbine at Ford Dagenham. The complex shape of the blade can be seen.

The SEP mini-turbine uses a toy aeroplane propeller. This is curved from one edge of the blade to the other. Normally, it is mounted so that it has a shallow pitch at the front and a deep pitch at the back. This is because when used as a propeller, the blades need to 'slice' through the air and then push it backwards in order to produce thrust. However, when the propeller is used for the mini-turbine, it is better to mount it 'back-to-front'. This is because the turbine blades need to slow the air down, and work best with a shallow pitch at the back.



This shows how the propeller is mounted on the shaft of the SEP mini-turbine; the wind hits the blades from left to right. Used as a propeller for a toy aeroplane, the engine would be on the left, and blades would push the air from right to left.

Looking at the toy propeller from the side shows how its pitch changes along it length.



The most effective pitch depends on the speed of the air striking the blade. When a turbine rotates, the tip of each blade travels the fastest and the point nearest the hub travels the slowest. So, the pitch of a real turbine blade changes along its length.

See Activity X3
Looking at the design of real blades (page 39)

Classroom activities

To make the effect of the orientation of blades more obvious for students, they can use a propeller that has a very visible 'front' and 'back'. By connecting a voltmeter to the mini-turbine and holding it in front of a desk fan, they can see that a higher voltage is produced with the nose cone pointing backwards.

When the blades are viewed 'end on', students should be able to see how the propeller works better for a turbine when the shallow pitch is at the back. As an additional experiment, students could try connecting the mini-turbine to a low-voltage power supply to use it as a motor. By feeling the air stream produced, or by holding a length of audiotape behind the mini-turbine, they can see how more thrust is generated when the nose cone is pointing forwards.

Because this propeller has a nose cone, it is easy to see which is the 'front'. Like the red propeller, its pitch also changes from shallow to deep from one edge to the other.



STUDENT ACTIVITIES

WIND POWER

Teachers' notes

The student materials consist of a series of practical activities using model wind turbines and a set of data analysis and modelling activities using computers that can be run alongside the practicals. The key ideas are:

- the energy of the wind can be transferred to a turbine and used to generate electricity
- the design of a wind turbine affects the amount of energy that can be extracted from the wind
- design features of a turbine include the size, shape and pitch of the blades
- experiments with simple models can help to explain the design of real wind turbines
- computer models can be used to predict the output from a turbine and to estimate its cost-effectiveness
- a range of factors needs to be considered when choosing suitable locations for wind turbines.

Visit the SEP website www.sep.org.uk for supporting resources including image files and editable versions of the student sheets. See page 52 for information on obtaining the practical resources.

Health and safety

The rotating blades of the wind turbine can cause injury. It is essential that eye protection is used at all times when doing experiments with the model wind turbines. Students should be told to keep their faces away from the blades and to turn off the desk fan when making adjustments to the turbine.

An overview of the activities

The activities are:

- **Activity A1:** How does a wind turbine work?
- **Activity A2:** Getting the most energy from the wind
- **Activity A3:** How many blades?
- **Activity A4:** How does blade shape affect output?
- **Activity A5:** Analysing fluctuations in turbine output
- **Activity A6:** Energy and costs
- **Activity A7:** Locating a wind farm

There are three extension activities:

- **Extension X1:** Investigating the effects of blade size
- **Extension X2:** Does the best pitch work in all wind speeds?
- **Extension X3:** Looking at the design of real blades

In addition, there are resource sheets that provide information for students:

- **Resource R1** Setting up the SEP wind turbine
- **Resource R2** Measuring the pitch of the blades
- **Resource R3** Template for measuring blade pitch
- **Resource R4** Detecting changes in wind speed
- **Resource R5** Output data from a model wind turbine

Notes on the activities

Activities A1 – A4 are practical activities that use the wind turbines; activities A5 – A7 involve data analysis, computer modelling and Internet research. Since it is unlikely that there would be sufficient equipment, particularly desk fans, for the whole class to be engaged in practical work at the same time, students can rotate through the activities. The practical activities A1 – A4 would be best done sequentially, though activities A5 – A7 could be done in any order.

Activity A1, which uses the mini-turbine, is less demanding than the others and could be used at KS3. If KS4 students have already had practical experience at KS3 with the qualitative exploration of wind turbines they could go straight on to using the SEP wind turbine in activities A2, A3 and A4. You could make the activities more directed by giving tables to students for recording the data, or make them more open-ended by allowing students to choose the variables to investigate.

All of the activities with the SEP wind turbine require students to use the template for measuring blade pitch. Activity A2, which looks at the effect of blade pitch on output, is used to introduce the technique. An interesting question is why nearly all modern turbines have three blades, so you could start instead with activity A3, which looks at the effect of blade number. Students would then need to be taught how to adjust the blades to the correct pitch before doing this activity. Using the template needs a little bit of practice, but can then be done quite quickly. It will be helpful to demonstrate this, and students should be encouraged not to spend too long trying to achieve great accuracy in the angles. They should be aware that, because of the variation in the air flow from the fan, this would not add significantly to the accuracy of their results.

Both the SEP mini-turbine and the SEP wind turbine use the same small electric motor (designed to operate at 3 – 6 V when used as a motor). It has been selected because it is relatively free-running and gives a good output when used as a dynamo in these experiments. To get reproducible results using the SEP wind turbine, it is important to stress to students that it must be placed directly in front of the fan and in line with the centre. The turbine is provided with a pole of just the right height to ensure that its centre is level with the centre of the desk fan described on page 52. Other models of low-cost fans can be obtained from many sources; for use with the SEP wind turbine it is best to have a fan of at least 12" diameter to provide a sufficiently wide stream of air. If you use another type of fan you may need to adjust the length of the pole.

Activity A1: How does a wind turbine work?

Students use the SEP mini-turbine to explore the basic principles of wind power (see also page 3 of this booklet 'How does a wind turbine work?' and page 5 'Winds and wind turbines').

LEARNING OBJECTIVE

Students will:

- recognise some of the basic principles behind the use of a wind turbine
- interpret their experimental results in terms of energy.

NOTES

It is important to get the red propeller the 'right way' round when mounted on the turbine. It should have the concave side facing the fan. This is in fact the opposite way it would be mounted if it were being used as a propeller (this idea is explored in more detail in Extension X3).

Before connecting the turbine to a voltmeter, students could connect it to a load, for example an LED or a small motor, to see that a wind turbine can do a 'useful job'. When connected like this, energy is transferred mechanically from the wind to the turbine, and then electrically from the turbine to the load; with no load, the energy is transferred from the wind to the turbine, but is then dissipated.

If you are using a digital multimeter, then it is best to use a 200 V scale or similar on the d.c. range. This gives readings with just one decimal place - there is less variation in the displayed values and makes it easier for students to read.

RESOURCES NEEDED

Each group needs:

- SEP mini-turbine with 2-blade red propeller (6")
- Voltmeter or digital multimeter
- 2 plug-plug leads
- Desk fan
- Metre rule
- Eye protection.

Activity A2: Getting the most energy from the wind

Students use the SEP model wind turbine to find the optimum pitch for the turbine blades (see also page 7 of this booklet 'Getting the most energy from the wind' and page 11 'What happens to the wind behind the turbine?').

LEARNING OBJECTIVE

Students will:
- identify the optimum pitch for a turbine blade
- interpret their experimental results in terms of energy.

NOTES

As for activity A1, if you are using a digital multimeter, then it is best to use a 200 V scale to make the values easier for students to read.

The activity suggests comparisons using a pitch of 20°, 30° and 40°. Students could look at a wider range of pitches from 0° to 90°. A pitch of between 10° to 20° will probably be the optimum pitch.

If students try a pitch of 90°, then the turbine will still probably rotate and this will need an explanation in terms of the rotating air stream from the fan. This can be demonstrated by sticking 3 pieces of audiotape about

80 cm long at 120° to each other on the fan.

It is important to emphasise to students that this effect arises from the limitations of the experimental model using a desk fan, and it does not apply to real wind turbines. Although there is a lot of turbulence in the wind, the rotating air stream is a particular consequence of using a fan to generate an air stream.

Note that because of the direction of rotation of the fan, blades set at 20° anticlockwise will be better than blades twisted at 20° clockwise. The template for setting the pitch of the blades has been designed so that the blades are twisted anticlockwise. (A possible extension activity would be to turn the template through 90° so that the blades could be twisted clockwise in order to see this difference.)

Although a voltmeter gives an indication of the performance of the turbine, students should understand that it does not measure its energy output. This could be done as an additional activity by using the wind turbine connected to a small motor, and with a voltmeter to measure the voltage across the turbine and an ammeter to measure the current through the circuit. The power output can be calculated from voltage (V) x current (I). The effect of adding the load however is to make the turbine turn more slowly, and this does make it more difficult to investigate the effects of changing the blade pitch. In practical terms, simple investigations into the effects of turbine design can more easily be done without a load.

RESOURCES NEEDED

Each group needs:
- SEP wind turbine
- 6 corriflute blades, 10 cm x 5 cm
- Voltmeter or digital multimeter
- 2 plug-plug leads
- Clamp stand, with 2 clamps and bossheads
- Desk fan
- Metre rule
- Small strip of paper, clear sticky tape
- Eye protection.

- Resource R1: Setting up the SEP wind turbine
- Resource R2: Measuring the pitch of the blades
- Resource R3: Template for measuring blade pitch
- Resource R4: Detecting changes in wind speed.

Activity A3: How many blades?

Students use the SEP model wind turbine to find the optimum number of turbine blades (see also page 12 of this booklet 'Choosing the number of blades').

LEARNING OBJECTIVE

Students will:
- identify the optimum number of blades for the model wind turbine
- relate the results of their experiment to the design of real wind turbines.

NOTES

The rods on the yellow wheel are designed to be fixed firmly in place so that when blades are removed, the corriflute is removed but not the rod.

With the conditions specified on the student worksheet, the maximum output may be given by three blades. However, this will be affected by factors such as the speed and nature of the air stream, the size and pitch of the blades, as well as experimental errors.

If students do happen to find that the maximum output is given by three blades, then this provides a convenient result to explain why modern turbines almost always have three blades. Even if this does not happen in the experiment and using a larger number of blades gives a higher output, what should still be apparent from the results is that the increase is not dramatic.

As an extension, different groups of students could be asked to work with different air speeds or pitches, and the class's results pooled to determine the optimum number of blades under different conditions.

RESOURCES NEEDED

- Same resources as for Activity A2.

Activity A4: How does blade shape affect output?

Students use the SEP wind turbine to compare turbine blades of the same area but different shapes (see also page 14 of this booklet 'Choosing the shape of blades').

LEARNING OBJECTIVES

Students will:

- compare the effects of different blade shapes on turbine output
- interpret their experimental result in terms of the energy passing through the area swept out by the blades.

NOTES

The long thin blades give a higher output than the short wide ones. This is because there is less energy passing through the area swept out by the short wide blades. Increasing the width of a blade, like increasing the number of blades, will not produce a greater output once the maximum energy is already being extracted from the wind.

RESOURCES NEEDED

Each group needs:

- Same resources as for Activity A2
- 3 blades 5 cm long and 10 cm wide (to compare with the blades used in Activity A2, which are 10 cm long and 5 cm wide).

Activity A5: Analysing fluctuations in turbine output

Students analyse secondary data collected using a datalogger with the SEP wind turbine (see also page 16 of this booklet 'Further investigations into turbine design').

LEARNING OBJECTIVES

Students will:

- analyse sets of data and make comparisons using maximum, minimum and mean values
- draw graphs showing variation over time
- interpret the results in terms of wind speed and turbulence.

NOTES

Except for the 10 cm readings, output steadily decreases with increasing distance from the fan. The anomalous result at 10 cm result arises from the shielding by the centre boss on the fan housing and the extreme shear on air leaving the fan blades.

There is a periodic variation in the output. There are two possible explanations. One is that the periodicity is related to the rotation of the desk fan, and the other that it is related to the rotation of the turbine. There are variations in the periodicity, but for most of the time, the period is about the same for each of the distances from the fan. However, the turbine rotates more slowly at greater distances from the fan. So, the periodic variation of the output is due to the turbulence caused by the rotation of the desk fan, which is constant. This would not occur with a real wind – although there is turbulence, the variations would not be periodic.

RESOURCES NEEDED

- Resource 2: Output data from a model wind turbine

or:

- Access to computer
- Computer spreadsheet: WND_TurbineData.xls.

Activity A6: Energy and costs

Students use a computer spreadsheet model to look at turbine design and cost-effectiveness (see also page 15 of this booklet 'Are wind turbines cost-effective?').

LEARNING OBJECTIVES

Students will:

- use a computer model to support explanations about the effects of rotor size, turbine performance, wind speeds and terrain on turbine output
- evaluate the economics of building a wind turbine.

NOTES

The information that students need to answer the questions in this activity can be found on the computer spreadsheet.

Increasing the size of the wind turbine rotor increases the output of the turbine. Turbines are designed to work at wind speeds of between 5 and 25 m s^{-1}. At low wind speeds, the turbines do not turn at all; at high wind speeds, the turbines are shut down to prevent damage.

As well as the average wind speed, the distribution of wind speeds is important in determining output. Since output is proportional to the cube of the wind speed, higher wind speeds are more significant. Winds nearer ground level are slowed down by rough terrain, so the nature of the terrain can influence the height chosen for the tower. As with any electricity generating plant, cost-effectiveness will depend on the initial outlay on construction, annual maintenance costs, and the selling price of electricity.

RESOURCES NEEDED

Each group needs:

- Access to computer
- Computer spreadsheet: WND_TurbineModel.xls.

Activity A7: Locating a wind farm

Students use maps and data on wind speeds to identify potential locations for turbines (see also page 15 of this booklet 'Are wind turbines cost-effective?').

LEARNING OBJECTIVES

Students will:

- carry out searches of wind speeds in a database
- use maps to find grid references
- relate wind speed data to the characteristics of a location
- evaluate the factors involved in locating a wind farm.

NOTES

As an alternative to students using the Internet directly, you could print out the relevant web pages for them to use instead.

The data for Sheffield show that wind speed increases with height. The average wind speeds at the Lizard are greater than that for Sheffield because it is on the coast and exposed to the prevailing south-westerly winds. Great Yarmouth is a much flatter area than the Lizard, and the wind speeds are similar in adjoining squares. Because of the elevation, the data for Snowdon do not show much variation of wind speed with height.

The computer file that contains the links to support this work, also includes suggestions for following up data related to topical plans for wind farms.

RESOURCES NEEDED

Each group needs:

- Access to computer with Internet connection
- Computer file: WND_Links.htm.

Notes on the extension activities

Extension X1: Investigating the effects of blade size

This is a more open-ended investigation into choosing appropriate shapes and sizes of turbine blades (see also page 16 of this booklet 'Further investigations into turbine design').

LEARNING OBJECTIVE

Students will:

- plan and carry out an investigation into other factors affecting turbine output
- synthesise the knowledge gained in previous activities in producing and testing their own design.

NOTES

For a real wind turbine, increasing the length of the blades will give a bigger output, and the length chosen depends on engineering and economic factors. For the model wind turbine, there is a limitation imposed on the length of the blade - it cannot be wider than the stream of air coming from the desk fan. Designs using longer blades could be tested outside in real wind conditions.

RESOURCES NEEDED

Each group needs:

- Same resources as for Activity A2
- Additional corriflute - blades can be pre-cut for students e.g. in addition to the standard 10 x 5 cm blades:

Task A – 3 each of 5 x 5 cm, 2.5 x 5 cm.

Task B – 3 each of 10 x 3 cm, 10 x 1.5 cm.

Extension X2: Does the best pitch work in all wind speeds?

Students look at the relationship between output and two independent variables - blade pitch and wind speed (see also page 16 of this booklet 'Further investigations into turbine design').

LEARNING OBJECTIVE

Students will:

- investigate the effect on output of two variables - pitch and wind speed
- relate their experimental results to the design of real turbines.

NOTES

Generally, a deeper pitch works better with low wind speeds and a shallower pitch works well with higher wind speeds. The results from this experiment will depend on the distance from the fan and the number of blades.

It may not be easy to adjust the conditions to give an 'ideal' set of results, in which there is an output voltage in each of the cells of the table and a maximum shown at different pitches.

However what should be apparent is that with higher wind speeds a smaller pitch is better, while with low wind speeds a larger pitch may be needed to get the turbine to turn at all.

RESOURCES NEEDED

Each group needs:

- Same resources as for Activity A2.

Extension X3: Looking at the design of real blades

Students explore the behaviour of model propeller blades that have more complex shapes (see also page 18 of this booklet 'Looking at the design of real blades').

LEARNING OBJECTIVE

Students will:

- interpret the behaviour of more complex blades using knowledge gained in previous activities.

NOTES

Each of the propellers gives a better output when the edge with the shallow pitch is at the back. This is the opposite orientation to when it is used as a propeller. You could demonstrate this by using the mini-turbine as a motor (connected to a 6 V d.c. supply).

The pitch of the blade becomes shallower from the hub where it is moving slowest, to the tip where it is moving fastest.

RESOURCES NEEDED

Each group needs:

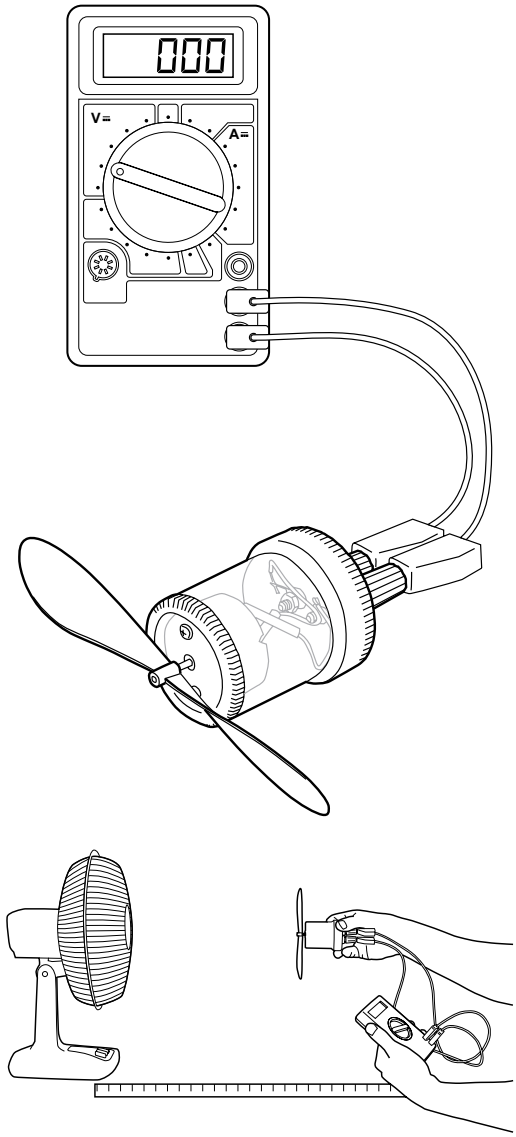
- Same as for Activity 1
- 2-blade red propeller (6")
- 3-blade black propeller (5").

WIND POWER:
HOW DOES A WIND TURBINE WORK?

More and more wind turbines are being built in the UK. In this activity, you will use a model of a wind turbine to explore how it works. The 'mini-turbine' has a small dynamo connected to a set of blades. In a stream of air, the blades can turn and the dynamo generates electricity.

Task A How does wind speed affect turbine output?

1. When would you expect a wind turbine to generate most power – in a high wind or a low wind?
2. Connect the mini-turbine to a voltmeter and give the blades a 'flick' to turn them round. What happens to the voltmeter reading?
3. Now hold the mini-turbine about 40 cm in front of a desk fan, directly in line with the centre.
4. Turn on the fan at the highest speed setting. Watch the meter reading for 20 seconds and record the highest value you see.
5. Repeat using the other fan speeds.
6. The result probably did not surprise you, but can you explain what is happening in terms of energy? On which fan setting did the wind have most energy? What happened to the energy when the wind hit the blades of the turbine?



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WIND POWER:

HOW DOES A WIND TURBINE WORK?

Task B Starting up a turbine and keeping it running

7. Which do you think it is easier – starting up a turbine or keeping it running once it has started?

8. Turn on the desk fan at its highest setting, and hold the mini-turbine in front of it. Move the turbine away slowly until the blades stop moving. How far from the fan is it?

9. Now move the turbine towards the fan until it starts to turn again. How far from the fan is it?

10. Does this confirm your prediction?

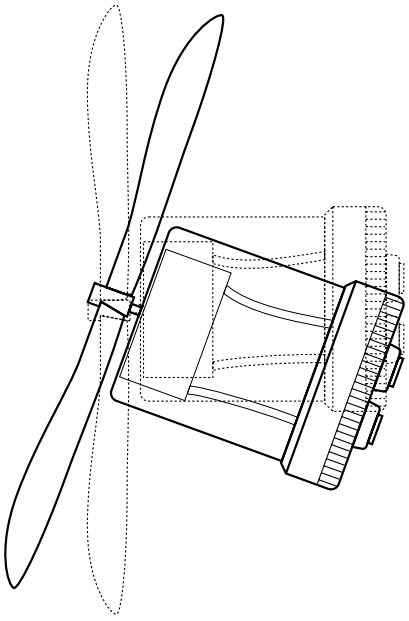
Task C How does the angle of the wind affect the output of a turbine?

11. When do you think a turbine generates most power – when it is facing the wind or when it is at an angle?

12. Find out how much difference the angle makes - hold the turbine about 40 cm in front of the desk fan on its highest setting. What happens to the meter reading as you change the angle of the turbine?

13. Does the energy of the wind change as you change the angle? Does the energy transferred to the turbine change as you change the angle?

14. The wind does not always blow in the same direction. Would this be a problem for real wind turbines? If so, how could it be solved?



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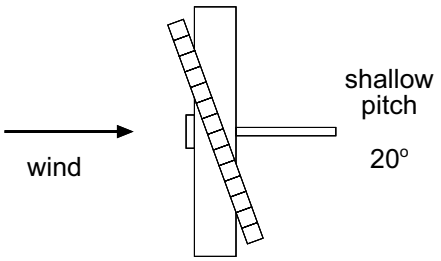
WIND POWER:
GETTING THE MOST ENERGY FROM THE WIND

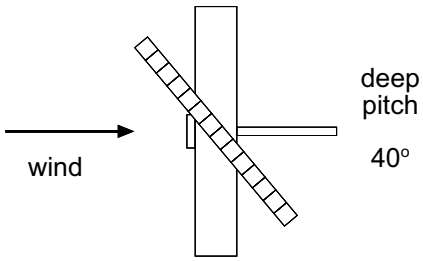
Making wind turbines as efficient as possible is essential if they are to be cost-effective. In this activity, you will look at one of the design factors – the angle or pitch of the blades.

The rotating blades of the wind turbine can cause injury. Always use eye protection when using the turbine and keep your face away from the blades. Turn off the desk fan when making adjustments to the turbine.

Task A How does blade pitch affect output?

The ***pitch*** of a blade is its angle to the direction in which it moves . A *shallow* pitch means that the angle is *small*. A *deep* pitch means that the angle is *large*.

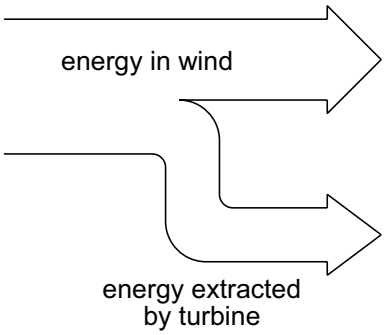




1. Which pitch do you think would give the highest output – 20°, 30° or 40°? Why do you think that?
2. Now test your prediction. First, set up the turbine (see *Resource R1: Setting up the SEP wind turbine*). Use 6 blades, and position the turbine 40 cm in front of the fan.
3. Set the pitch of the blades at 40° (see *Resource R2: Measuring the pitch of the blades*). Use the highest fan setting and measure the maximum voltage over 20 seconds.
4. Repeat for pitch settings of 30° and 20°.
5. Which pitch setting is best for the turbine to extract the maximum energy from the wind?

Task B The wind behind the turbine

6. To see what happens to the wind behind the turbine, you can use a strip of paper (see *Resource R4: Detecting changes in wind speed*).
7. When does the paper move more – with a 20° or a 40° blade pitch? What does this tell you about the amount of energy in the wind behind the turbine?
8. Why is there less energy in the wind behind the turbine than in front of it?
9. Do the results show that more energy is extracted by the turbine when you use a *shallow pitch* or a *deep pitch*?



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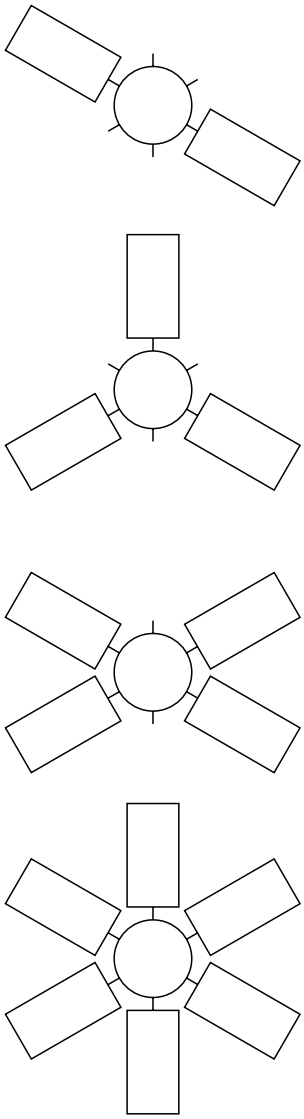
WIND POWER:
HOW MANY BLADES?

Perhaps the best way to extract most energy from the wind is to have a large number of blades. On the other hand, constructing more blades means a greater cost, so perhaps this would not be economical.

The rotating blades of the wind turbine can cause injury. Always use eye protection when using the turbine and keep your face away from the blades. Turn off the desk fan when making adjustments to the turbine.

Traditional windmills usually had four blades. Wind pumps, which are used for pumping water, tend to have many more blades. Modern turbines for generating electricity have fewer. This activity will help you to understand why.

1. What do you think might be the optimum number of blades for the model wind turbine? Make a prediction, before testing your idea.
2. Set up the turbine 40 cm in front of the desk fan.
3. Start with 2 blades at a 20° pitch, and use the highest fan setting. Record the maximum voltage in a 20 second period.
4. Repeat with 3, 4 and 6 blades (keeping the same pitch of 20°).
5. Predict what would happen if you used only one blade. Try this.
6. For the model wind turbine, what is the optimum number of blades for extracting the most energy from the wind?
7. Why do you think that modern wind turbines have three blades?



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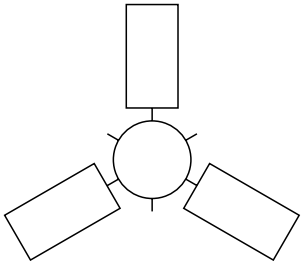
WIND POWER:
HOW DOES BLADE SHAPE AFFECT OUTPUT?

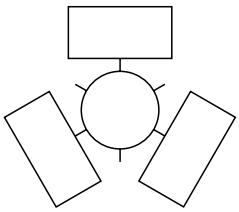
Another factor that affects the efficiency of a wind turbine is the shape of the blades. Different designs of blade will behave differently even when they have the same surface area.

The rotating blades of the wind turbine can cause injury. Always use eye protection when using the turbine and keep your face away from the blades. Turn off the desk fan when making adjustments to the turbine.

In this activity, you will use two types of blade. They have the same area, but they have different shapes.

The first set of blades are 5 cm wide and 10 cm long. The second are 10 cm wide and 5 cm long.





1. Which type of blade do you think would be better at transferring energy from the wind to the turbine – the long blade or the wide blade?
2. Now test your idea. Set up the turbine 40 cm in front of the desk fan.
3. Start with the first set of blades at a 20° pitch and the fan at its highest setting. Record the maximum voltage on the meter in a 20 second period.
4. Repeat this with the second set of blades, again at 20°.
5. For the model wind turbine, which shape is better for extracting more energy from the wind?
6. Why might this shape be better? (Think about the amount of energy passing through the area that is being 'swept out' by the wind turbine blades.)

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WIND POWER:
ANALYSING FLUCTUATIONS IN TURBINE OUTPUT

When you use a voltmeter to measure the output from the model wind turbine, you can see that the output values vary. A datalogger allows a large number of repeated measurements to be taken, which can be used to look at these variations in more detail.

In this data analysis activity, you can use either a printed table of data or a computer spreadsheet:

- *Resource R5: Output data from a model wind turbine* (data collected over a 1-second interval)
- *Spreadsheet: WND_TurbineData* (a much larger set of data collected over 25 seconds).

1. How would you expect the output of the turbine to vary with the distance from the fan?

2. Look at the results from the datalogger. Do the data seem to confirm your prediction?

3. To get a better idea, find the maximum value for each column of data. Plot these against distance from the fan.

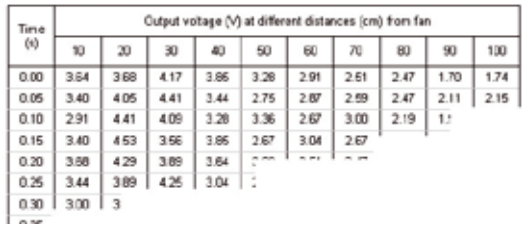
4. Are there any results that do not fit the pattern? How could you explain this?

5. Choose one column of data, and draw a graph showing output against time. How would you describe its shape?

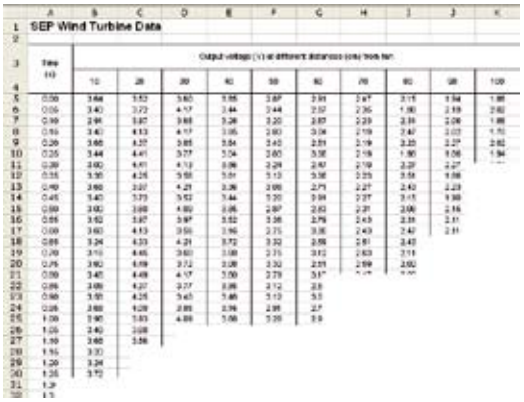
6. The output from real turbines varies because of random fluctuations in the wind. Does the variation on your graph look random or not? If not, how could you explain this?

7. If you are using the computer spreadsheet, you could also try:

- finding the minimum and mean (or average) values for each column of data, and comparing with the plot of maximum values
- plotting other columns of data against time and making a comparison between them.



Time (s)	Output voltage (V) at different distances (cm) from fan									
	10	20	30	40	50	60	70	80	90	100
0.00	3.64	3.68	4.17	3.86	3.28	2.91	2.61	2.47	1.70	1.74
0.05	3.40	4.05	4.41	3.44	2.75	2.87	2.59	2.47	2.11	2.15
0.10	2.91	4.41	4.09	3.28	3.36	2.67	3.00	2.19	1.1	
0.15	3.40	4.53	3.56	3.86	2.67	3.04	2.67			
0.20	3.68	4.29	3.89	3.64						
0.25	3.44	3.89	4.26	3.04						
0.30	3.00	3								



SEP Wind Turbine Data

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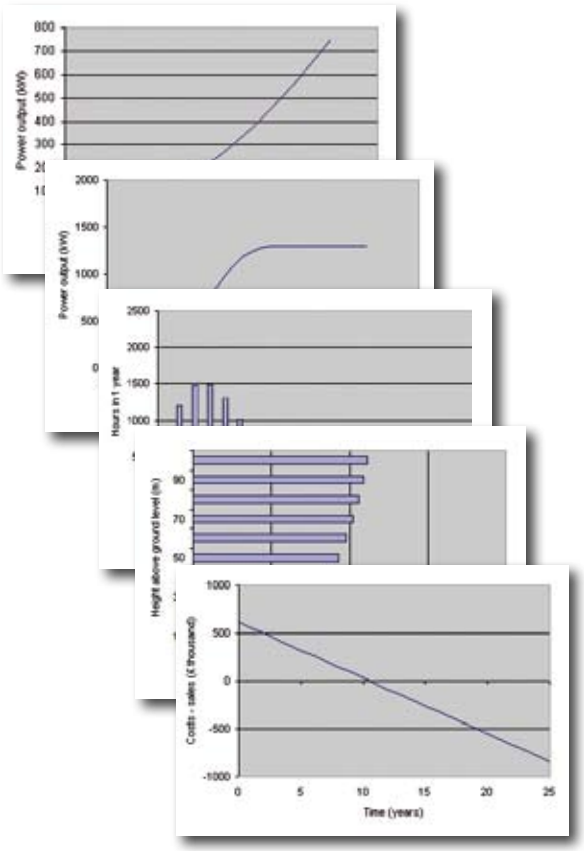
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WIND POWER:
ENERGY AND COSTS

In this activity, you can use a computer model to explore the factors that affect the energy output of a wind turbine, and estimate the costs involved.

To find the answers to the questions in this activity, you will need the computer spreadsheet *WND_TurbineModel*.

1. Click on the tab *Rotor size*. What effect does the size of the wind turbine rotor have on its output?
2. Manufacturers give data for wind turbines about their performance in different wind speeds. Click on the tab *Performance*. Look at the graph showing output against wind speed. How would you describe the shape of this graph? Why does the graph become flatter at high wind speeds?
3. Knowing the average wind speed for a location is helpful, but it is not the whole story. Click on the tab *Wind speed*. What does this graph show you about the way that the wind varies? Why is this important for finding a good location for a turbine?
4. Wind speed varies with the height above ground. Click on the tab *Height and terrain*. What effect does the terrain have on wind speed? How does this affect turbine design?
5. Finally, click on the tab *Costs*. Choose your turbine design, and enter data about the environment (wind speed and terrain). How much would your turbine cost? How long would it take before it started to pay for itself?



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WIND POWER:
LOCATING A WIND FARM

When choosing a site for a wind farm, data about the speed of the wind is needed. There are also many other factors to consider.

To find the answers to the questions in this activity, you will need the file *WND_Links*. This gives you the addresses of the web sites that you need.

Task A Finding the information

The Department of Trade and Industry has a database of wind speeds that covers the whole country in 1 km squares.

1. Find the wind speeds for Sheffield. How is wind speed affected by the height above the ground? Find the highest and lowest wind speeds in the adjoining squares.

2. Find out where the Lizard is. Would you expect its wind speed to be higher or lower than that for Sheffield? Why? Find out.

3. Find the wind speed data for Great Yarmouth. In what ways is this data different from that for the Lizard? Use a map to explain why.

4. Find the wind speed data for Snowdon. How does the wind speed vary with height above ground level? Why?

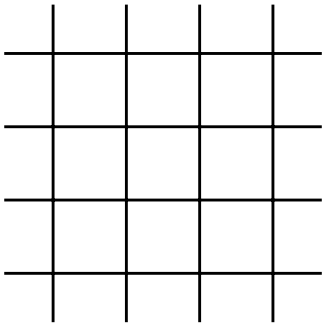
Task B Your own area

5. Look at the list of criteria for building a wind turbine.

6. Use a map of your area to find a possible location for a wind turbine. If you cannot find one, choose another area.

7. Get the data on wind speeds for this location. Would the wind speed be suitable for a wind turbine?

The wind speeds in the database are averages over each 1 km square.



Wind speeds are given at three different heights above ground level.

45 metres _____

25 metres _____

10 metres _____

Ground level _____

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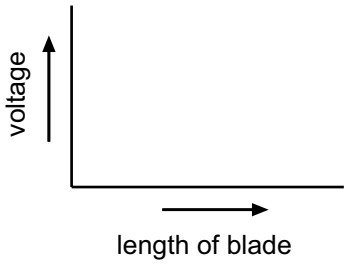
WIND POWER:
INVESTIGATING THE EFFECTS OF BLADE SIZE

This activity gives you an opportunity to carry out open-ended investigations on how the length and width of blades affect the power output, and on designing a blade that gives the maximum output.

The rotating blades of the wind turbine can cause injury. Always use eye protection when using the turbine and keep your face away from the blades. Turn off the desk fan when making adjustments to the turbine.

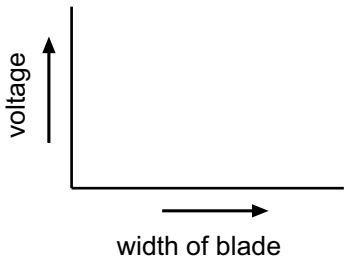
Task A How does blade length affect the output of a wind turbine?

1. Plan an investigation to find the effect of blade length on output. Use a set of blades that are the same width but of different lengths.
2. Carry out the investigation. What is your conclusion?
3. Using a desk fan imposes a limit on the blade length that you can use. Why?



Task B How does blade width affect the output of a wind turbine?

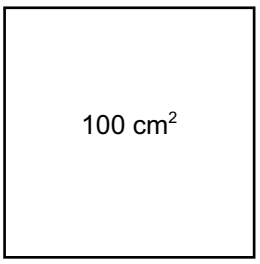
4. Plan an investigation to find the effect of blade width on output. Use a set of blades that are the same length but of different widths.
5. Carry out the investigation. What is your conclusion?



Task C Working within a budget

Imagine that you are working within a budget that allows you the cost of 100 cm^2 of material.

6. How would you use this most effectively? Draw on all the knowledge that you have gained about the number of blades, pitch, size and shape to come up with an optimal design.
7. If you have time, test out your design, and measure the output.



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WIND POWER:
DOES THE BEST PITCH WORK IN ALL WIND SPEEDS?

You have already investigated in Activity A2 how the blade pitch affects turbine output. You did this using the highest speed setting on the fan. But in real life, the wind speed is variable. So, in this activity, you will find out whether the optimum pitch is different for different wind speeds.



The rotating blades of the wind turbine can cause injury. Always use eye protection when using the turbine and keep your face away from the blades. Turn off the desk fan when making adjustments to the turbine.

1. Attach three blades to the turbine hub, and set up the turbine 40 cm in front of the desk fan.
2. Start with the highest fan speed and a pitch of 10°. Record the maximum voltage on the meter in a 20 second period.
3. Switch the fan off. Repeat with the fan speed on medium. Switch the fan off again, and repeat with the lowest fan speed.
4. Do the same thing for the other pitch settings.

Pitch	Voltage reading (V) at different fan speeds		
	High	Medium	Low
10°			
20°			
30°			
40°			

5. Which pitch seems to work best in low wind speeds? Which pitch is best for high wind speeds?
6. Would this be a problem for real wind turbines? If so, how could it be solved?

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WIND POWER:
LOOKING AT THE DESIGN OF REAL BLADES

A flat blade has the same pitch along its length and across its width. Real blades have more complex shapes, with different pitches in different parts of the blade.

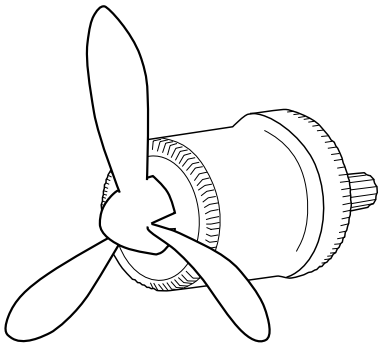
Task A Which way round should the blades be mounted?

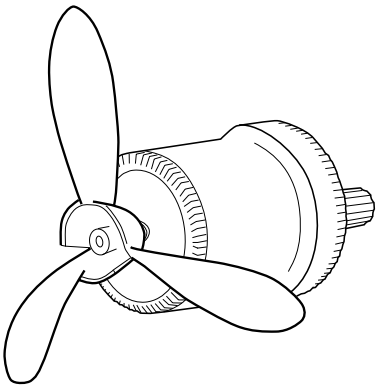
In this activity you will look at the effectiveness of different shaped blades for a wind turbine. You need a mini-turbine, a 2-blade propeller (red) and a 3-blade propeller (black). These propellers were designed for toy aircraft.

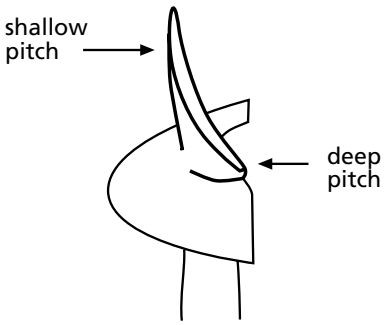
1. Start with the 3-blade propeller. Do you think that the turbine will work better with the nose cone pointing forwards or backwards?
2. Test your idea, by connecting the mini-turbine to a voltmeter and pointing it at a desk fan.
3. Which propeller position gives the better output?
4. Look carefully at the way that the blade curves. One edge has a shallower pitch than the other.
5. When does the turbine work better – when the edge with the shallow pitch is at the back or the front?
6. Can you explain this? (Think about what you found out about the effect of pitch in Activity A2.)
7. Now repeat the experiment with the 2-blade propeller. Which way does it work better – when the edge with the shallow pitch is at the back or the front?

Task B How does the pitch change along the blade?

8. Look at the way the pitch changes along the length of the blade from hub to tip. Is it shallower near the hub or near the tip?
9. Where does the blade move faster through the air – near the hub or near the tip? Is the blade designed with a shallower pitch where it moves faster or where it moves slower?







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WIND POWER:
SETTING UP THE SEP WIND TURBINE

The SEP wind turbine allows you to carry out experiments to investigate the effects of various factors on the output of the turbine.

To set up the turbine you will need:

- SEP wind turbine
- desk fan
- clamp stand with two clamps
- metre rule
- sticky tape
- 2 leads
- voltmeter or multimeter

You need to make sure the turbine is clamped securely. Slot the turbine case into the plastic post, and clamp the case to stop it moving from side to side.

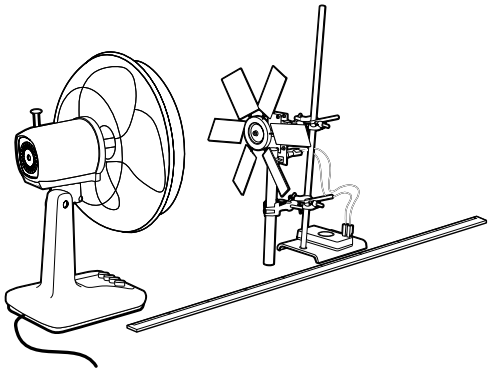
Position the turbine so that the hub is directly in front of the centre of the desk fan. Tape a metre rule to the bench so that one end is level with the centre of the desk fan blades; you can then measure distances to the turbine hub.

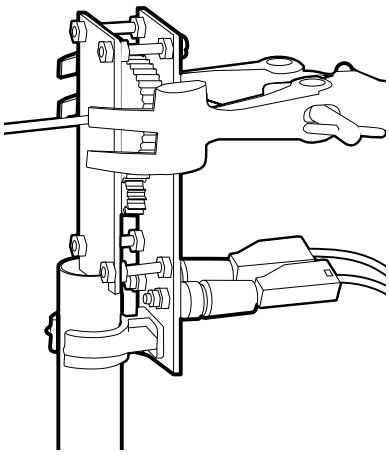
To test it is working, turn the blades so that they are all at roughly the same angle. Switch on the desk fan at its highest setting. The turbine should turn round and you should get a reading on the voltmeter.

The readings will vary, so in your experiments, record the highest value you see on the meter in a 20 second period.



The rotating blades of the wind turbine can cause injury. Always use eye protection when using the turbine and keep your face away from the blades. Turn off the desk fan when making adjustments to the turbine.





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WIND POWER:
MEASURING THE PITCH OF THE BLADES

To set the pitch of the blades on the SEP wind turbine, you will need *Resource R3: Template for measuring blade pitch*.

Put this template on the floor.

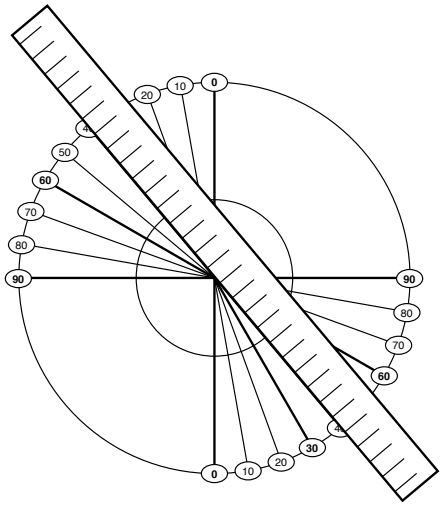
On top of the template, position a ruler at the angle that you want to use. (In this example, it has been set at 40°.)

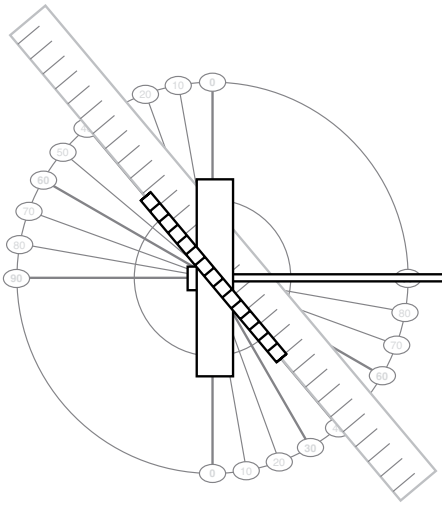
Put the turbine and clampstand over the template, and look straight down from above. Adjust its position, so that:

- the turbine axle is over the horizontal line
- the centre of the yellow hub wheel is over the centre of the circle.

Turn the turbine hub until the top blade is vertical. Look down and twist the blade until it lies along the ruler's edge.

Turn the hub again until the next blade is at the top. Repeat the process, until all the blades have the same pitch.

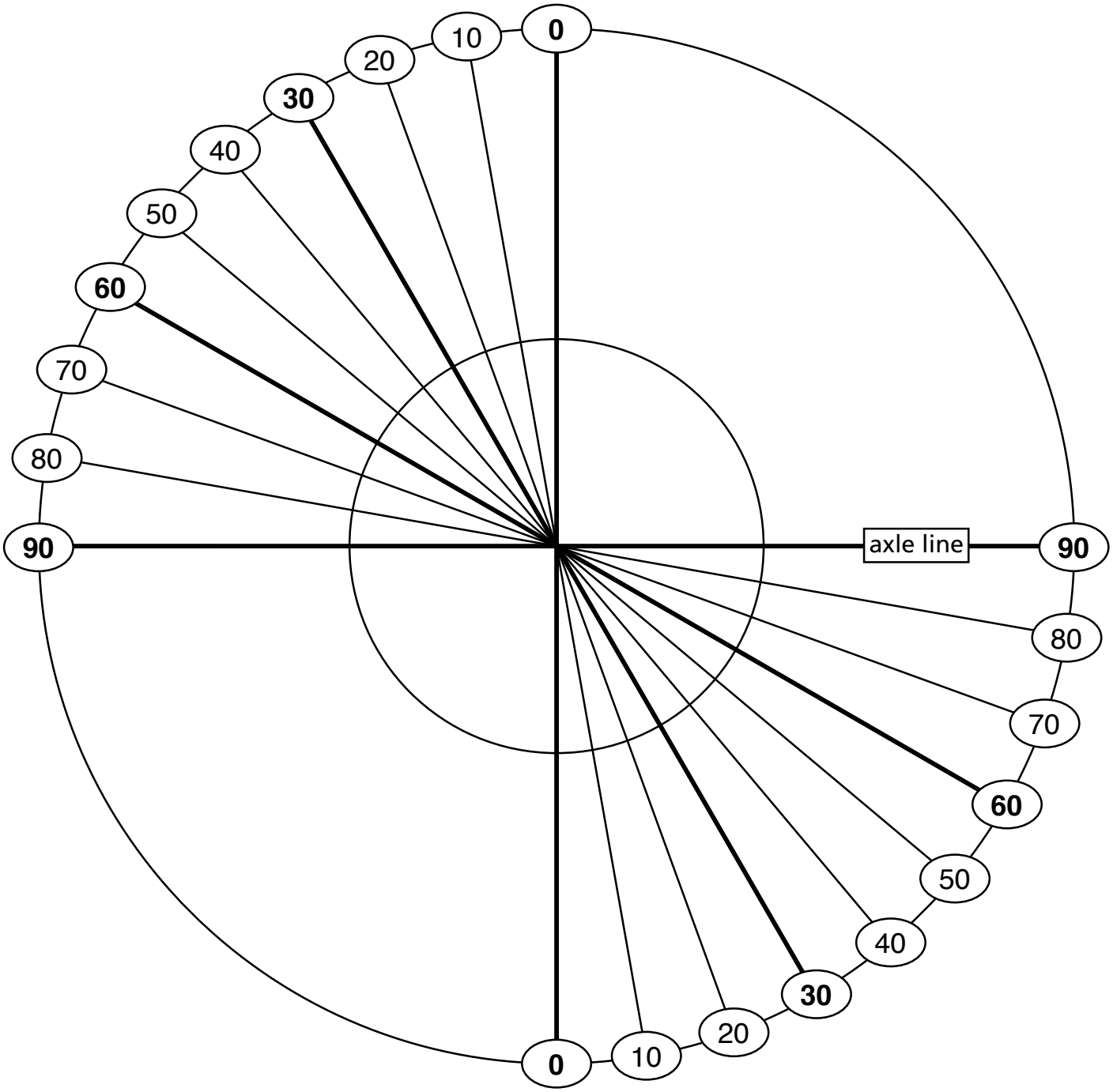




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Resource R3

WIND POWER:
TEMPLATE FOR MEASURING BLADE PITCH



1 of 1

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WIND POWER:
DETECTING CHANGES IN WIND SPEED

The purpose of a wind turbine is to extract energy from the wind. So, the air behind a turbine has less energy and moves more slowly than the air in front of the turbine.

You can see this effect by using a strip of paper behind the turbine. Cut out a piece of paper about 6 cm long and 0.5 cm wide. Use a piece of sticky tape to attach it to the back of the turbine case as shown.

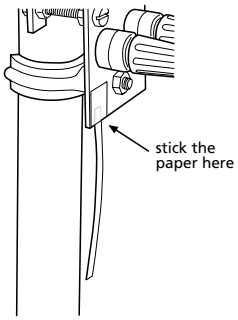
Hold the turbine blades still and turn on the desk fan. You should see the strip of paper flapping in the wind. Now let go of the blades so that they are free to turn. You should see the strip of paper flapping less.

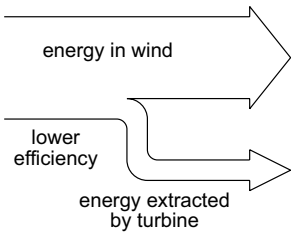
You can judge the efficiency of the turbine by the effect that it has on the strip of paper. A turbine operating at a lower efficiency extracts less energy from the wind.

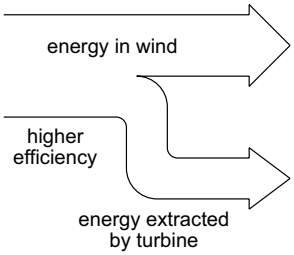
A turbine operating at a higher efficiency extracts more energy from the wind. The more efficient the turbine, the more slowly the air behind it moves, and the less the strip of paper flaps.



The rotating blades of the wind turbine can cause injury. Always use eye protection when using the turbine and keep your face away from the blades. Turn off the desk fan when making adjustments to the turbine.







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WIND POWER:
OUTPUT DATA FROM A MODEL WIND TURBINE

This data was collected using a datalogger connected to the SEP wind turbine. The output voltage was measured at different distances from a desk fan. Each column of data was collected over a period of 1 second, with an interval between readings of 0.05 seconds.

Time (s)	Output voltage (V) at different distances (cm) from fan									
	10	20	30	40	50	60	70	80	90	100
0.00	3.64	3.68	4.17	3.85	3.28	2.91	2.51	2.47	1.70	1.74
0.05	3.40	4.05	4.41	3.44	2.75	2.87	2.59	2.47	2.11	2.15
0.10	2.91	4.41	4.09	3.28	3.36	2.67	3.00	2.19	1.98	1.90
0.15	3.40	4.53	3.56	3.85	2.67	3.04	2.67	2.06	1.94	1.90
0.20	3.68	4.29	3.89	3.64	3.36	2.51	2.47	2.31	2.11	2.11
0.25	3.44	3.89	4.25	3.04	2.75	3.08	2.79	2.47	1.74	1.74
0.30	3.00	3.68	4.37	3.56	3.36	2.47	2.91	2.27	2.11	2.02
0.35	3.36	4.17	3.97	3.81	2.67	3.08	2.47	1.94	1.90	2.02
0.40	3.68	4.53	3.52	3.36	3.36	2.71	2.71	2.35	1.98	1.82
0.45	3.40	4.57	3.93	3.44	2.67	2.91	2.91	2.39	2.06	2.11
0.50	3.00	4.29	4.37	3.85	3.32	2.83	2.67	2.02	1.70	1.74
0.55	3.52	3.81	4.33	3.52	2.75	2.79	2.43	2.15	2.11	2.02
0.60	3.68	3.81	3.85	3.16	3.24	3.00	2.75	2.43	1.90	1.98
0.65	3.24	4.21	3.60	3.72	3.00	2.59	2.87	2.19	1.82	1.78
0.70	3.16	4.53	4.13	3.68	2.96	3.12	2.59	1.98	2.11	2.11
0.75	3.60	4.49	4.33	3.08	3.24	2.51	2.43	2.35	1.74	1.94
0.80	3.48	4.29	4.09	3.60	2.79	3.12	2.79	2.39	1.94	1.74
0.85	3.08	3.81	3.85	3.85	3.36	2.59	2.91	2.15	2.02	1.98
0.90	3.56	3.72	3.60	3.48	2.87	3.00	2.59	2.02	1.66	1.98
0.95	3.68	4.17	4.17	3.16	3.32	2.79	2.35	2.39	2.11	1.66
1.00	2.96	4.41	4.41	3.68	2.96	2.91	2.59	2.35	2.02	1.74

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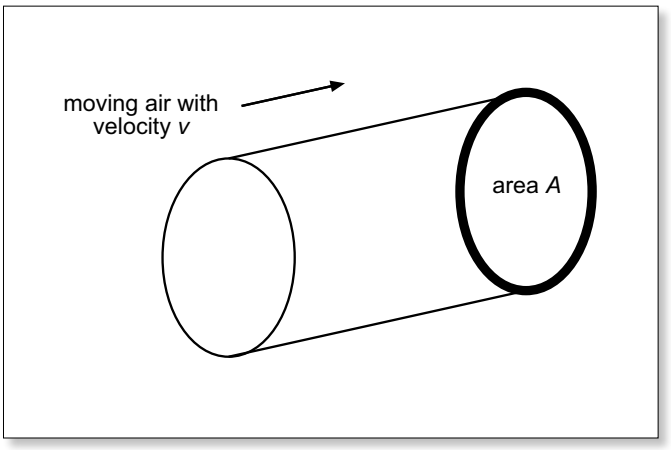
Science Enhancement Programme

BACKGROUND SCIENCE

The output from a wind turbine will depend of a variety of factors including its location (wind speeds and terrain) and its design (rotor size, efficiency, hub height). The SEP website has a computer spreadsheet that can be used to model the output of a wind turbine.

The computer model is designed to be used by students and does not require any knowledge of the equations used to create the model. For those who are interested though, this section explains the calculations that are used, including how to work out the amount of energy in the wind, what affects turbine efficiency, how to model the variation in wind speeds in a location, and how to estimate the cost-effectiveness of a wind turbine.

ENERGY IN THE WIND



Since a wind turbine is designed to extract energy from the wind, an obvious first question is: how much energy is there in the wind?

Imagine that there is a hollow ring with a wind blowing through it. If the wind is travelling at $\boldsymbol{v}$ m s^{-1}, then in 1 second a cylinder of air of length $\boldsymbol{v}$ metres will have passed through the ring. If the cross-sectional area of the ring is $\boldsymbol{A}$, and the density of the air is ρ, then the mass, $\boldsymbol{m}$, of the cylinder of the air is given by:

$$mass = volume \times density$$
$$m = A\, v\, \rho$$

This cylinder of air is moving at a velocity of v, so its kinetic energy is given by:

$$E_k = \frac{1}{2} m v^2$$

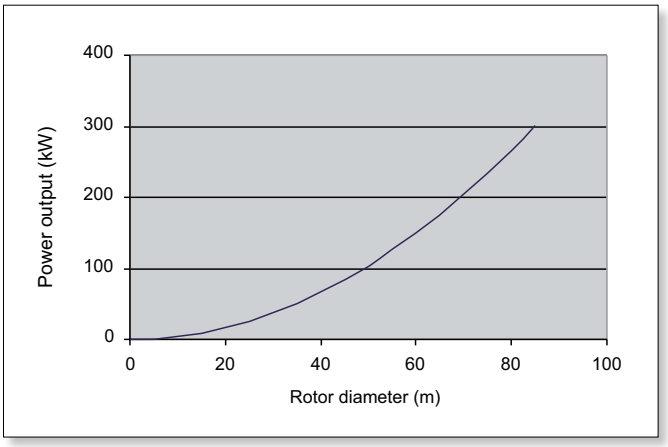
$$= \frac{1}{2} A \rho v^3$$

This represents the kinetic energy of the wind passing though this ring in 1 second, i.e. its power. What can be seen from this is that the energy obtained from the wind is proportional to the cube of the wind speed. This means that high wind speeds will contribute proportionally a great deal more to total energy output than low wind speeds, and this point is considered in more detail later.

Now, to put in some values to get a sense of how much energy can be extracted by a wind turbine. Take a wind turbine with a rotor diameter of 30 metres – the area swept out by the blades (πr^2) is about 707 m^2. With a wind speed of 6 m s^{-1} (a typical average value for the UK) and taking the density of air as 1.225 kg m^{-3}, the energy passing through this area in one second is:

$$E_k = \frac{1}{2} \times 707 \times 1.225 \times 6^3 \text{ J}$$

$$= 93.5 \text{ kJ}$$



This graph shows how the power output of a turbine varies with the rotor diameter, assuming a wind speed of 6 m s^{-1} and an efficiency of 40%.

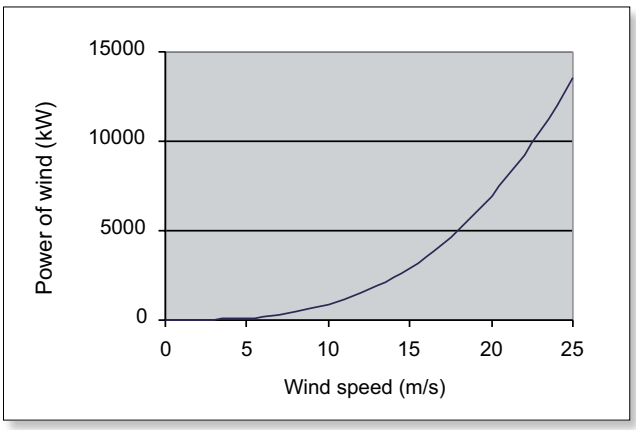
So the power of the wind passing through the area swept out by a rotor with a 30 metre diameter is 93.5 kW. If the turbine operates at an efficiency of, say, 40%, then the power output of the turbine is 37.4 kW at this wind speed. Doubling the rotor diameter to 60 metres (with all other factors remaining the same) would mean that the power output would be 4 times the size, i.e.149.6 kW.

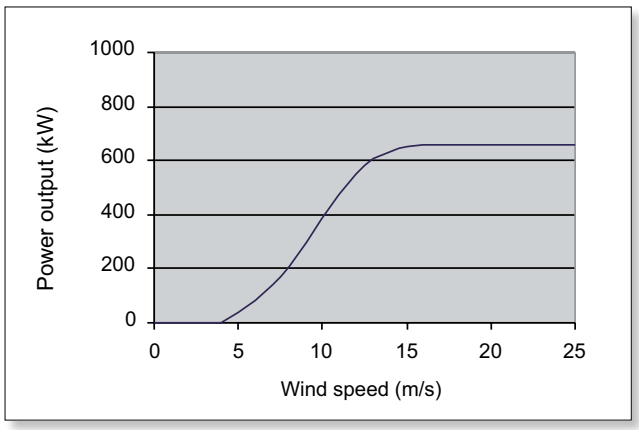
EFFICIENCY OF TURBINES

There is a theoretical limit to the maximum efficiency of a wind turbine given by Betz Law. Essentially, what this law shows it is that the maximum efficiency is achieved when $^2/_3$ of the air passes through the area swept out by the rotor blades, and $^1/_3$ passes around the outside. The air that passes through the turbine blades is slowed to $^1/_3$ of its original velocity, and thus is reduced to $^1/_9$ of its original energy. This means that the total energy extracted is $^8/_9$ of the air passing through. Thus the efficiency is $^8/_9 \times {}^2/_3 = {}^{16}/_{27} = 59\%$.

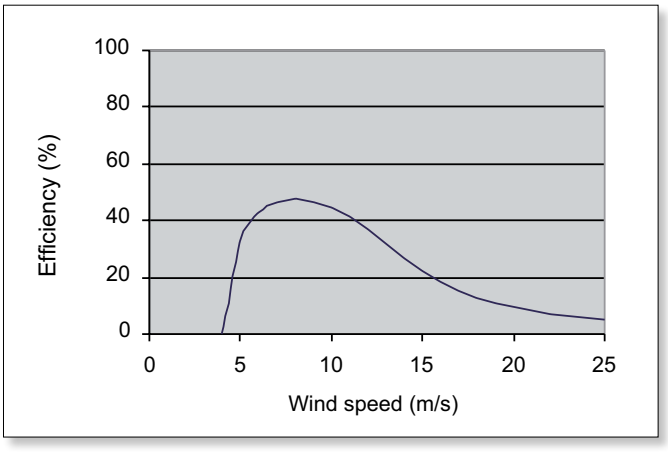
In practice the efficiency of the turbine is less than the theoretical limit of 59%, and its value varies with the wind speed. Typically, turbines are designed to achieve their maximum efficiency at wind speeds of around 8 m s^{-1}. This is higher than the average wind speed for the UK, because it is in these higher wind speeds that most of the energy is to be found - this is a consequence of the energy being proportional to the cube of the wind speed.

The following graphs are based on data for a commercial wind turbine with a rotor diameter of 47 metres. The first graph shows the power available in the wind for a range of different wind speeds. The second graph gives the power curve for the turbine, which shows the actual power output of the turbine at a range of different wind speeds.





A comparison based on a rotor diameter of 47 metres of the power available in the wind (left) and the power output of a commercial turbine (right).



Turbine efficiency at different wind speeds.

Using these two sets of values it is possible to calculate the efficiency of the turbine. This graph shows the efficiency of the turbine at different wind speeds. The turbine is not designed to work at very low wind speeds. The power output of the turbine increases with wind speed up to a maximum, since the turbine is designed to have a maximum speed of rotation. At wind speeds of 25 m s^{-1} or more, turbines are normally shut down to prevent damage.

The power curves of wind turbines are provided by the manufacturers, and the computer spreadsheet model contains data for a number of commercial wind turbines of a range of sizes.

VARIATION IN WIND SPEEDS

The output of a wind turbine will clearly depend on the wind speeds at the location where it is built. There is a database of wind speeds on the DTI Renewable Energy website. Average values are given for 1 km squares across the UK. Grid references for can be found from a map and then entered in the database to display the wind speed for the 1 km square corresponding to that reference, and the eight adjoining squares. The wind speeds are given at heights above ground level of 10, 25 and 45 metres. The tables below show some examples from three locations.

Sheffield SK3687

4.1	4.1	3.9
3.7	4.4	4.3
4.2	4.9	5.3

Lizard SW7012

7.1	7.3	6.1
6.5	7.2	6.3
6.3	6.3	6.1

Great Yarmouth TG5206

5.2	5.3	5.8
5.2	5.3	5.8
5.2	5.2	5.8

Wind speed at 10 metres above ground level (in m/s).

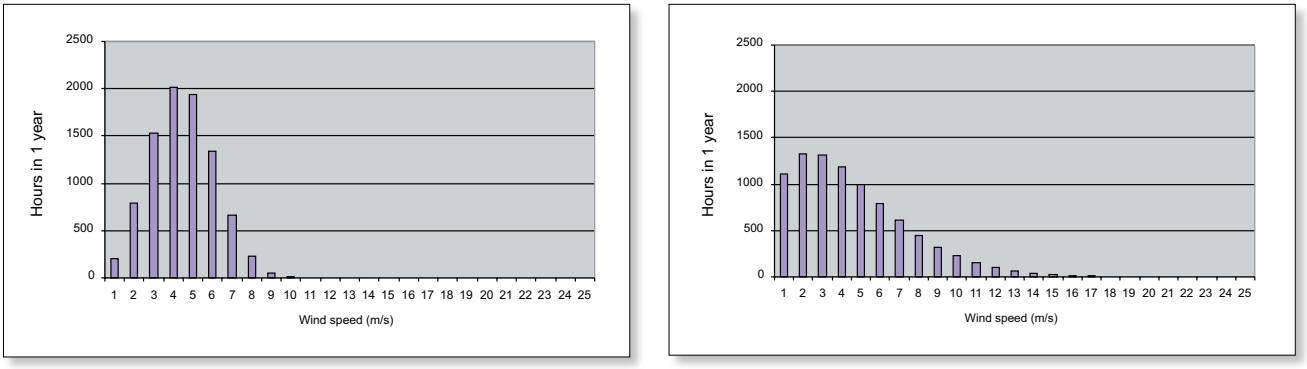
The wind speeds for Sheffield and the area around it are lower than that for the Lizard. This is because Sheffield is an inland area, whereas the Lizard is on the coast and is exposed to the prevailing south-westerly winds. Great Yarmouth is also on the coast but the wind speeds show a different pattern; whereas the area around the Lizard is quite hilly, Great Yarmouth is very flat. The three squares in the right-hand column show values for sea areas, the other six are for land. The wind is slowed over the land, but being flat, the values are similar in each of the squares.

However, knowing the average wind speed for a location is not sufficient to find the total output of a turbine over the course of the year. As explained in the previous section, the power curve for a wind turbine shows that higher wind speeds contribute proportionally more to the power output than lower wind speeds. Thus, it is also important to know about the distribution of wind speeds. The wind speed database gives only average values, but it is

possible to model the variation in wind speeds using the Weibull distribution. The following formula can be used to estimate the probability, ***p(u)***, of any given wind speed, ***u***, from the value of the average wind speed, ***c***:

$$p(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left(-\left(\frac{u}{c}\right)^{k}\right)$$

The value, ***k***, is a parameter that determines how 'spread out' the distribution of the winds is – a higher value of ***k*** produces a distribution with wind speeds closes the to mean, a lower value of ***k*** produces a distribution with a greater spread. This is illustrated in the two graphs below; each graph is calculated using the same average wind speed, but they use different values for ***k***.



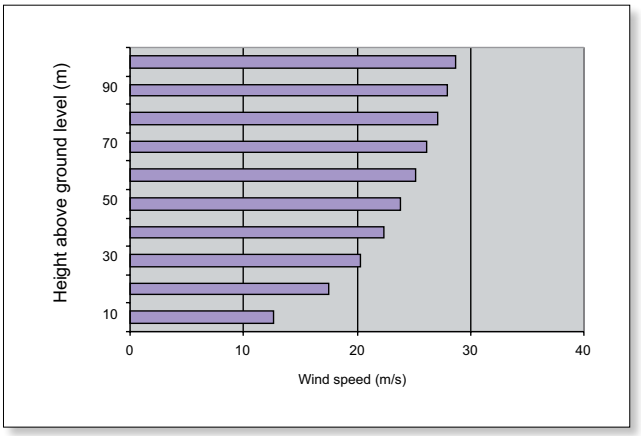
Wind speed distribution calculated using computer model for average wind speed of 5 m s^{-1} and *k*=3 (left) and *k*=1.5 (right).

Although the average speeds are the same in each case, the distribution shown on the right would produce a greater average power output from a turbine. The wider spread means that there are longer periods of time when the wind speed is 8 m s^{-1} or more. In most of Northern Europe, ***k*** factors are generally close to 2, and using this value gives a good prediction of the distribution of wind speeds for locations in the UK.

Wind speeds also vary with height. The size of this variation depends on the nature of the terrain; in a town, the buildings will slow the wind down near ground level, but at sea, the wind near the surface will only be slowed a little. Again, this variation can be modelled. The computer model uses the following equation to calculate the wind speed, ***u***, at height, ***z***, from a reference wind speed, u_R, at height z_R:

$$u = u_R \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_R}{z_0}\right)}$$

The factor z_0 is called the roughness length, and its values depends on the nature of the terrain; for example, water surface (0.0002), open land (0.03), farmland with small buildings (0.1), villages and towns (0.4) and large cities (1.6).



Variation of wind speeds with height using value of 1.6 for roughness length.

The variation in wind speed with height will determine the cost-effectiveness of building a higher tower. At sea, wind turbines tend to be mounted closer to the surface; in rougher terrains, it may be worth the extra expense of building a higher tower so that the rotor is operating where wind speeds are greater.

ECONOMICS OF WIND POWER

The final section of the spreadsheet model includes a simple calculation on cost-effectiveness. The figures used in the calculation are for illustration only and are not intended to represent accurately the current economics of the energy industry. However, they should be sufficient to demonstrate to students some of the basic principles involved.

The cost-effectiveness of a wind turbine will depend on the initial costs of purchasing and installing it, on the annual maintenance costs, and on the selling price of the electricity generated.

The purchase and installation costs of a turbine are calculated from the following equations:

$$\text{purchase cost of turbine} = £1000 \times \left(25 + \frac{\text{maximum power output in kW}}{3}\right)$$

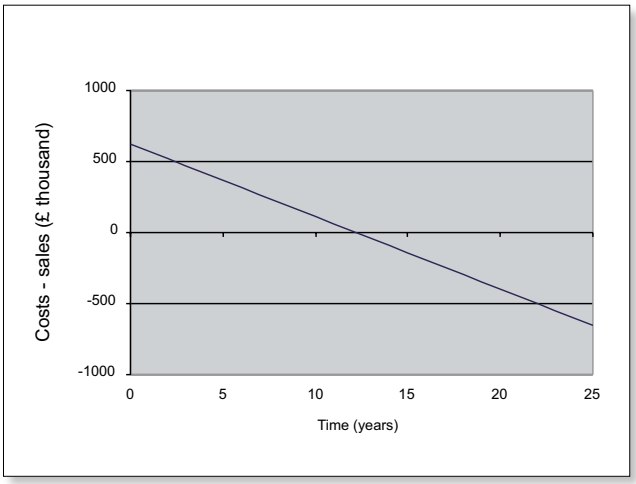
$$\text{installation cost of turbine} = 0.3 \times \text{purchase cost of turbine}$$

These figures include the cost of erecting a tower with a 'standard' height of 40 metres. If a taller tower is used, then an additional cost needs to be added to the initial outlay.

$$\text{cost of tower} = £800 \times (\text{height of tower in metres} - 40)$$

In addition to the initial outlay, there will be continuing running costs and maintenance for the turbine, which are calculated from a percentage of the total purchase and installation costs.

$$\text{annual maintenance costs} = 2\% \times \text{total costs of turbine and installation}$$



Using estimated values of turbine costs and the selling price of electricity, a graph can be produced showing the time taken to recover the initial outlay.

At the time of writing, the cost of electricity for consumers is of the order of 10p per kWh, though prices vary considerably from scheme to scheme and from one supplier to another. The selling price for an electricity producer is much less than this, and the spreadsheet allows values from 0 to 3p per kWh to be entered. This figure depends a lot on current market conditions, and is affected by the availability of other energy resources such as natural gas.

REFERENCES AND FURTHER READING

SEP website

For additional resources, visit the 'Innovations in practical work' section on the SEP website (www.sep.org.uk/practical). You can download the following:

- PDF file of this booklet
- PDF files of individual student sheets
- Word documents of classroom activities (can be edited)
- PowerPoint slides with photographs and graphics
- Output data from model wind turbine (spreadsheet)
- Computer spreadsheet model on the cost and energy output of turbines.

Other websites

Some particularly relevant websites are listed below. More links can be found on the SEP website.

Danish Wind Industry Association (www.windpower.org)
A comprehensive guide to wind power with clear information and excellent resources, and a very well-produced section for students 'Wind with Miller'.
British Wind Energy Association (www.bwea.com)
The BWEA represents the UK wind and marine renewables industries, and its website contains many useful resources including a 'Frequently Asked Questions' section.
National Energy Foundation: Green Schools (www.nef.org.uk/greenschool/)
This includes details on obtaining the NEF wind turbine, and has some useful information sheets for students.
Centre for Alternative Technology (www.cat.org.uk)
Details of a wide range of educational materials on alternative technologies; the centre also provides visits and course for students.
CREATE (www.create.org.uk)
The Centre for Research, Education and Training in Energy website provides some downloads and links to other useful sites concerned with energy education.
Encyclopedia of the Atmospheric Environment (www.ace.mmu.ac.uk/eae/english.html)
Contains a series of short hyperlinked pages (with different versions aimed at younger and older students) covering topics such as weather, climate change and sustainability.
BERR: Energy (www.berr.gov.uk/energy/)
As well as the windspeed database for the UK, this website includes a section for schools on renewable energy with much useful material including a series of case studies.

SOURCES

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OBTAINING THE PRACTICAL RESOURCES

The wind turbine equipment described in this booklet can be obtained from Middlesex University Teaching Resources, which supplies a wide range of low-cost resources for school science and technology. Check their website (www.mutr.co.uk) for the latest prices of the products shown below.



SEP wind turbine
211-010
This comes ready-assembled, and allows students to carry out a wide range of investigations into the effects of changing the number, size, pitch and shape of the blades.



SEP mini-turbine
211-012
This mini-turbine can be held in the hand or put in a clamp stand. It can be used to introduce the ideas behind wind power, or for more challenging work on the effects of blade design on turbine output.



Desk fan (12")
TOO 106
Includes 3-speed control and 40 W motor.



Pedestal fan (16")
TOO 107
Includes 3-speed control and 50 W motor.



Digital multimeter
MET 001
Robust and low-cost meter suitable for measuring turbine output.



Propeller (2-blade, 6")
CP2 001
Fits onto the SEP mini-turbine.



Corriflute (3 mm)
CS6 001J
For making the SEP wind turbine blades.



Propeller (3-blade, 5")
CP2 002
Fits onto the SEP mini-turbine.

Orders can be made by post, telephone, fax or email by providing an official school order number. Alternatively, payment can be made by credit card. See the back cover of this booklet for contact details. Further information can be obtained from www.mutr.co.uk, or by requesting their latest catalogue.

You can download the written materials in this booklet, and find further information from: Science Enhancement Programme www.sep.org.uk

The Science Enhancement Programme (SEP) is part of Gatsby Technical Education Projects. It undertakes a range of activities concerned with the development of curriculum resources and with teacher education.

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The Gatsby Charitable Foundation

You can order the SEP wind turbine and other practical resources from Middlesex University Teaching Resources.

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