Exploiting the wind

Global reserves of *fossil fuels* are becoming more costly to exploit and less accessible. With the demand for energy growing at an ever increasing rate there are valid concerns about the availability and *sustainability* of energy supplies for future generations. As an alternative to fossil fuels, sources of renewable energy like wind power are becoming increasingly popular in many countries. Wind power is one of the cleanest sources of energy available. It involves very low emissions of greenhouse gases and the 'fuel' is free. As Ireland is one of the windiest countries in Western Europe there is great potential for making use of this resource.

Energia, a leading supplier of electricity to the Irish market is busy expanding its renewable energy portfolio. In effect this clean energy supply reduces our output of CO_2 by 150,000 tonnes of per annum – the equivalent to removing 40,000 cars. In this lesson we look the fundamental physics underlying the ***generation*** of electricity using the wind.

Basics

In comparison with water air seems to have no appreciable ***mass***. However it is relatively easy to show that a litre of air under ordinary conditions has a mass of about 1.2 grams. A cubic metre of air is therefore about 1.2 kg. The large classroom of say 12 × 7 × 3 m would have about 300 kg of air – about a third of a tonne. The ***kinetic energy*** of such a mass of air moving at say 100 km/h would be over 100 kJ.

Fig. 1 Wind turbine generators

Kinetic energy

If a ***force*** acts on a body it ***accelerates*** it. For example if a force of a ***newton*** acts on a kilogram for 6 seconds then the kilogram gains a ***velocity*** of 6 m/s. If it starts from rest (zero velocity) then its average velocity during the 6 seconds would be 3 m/s and so it would travel 18 m while being accelerated. The ***work*** done is defined as the force × the distance; in this case 1 N × 18 m = 18 J (joule). Now if the force acted for a further 6 seconds then the kilogram would reach a final velocity of 12 m/s. However its average velocity for the full 12 s would be 6 m/s; since it has this average velocity for 12 seconds it travels 72 m. The total work done is 1 N × 72 m = 72 J. In other words the velocity gained is ***proportional*** to the time but the energy gained is proportional to the time squared.

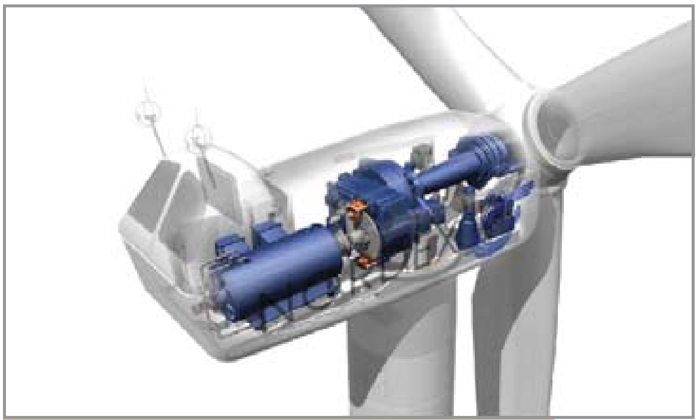


Fig. 2 The nacelle of a wind turbine generator

In general terms we can say that the kinetic energy $(KE) = \frac{1}{2} m v^2$; the examples above illustrate this ($\frac{1}{2} .1. 6^2 = 18$ and $\frac{1}{2} .1. 12^2 = 72$).

The energy of the wind

The diagram shows a ***cylindrical*** mass of air moving at a velocity v towards a wind turbine. If this air goes through the turbine in one second then the length of the cylinder in metres is numerically the same as the velocity in metres per second. In other words if the velocity of the wind is 15 m/s then the length of the cylinder of air that goes through in one second is 15 metres. If A is the ***cross-sectional area*** then the volume of the air is $A.v$ m³.

Since ***density*** is equal to mass divided by volume, mass equals density multiplied by volume. The density of air is 1.2 kg / m³ so the mass of the cylinder of air is (1.2)(A v) kg.

$$KE = \tfrac{1}{2} m v^2$$
$$= \tfrac{1}{2} (1.2)(A\ v)(v^2)$$
$$= 0.6\ A\ v^3$$

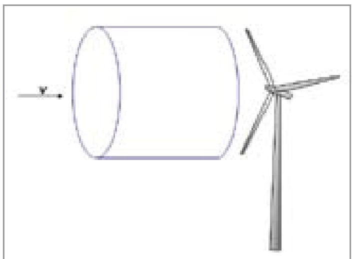


Fig. 3 A mass of air approaching a turbine

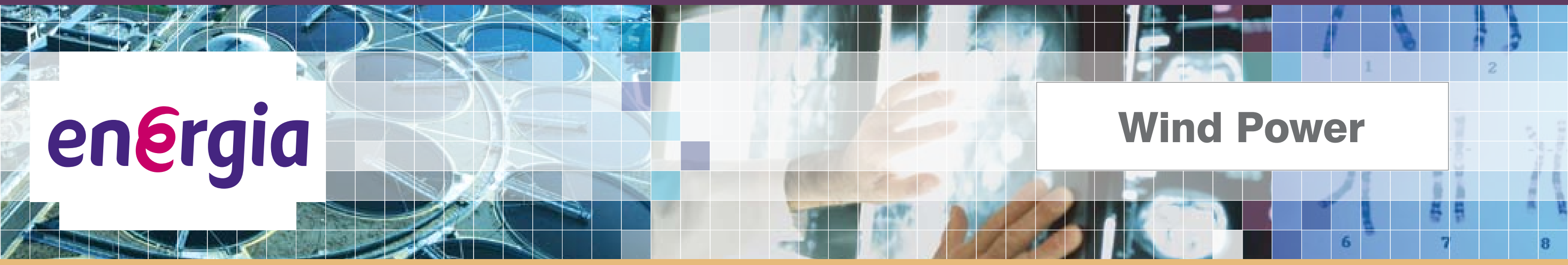
This indicates that the energy of the wind is proportional to its velocity cubed; if the wind speed doubles its energy is eight times as great.

Energy efficiency

If energy is extracted from the wind then its velocity is reduced. It is not possible to extract all its kinetic energy; that would require reducing its velocity to zero. If the blades are 25 m long then the area swept out (A) is πr^2 or approximately 2000 m².

The maximum ***theoretical efficiency*** of a wind turbine is about 59% (Betz's Limit). For any particular blade design the efficiency depends on the wind speed.

The ***pitch*** of modern turbine blades can be varied ***dynamically*** to maximise efficiency. Wind turbines are generally designed to operate most efficiently in wind speeds of around 13 m/s (55 km/h or 35 mph).



Location

Ideally wind turbines would be located in windy places. Because of the ***aerofoil*** shape of the wing of an aeroplane, air speed is higher on the upper ***convex*** surface. Smooth, curved hills can act as aerofoils; the speed of the wind is higher at the top of the hill than at the bottom.

RMS voltage

Mains voltage is not constant; the voltage on the 'live' wire alternates smoothly between -380 V and +380 V and back again fifty times a second. The 'average' voltage is therefore zero. A more useful 'average' of alternating voltages can be calculated as follows:

1) Square the instantaneous voltage values (these will all be positive)
2) Find the average squared voltage and
3) Get the square root of this value.

This special average is called the ***RMS*** (root-mean-square) voltage. If the voltage varies in ***simple harmonic motion*** (i.e. as a ***sine wave***) then the RMS voltage is the peak voltage divided by 1.414 (the square root of 2). The RMS voltage of the mains in Europe is generally 230 V. The RMS value is much more useful than the peak voltage in calculating electrical power.

Phase complications

Batteries can be connected in series to achieve a higher voltage. They can be connected in parallel to achieve a higher maximum current; however in this case their voltage must be the same. Electricity ***generators*** on the national grid are connected in parallel and so they must all produce the same voltage. However, because the voltage varies they must all be exactly in step or 'in phase'; in other words they must all produce their peak voltage at the same instant and remain in step throughout each cycle.

To complicate matters further the national grid is a three-phase system; it uses three live wires. The peak voltages are separated by one third of a cycle; they are said to be 120° out of phase. This system is more efficient for power transmission and is also more useful for large industrial electric motors.

Matching the Grid

If a generator is to be connected to the national electricity grid then it must match the mains in

1) voltage (10 kV or 30 kV)
2) frequency (50 Hz) and
3) phase.

The output voltage from a wind generator varies with the wind speed; so does its frequency (and therefore its phase). The problem can be solved by converting the output of the generator to direct current and then using sophisticated electronics to produce alternating voltage with the desired characteristics. The ***alternating current*** output can be connected to the grid regardless of the generator speed (within certain limits). The disadvantages include the cost of the extra electronics and energy loss (as heat) in the AC-DC-AC conversion process.

Ireland is one of the windiest places in Western Europe and has a tremendous potential for wind energy. Wind power can make an important contribution to Ireland's energy policy objectives of securing diverse and sustainable supplies of energy at competitive prices.

Renewable Energy and wind energy in particular is inherently sustainable; i.e. using it does not have an ongoing negative impact on life in the future. It has a number of key advantages over conventional means of electricity generation:

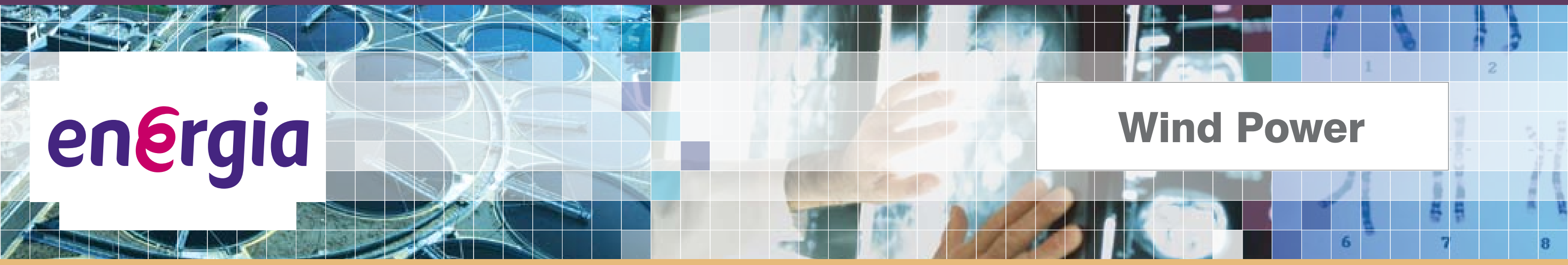
- It involves very low emissions of "greenhouse gases"
- The fuel supplies will not run out
- The fuel is free and indigenous – it is not subject to fuel price variations and does not have to be imported

Energia supplies green electricity to its customers from a range of wind farm contracts, in addition to conventional supply from Viridian's two major gas fired generating stations at Huntstown in north Dublin. Energia has in place 400 MW of long term offtake contracts on the island of Ireland and a renewable development pipeline of over 300MW..

Energia is a wholly owned subsidiary of the Viridian Group plc, which also owns Huntstown Power Station, Northern Ireland Electricity, Powerteam \Electrical Services and NIE Energy, the main electricity supplier in Northern Ireland with around 770,000 customers. The Group has a turnover of around €1.5 billion and employs around 1,500 staff.

Energia has offices in Dublin, Belfast, Cork, Galway and Omagh and employs in excess of 120 people. Energia was the first independent supplier to supply electricity in the de regulated market in 1999, the first independent power plant to supply electricity to the grid in 2002 and has also the newest power plant to supply the grid connected and fully operational in 2007.

You can find out more about Energia at **www.energia.ie** and about the Viridian Group at **www.viridiangroup.co.uk**



Wind Power

Syllabus Reference

Junior Certificate Science

Understand the relationship between pressure, force and area.

Perform simple calculations using this relationship.

Show that air had mass and occupies space.

Define and give units for work, energy and power.

Leaving Certificate Physics Ordinary and Higher Levels

Define energy.

$KE = \frac{1}{2}mv^2$

Understand conversions from one form of energy to another.

Higher Level Only.

Understand conversions from alternating current to direct current.

Understand RMS and calculations.

Know the structure and principles of operating a simple AC generator.

Learning Outcomes

On completing this section, the student will be able to:

- Explain kinetic energy and how it can be exploited by wind turbines
- Understand the basic principles involved in converting wind energy to electrical energy
- Appreciate that there are limitations to the efficiency of wind turbines, according to Betz's Law
- Recall the meaning of RMS voltage and how it can be calculated
- Appreciate the complexity of matching the outputs (voltage, frequency and phase) of the wind generator to the national electricity grid.

General Learning Points

- Air has mass, so therefore air in motion has kinetic energy.
- Work is done when a force acts on a body through a distance.
- Kinetic energy is the energy possessed by a body by virtue of its motion; $KE = \frac{1}{2} mv^2$
- A wind turbine enables the conversion of kinetic energy in wind to mechanical energy.
- The energy of the wind is proportional to its velocity cubed.
- Wind turbines extract energy and so must reduce the speed of the wind passing through them; for a turbine to be 100% efficient it would have to stop the wind, but then the blades would not turn.
- Betz's Law states that the maximum efficiency of a wind turbine is 59%.
- Ideally wind turbines should be located in areas with aerofoil shapes.
- RMS voltage values are more useful than peak values for calculating power.

- The national grid uses alternating current; all linked power lines must have the same voltage, frequency and phase.
- Complex electronic circuits are required to match the output from a wind generator to the national grid.

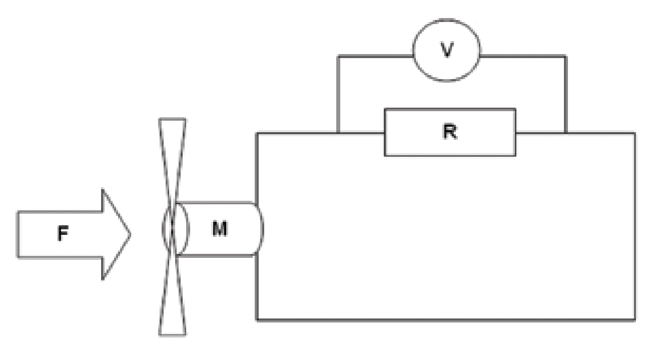
Student Activities

- Find out how aerofoils are used on aeroplanes; draw a picture illustrating how they work.
- Design turbine blades.

Aim: To design turbine blades that will effectively convert the kinetic energy in wind into mechanical energy:

You will need a fan, a small motor, dowel (about 10 cm long and 3 mm in diameter), lollipop sticks, tape, electrical leads, a small resistor and a voltmeter

In this activity the motor is used as a generator.



R - Resistor V - Voltmeter M - Motor F - Fan

Drill a hole through the centre of the length of dowel; glue the dowel to axle of the motor. Attach your turbine blades (lollipop sticks) to the dowels with adhesive tape. Set up the circuit as shown. Record the output of the turbine using the voltmeter. The power output can be calculated using the following equations:

$$V = IR$$
$$P = V^2/R$$

Set the blades at a variety of angles and record the output.

Change the number of blades.

What is the best number of blades?

What is the most efficient angle for the blades?

You may be able to construct a version with blades whose pitch can be adjusted. This would make it easier to find the most efficient angle.

Does the most efficient angle vary with the wind speed?

energia

Wind Power

True/False Questions

a) A kilogram of still air has a kinetic energy of 1000 joules. **T F**

b) If a force of one newton acts on a body it gains velocity. **T F**

c) Work = force × mass **T F**

d) The energy of the wind is proportional to its velocity cubed. **T F**

e) To extract all the kinetic energy from the wind, wind speed would have to be reduced to zero. **T F**

f) Changing the pitch of a blade can increase its efficiency. **T F**

g) The average of an alternating current is zero. **T F**

h) Batteries connected in series can produce a higher maximum current. **T F**

Check your answers to these questions on www.sta.ie

Examination Questions

Leaving Certificate Physics, 2006 Higher Level

What is an electric current? Define the ampere, the SI unit of current.

Describe an experiment to demonstrate the principle on which the definition of the ampere is based.

Sketch a graph to show the relationship between current and time for

(i) alternating current;

(ii) direct current.

The peak voltage of the mains electricity is 325 V. Calculate the rms voltage of the mains?

Junior Certificate Science, 2008 Higher Level

Nikola Tesla (1856-1943) showed at the Frankfurt Fair in 1891 that alternating current could be transmitted over much longer distances than direct current. This is why the electricity supply to our homes is alternating current.

Distinguish between alternating and direct current.

What is the average voltage of domestic alternating current in Ireland?

For further examples of past questions check www.sta.ie

Did You Know?

- Early Egyptians (3200 BC) used wind to sail boats on the river Nile.
- The first windmills were developed as early as 950 AD in Persia (Iran). They were used to grind corn and pump water.
- In 1888 an American inventor, Charles Brush, built a giant windmill on his property and supplied electricity to his entire house.
- In 2007 only 1% – 2% of the world's energy supply came from wind energy.
- An ideal wind speed for a wind turbine depends on its size and strength. Very high wind speed are not ideal.
- February 2008, Minister Eamon Ryan decided to introduce a support mechanism for the development of Irish off-shore wind farms. The project will cost €13 – €15 billion and should produce 4000 MW.
- In 2004 construction started on the first stage of Ireland largest wind farm. Its seven turbines produce 3.6 MW each. It may eventually eliminate Ireland's need to import one million tonnes of coal each year.
- The physically largest wind turbine in the world is in Hawaii. Its two blades are each 50 m long and its output is 3 MW.
- If mechanical energy from a wind turbine is used directly by machinery to pump water or crush stones for example, the machine is usually called a windmill. If the mechanical energy is converted to electricity, the machine is usually called a wind generator or wind turbine.
- The most common type of wind turbine has a horizontal axis. These turbines have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind.

  Vertical-axis turbines – also known as Savonius wind turbines – are less common but have the advantage that they can be driven by wind from any direction. They are not as efficient as the horizontal axis type because they are nearer the ground where the wind speed tends to be lower.

Biographical Notes

Daniel Bernoulli
(1770 – 1782)

Bernoulli is remembered for his application of mathematics to mechanics, especially fluid mechanics. He was the first to try to formulate the kinetic theory of gases. He contributed greatly to the field of aerodynamics with the development of what is now known as Bernoulli's Principle. This states that an increase in velocity of fluid flow occurs simultaneously with a decrease in pressure, or a decrease in the fluid gravitational potential energy. The lift produced by the wings of an aeroplane can be analysed by applying Bernoulli's Principle. The air flowing over the top of a wing or turbine blade is moving faster than the air flowing past the underside of the wing or blade. The air pressure on the top is therefore lower than the air pressure on the under-side; this pressure difference produces a net force.

Revise the Terms

Can you recall the meaning of the following terms?

accelerate, aerofoil, convex, cross-sectional area, density, dynamically, force, generator, green electricity, kinetic energy, mass, newton, pitch, proportional, RMS, renewable, simple harmonic motion, sine wave, theoretical efficiency, wind farm, theoretical, velocity, work.

Check the Glossary of Terms for this lesson at www.sta.ie