

Energy and power generation – Sankey diagram

ENERGY CONVERSIONS

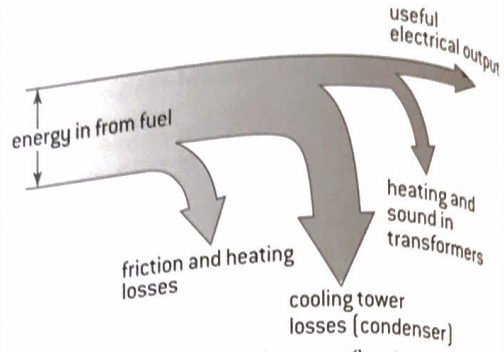
The production of electrical power around the world is achieved using a variety of different systems, often starting with the release of thermal energy from a fuel. In principle, thermal energy can be completely converted to work in a single process, but the continuous conversion of this energy into work implies the use of machines that are continuously repeating their actions in a fixed cycle. Any cyclical process must involve the transfer of some energy from the system to the surroundings that is no longer available to perform useful work. This unavailable energy is known as **degraded energy**, in accordance with the principle of the second law of thermodynamics (see page 162).

Energy conversions are represented using **Sankey diagrams**. An arrow (drawn from left to right) represents the energy changes taking place. The width of the arrow represents the power or energy involved at a given stage. Created or degraded energy is shown with an arrow up or down.

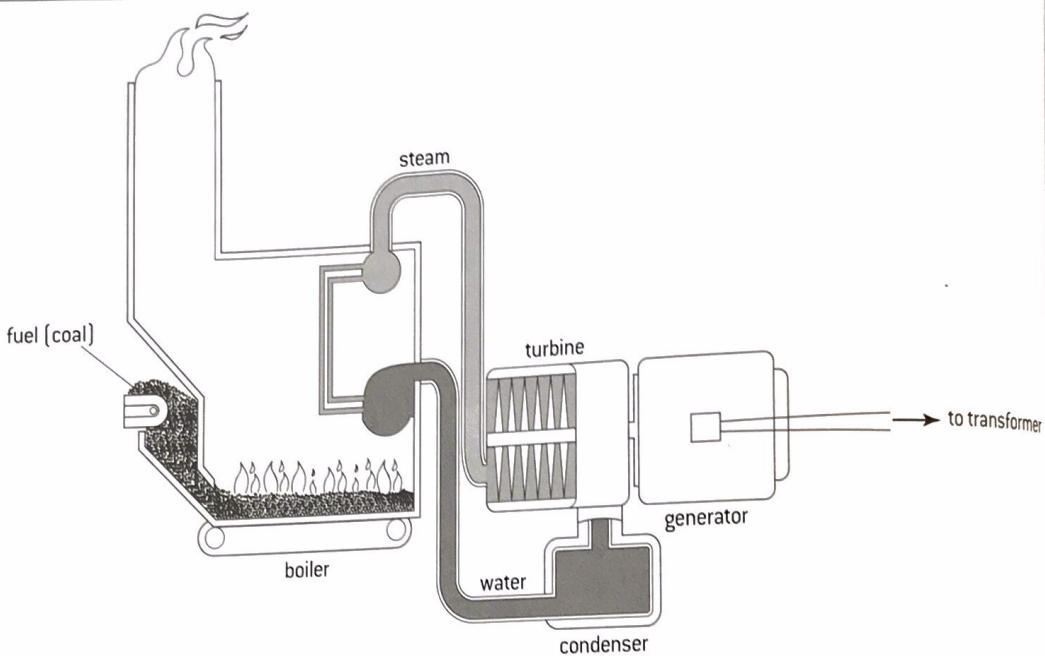
Note that Sankey diagrams are to scale. The width of the useful electrical output in the diagram on the right is 2.0 mm compared with 12.0 mm for the width of the total energy from the fuel. This represents an overall efficiency of 16.7%.

ELECTRICAL POWER PRODUCTION

In all electrical power stations the process is essentially the same. A fuel is used to release thermal energy. This thermal energy is used to boil water to make steam. The steam is used to turn turbines and the motion of the turbines is used to generate electrical energy. Transformers alter the potential difference (see page 114).



Sankey diagram representing the energy flow in a typical power station



Electrical energy generation

POWER

Power is defined as the rate at which energy is converted. The units of power are J s^{-1} or W.

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

Primary energy sources

RENEWABLE / NON-RENEWABLE ENERGY SOURCES

The law of conservation of energy states that energy is neither created nor destroyed, it just changes form. As far as human societies are concerned, if we wish to use devices that require the input of energy, we need to identify sources of energy. **Renewable** sources of energy are those that cannot be used up, whereas **non-renewable** sources of energy can be used up and eventually run out.

Renewable sources	Non-renewable sources
hydroelectric	coal
photovoltaic cells	oil
active solar heaters	natural gas
wind	nuclear
biofuels	

Sometimes the sources are hard to classify so care needs to be taken when deciding whether a source is renewable or not. One point that sometimes worries students is that the Sun will eventually run out as a source of energy for the Earth, so no source is perfectly renewable! This is true, but all of these sources are considered from the point of view of life on Earth. When the Sun runs out, then so will life on Earth. Other things to keep in mind include:

- Nuclear sources (both fission and fusion) consume a material as their source so they must be non-renewable.

On the other hand, the supply available can make the source **effectively** renewable (fusion).

- It is possible for a fuel to be managed in a renewable or a non-renewable way. For example, if trees are cut down as a source of wood to burn then this is clearly non-renewable. It is, however, possible to replant trees at the same rate as they are cut down. If this is properly managed, it could be a renewable source of energy.

Of course these possible sources must have got their energy from somewhere in the first place. Most of the energy used by humans can be traced back to energy radiated from the Sun, but not quite all of it. Possible sources are:

- the Sun's radiated energy
- gravitational energy of the Sun and the Moon
- nuclear energy stored within atoms
- the Earth's internal heat energy.

Although you might think that there are other sources of energy, the above list is complete. Many everyday sources of energy (such as coal or oil) can be shown to have derived their energy from the Sun's radiated energy. On the industrial scale, electrical energy needs to be generated from another source. When you plug anything electrical into the mains electricity you have to pay the electricity-generating company for the energy you use. In order to provide you with this energy, the company must be using one (or more) of the original list of sources.

SPECIFIC ENERGY AND ENERGY DENSITY

Two quantities are useful to consider when making comparisons between different energy sources – the **specific energy** and the **energy density**.

Specific energy provides a useful comparison between fuels and is defined as the energy liberated per unit mass of fuel consumed. Specific energy is measured in J kg^{-1}

specific energy

$$= \frac{\text{energy released from fuel}}{\text{mass of fuel consumed}}$$

Fuel choice can be particularly influenced by specific energy when the fuel needs to be transported: the greater the mass of fuel that needs to be transported, the greater the cost.

Energy density is defined as the energy liberated per unit volume of fuel consumed. The unit is J m^{-3}

energy density

$$= \frac{\text{energy release from fuel}}{\text{volume of fuel consumed}}$$

COMPARISON OF ENERGY SOURCES

Fuel	Renewable?	CO ₂ emission	Specific energy (MJ kg^{-1}) (values vary depending on type)	Energy density (MJ m^{-3})
Coal	No	Yes	22–33	23,000
Oil	No	Yes	42	36,500
Gas	No	Yes	54	37
Nuclear (uranium)	No	No	8.3×10^7	1.5×10^{12}
Waste	No	Yes	10	variable
Solar	Yes	No	n/a	n/a
Wind	Yes	No	n/a	n/a
Hydro – water stored in dams	Yes	No	n/a	n/a
Tidal	Yes	No	n/a	n/a
Pumped storage	n/a	No	n/a	n/a
Wave	Yes	No	n/a	n/a
Geothermal	Yes	No	n/a	n/a
Biofuels e.g. ethanol	Some types	Yes	30	21,000

Fossil fuel power production

ORIGIN OF FOSSIL FUEL

Coal, oil and natural gas are known as **fossil fuels**. These fuels have been produced over a timescale that involves tens or hundreds of millions of years from accumulations of dead matter. This matter has been converted into fossil fuels by exposure to the very high temperatures and pressure that exist beneath the Earth's surface.

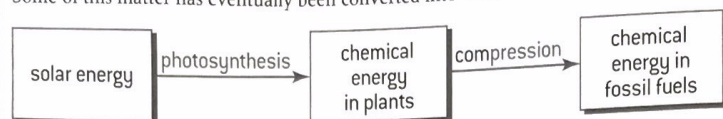
Coal is formed from the dead plant matter that used to grow in swamps. Layer upon layer of decaying matter decomposed.

As it was buried by more plant matter and other substances, the material became more compressed. Over the geological timescale this turned into coal.

Oil is formed in a similar manner from the remains of microscopic marine life. The compression took place under the sea. Natural gas, as well as occurring in underground pockets, can be obtained as a by-product during the production of oil. It is also possible to manufacture gas from coal.

ENERGY TRANSFORMATIONS

Fossil fuel power stations release energy in fuel by burning it. The thermal energy is then used to convert water into steam that once again can be used to turn turbines. Since all fossil fuels were originally living matter, the original source of this energy was the Sun. For example, millions of years ago energy radiated from the Sun was converted (by photosynthesis) into living plant matter. Some of this matter has eventually been converted into coal.



Energy storage in fossil fuels

EXAMPLE

Use the data on this page and the previous page to calculate the typical rate (in tonnes per hour) at which coal must be supplied to a 500 MW coal fired power station.

Answer

$$\text{Electrical power supply} = 500 \text{ MW} = 5 \times 10^8 \text{ J s}^{-1}$$

$$\begin{aligned} \text{Power released from fuel} &= 5 \times 10^8 / \text{efficiency} \\ &= 5 \times 10^8 / 0.35 \\ &= 1.43 \times 10^9 \text{ J s}^{-1} \end{aligned}$$

$$\begin{aligned} \text{Rate of consumption of coal} &= 1.43 \times 10^9 / 3.3 \times 10^7 \text{ kg s}^{-1} \\ &= 43.3 \text{ kg s}^{-1} \\ &= 43.3 \times 60 \times 60 \text{ kg hr}^{-1} \\ &= 1.56 \times 10^5 \text{ kg hr}^{-1} \\ &\approx 160 \text{ tonnes hr}^{-1} \end{aligned}$$

EFFICIENCY OF FOSSIL FUEL POWER STATIONS

The efficiency of different power stations depends on the design. At the time of publishing, the following figures apply.

Fossil fuel	Typical efficiency	Current maximum efficiency
Coal	35%	42%
Natural gas	45%	52%
Oil	38%	45%

Note that thermodynamic considerations limit the maximum achievable efficiency (see page 163).

ADVANTAGES AND DISADVANTAGES

Advantages

- Very high 'specific energy' and 'energy density' – a great deal of energy is released from a small mass of fossil fuel.
- Fossil fuels are relatively easy to transport.
- Still cheap when compared to other sources of energy.
- Power stations can be built anywhere with good transport links and water availability.
- Can be used directly in the home to provide heating.

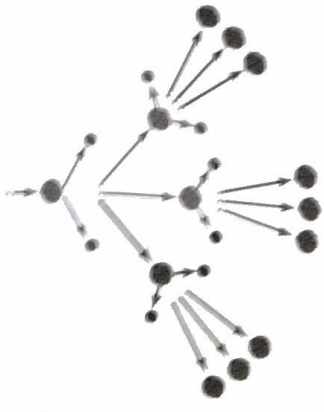
Disadvantages

- Combustion products can produce pollution, notably acid rain.
- Combustion products contain 'greenhouse' gases.
- Extraction of fossil fuels can damage the environment.
- Non-renewable.
- Coal-fired power stations need large amounts of fuel.

Nuclear power – process

PRINCIPLES OF ENERGY PRODUCTION

Many nuclear power stations use uranium-235 as the fuel. This fuel is not burned – the release of energy is achieved using a fission reaction. An overview of this process is described on page 74. In each individual reaction, an incoming neutron causes a uranium nucleus to split apart. The fragments are moving fast. In other words the temperature is very high. Moving the fragments are more neutrons. If these neutrons go on to initiate further reactions then a chain reaction is created.



The design of a nuclear reactor needs to ensure that, on average, only one neutron from each reaction goes on to initiate a further reaction. If more reactions took place then the number of reactions would increase all the time and the chain reaction would run out of control. If fewer reactions took place, then the number of reactions would be decreasing and the fission process would soon stop.

The chance that a given neutron goes on to cause a fission reaction depends on several factors. Two important ones are:

- the number of potential nuclei 'in the way'
- the speed (or the energy) of the neutrons.

As a general trend, as the size of a block of fuel increases so do the chances of a neutron causing a further reaction (before it is lost from the surface of the block). As the fuel is assembled together a stage is reached when a chain reaction can occur. This happens when a so-called critical mass of fuel has been assembled. The exact value of the critical mass depends on the exact nature of the fuel being used and the shape of the assembly.

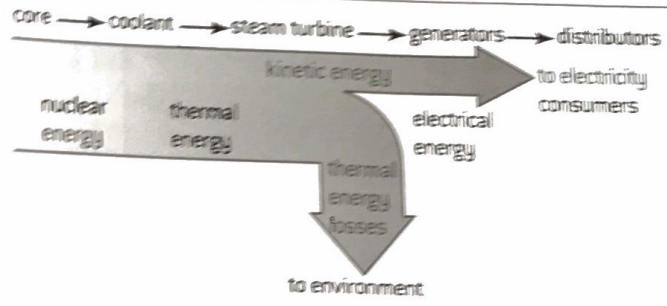
There are particular neutron energies that make them more likely to cause nuclear fission. In general, the neutrons created by the fission process are moving too fast to make reactions likely. Before they can cause further reactions the neutrons have to be slowed down.

MODERATOR, CONTROL RODS AND HEAT EXCHANGER

Three important components in the design of all nuclear reactors are the **moderator**, the **control rods** and the **heat exchanger**.

- Collisions between the neutrons and the nuclei of the moderator slow them down and allow further reactions to take place.
- The control rods are movable rods that readily absorb neutrons. They can be introduced or removed from the reaction chamber in order to control the chain reaction.
- The heat exchanger allows the nuclear reactions to occur in a place that is sealed off from the rest of the environment. The reactions increase the temperature in the core. This thermal energy is transferred to heat water and the steam that is produced turns the turbines.

A general design for one type of nuclear reactor (PWR or pressurized water reactor) is shown here. It uses water as the moderator and as a coolant.



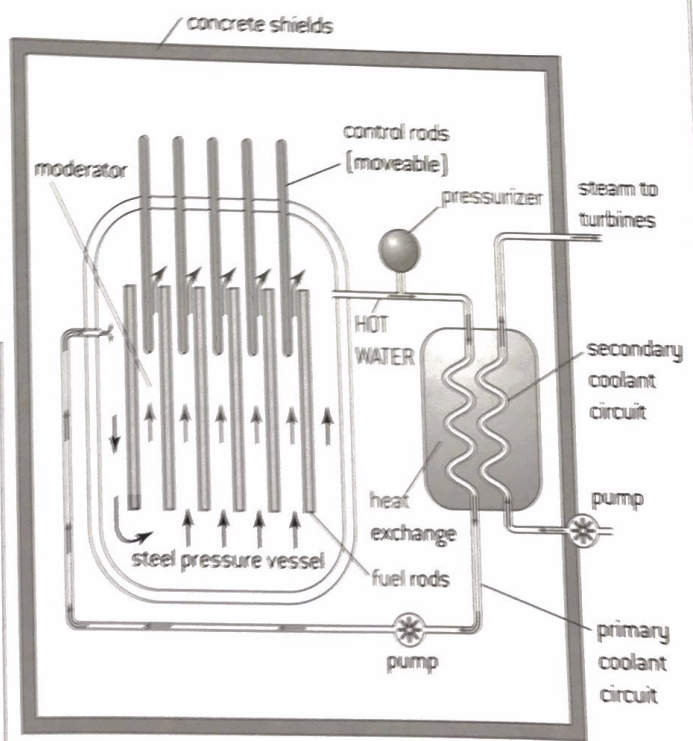
ADVANTAGES AND DISADVANTAGES

Advantages

- Extremely high 'specific energy' – a great deal of energy is released from a very small mass of uranium.
- Reserves of uranium large compared to oil.

Disadvantages

- Process produces radioactive nuclear waste that is currently just stored.
- Larger possible risk if anything should go wrong.
- Non-renewable (but should last a long time).



Pressurized water nuclear reactor (PWR)

Nuclear power – safety and risks

ENRICHMENT AND REPROCESSING

Naturally occurring uranium contains less than 1% of uranium-235. Enrichment is the process by which this percentage composition is increased to make nuclear fission more likely.

In addition to uranium-235, plutonium-239 is also capable of sustaining fission reactions. This nuclide is formed as a by-product of a conventional nuclear reactor. A uranium-238 nucleus can capture fast-moving neutrons to form uranium-239. This undergoes β -decay to neptunium-239 which undergoes further β -decay to plutonium-239:



Reprocessing involves treating used fuel waste from nuclear reactors to recover uranium and plutonium and to deal with other waste products. A fast breeder reactor is one design that utilizes plutonium-239.

HEALTH, SAFETY AND RISK

Issues associated with the use of nuclear power stations for generation of electrical energy include:

- If the control rods were all removed, the reaction would rapidly increase its rate of production. Completely uncontrolled nuclear fission would cause an explosion and **thermal meltdown** of the core. The radioactive material in the reactor could be distributed around the surrounding area causing many fatalities. Some argue that the terrible scale of such a disaster means that the use of nuclear energy is a risk not worth taking. Nuclear power stations could be targets for terrorist attacks.
- The reaction produces radioactive nuclear waste. While much of this waste is of a low level risk and will radioactively decay within decades, a significant amount of material is produced which will remain dangerously radioactive for millions of years. The current solution is to bury this waste in geologically secure sites.
- The uranium fuel is mined from underground and any mining operation involves significant risk. The ore is also radioactive so extra precautions are necessary to protect the workers involved in uranium mines.
- The transportation of the uranium from the mine to a power station and of the waste from the nuclear power station to the reprocessing plant needs to be secure and safe.
- By-products of the civilian use of nuclear power can be used to produce nuclear weapons.

NUCLEAR WEAPONS

A nuclear power station involves controlled nuclear fission whereas an uncontrolled nuclear fission produces the huge amount of energy released in nuclear weapons. Weapons have been designed using both uranium and plutonium as the fuel. Issues associated with nuclear weapons include:

- Moral issues associated with any weapon of aggression that is associated with warfare. Nuclear weapons have such destructive capability that since the Second World War the threat of their deployment has been used as a deterrent to prevent non-nuclear aggressive acts against the possessor of nuclear capability.
- The unimaginable consequences of a nuclear war have forced many countries to agree to non-proliferation treaties, which attempt to limit nuclear power technologies to a small number of nations.
- A by-product of the peaceful use of uranium for energy production is the creation of plutonium-239 which could be used for the production of nuclear weapons. Is it right for the small number of countries that already have nuclear capability to prevent other countries from acquiring that knowledge?

FUSION REACTORS

Fusion reactors offer the theoretical potential of significant power generation without many of the problems associated with current nuclear fission reactors. The fuel used, hydrogen, is in plentiful supply and the reaction (if it could be sustained) would not produce significant amounts of radioactive waste.

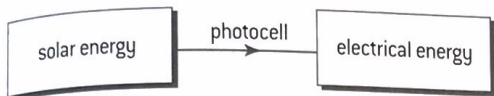
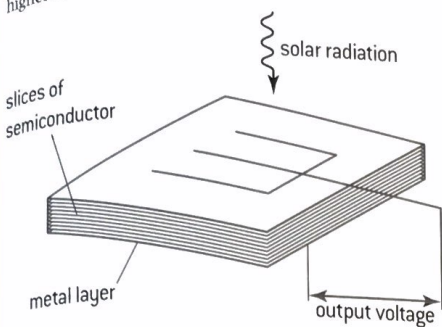
The reaction is the same as takes place in the Sun (as outlined on page 76) and requires creating temperatures high enough to ionize atomic hydrogen into a plasma state (this is the 'fourth state of matter', in which electrons and protons are not bound in atoms but move independently). Currently the principal design challenges are associated with maintaining and confining the plasma at sufficiently high temperature and density for fusion to take place.

Solar power and hydroelectric power

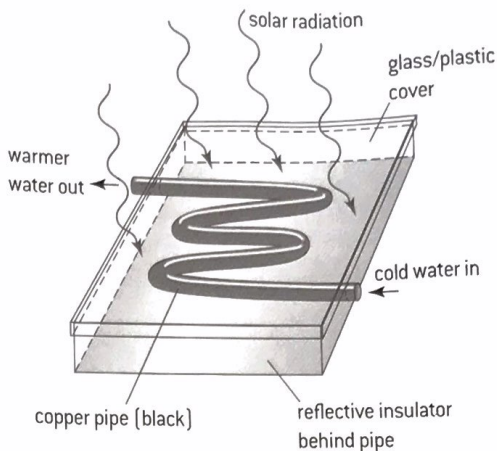
SOLAR POWER (TWO TYPES)

There are two ways of harnessing the radiated energy that arrives at the Earth's surface from the Sun.

A **photovoltaic cell** (otherwise known as a solar cell or photocell) converts a portion of the radiated energy directly into a potential difference ('voltage'). It uses a piece of semiconductor to do this. Unfortunately, a typical photovoltaic cell produces a very small voltage and it is not able to provide much current. They are used to run electrical devices that do not require a great deal of energy. Using them in series would generate higher voltages and several in parallel can provide a higher current.



An **active solar heater** (otherwise known as a solar panel) is designed to capture as much thermal energy as possible. The hot water that it typically produces can be used domestically and would save on the use of electrical energy.



ADVANTAGES AND DISADVANTAGES

Advantages

- Very 'clean' production – no harmful chemical by-products.
- Renewable source of energy.
- Source of energy is free.

Disadvantages

- Can only be utilized during the day.
- Source of energy is unreliable – could be a cloudy day.
- A very large area would be needed for a significant amount of energy.

HYDROELECTRIC POWER

The source of energy in a hydroelectric power station is the gravitational potential energy of water. If water is allowed to move downhill, the flowing water can be used to generate electrical energy.

The water can gain its gravitational potential energy in several ways.

- As part of the 'water cycle', water can fall as rain. It can be stored in large reservoirs as high up as is feasible.
- Tidal power schemes trap water at high tides and release it during a low tide.
- Water can be pumped from a low reservoir to a high reservoir. Although the energy used to do this pumping must be more than the energy regained when the water flows back down hill, this '**pumped storage**' system provides one of the few large-scale methods of storing energy.

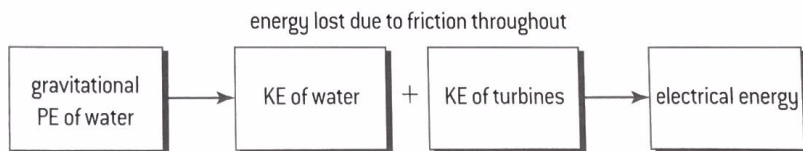
ADVANTAGES AND DISADVANTAGES

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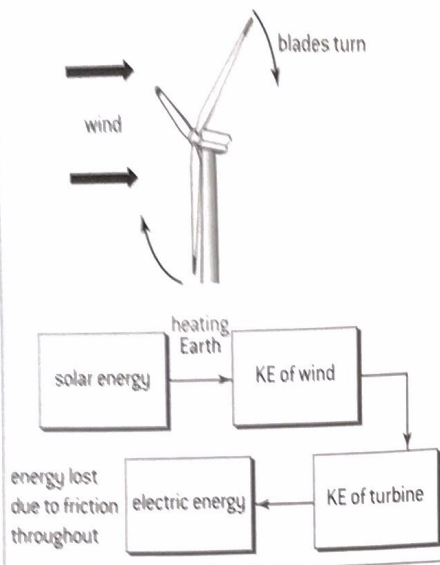
- Can only be utilized in particular areas.
- Construction of dams will involve land being submerged under water.



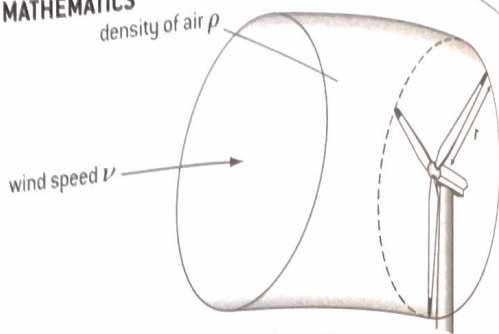
Wind power and other technologies

ENERGY TRANSFORMATIONS

There is a great deal of kinetic energy involved in the winds that blow around the Earth. The original source of this energy is, of course, the Sun. Different parts of the atmosphere are heated to different temperatures. The temperature differences cause pressure differences, due to hot air rising or cold air sinking, and thus air flows as a result.



MATHEMATICS



The area 'swept out' by the blades of the turbine $= A = \pi r^2$
 In one second the volume of air that passes the turbine $= vA$
 So mass of air that passes the turbine in one second $= vA\rho$
 Kinetic energy m available per second $= \frac{1}{2} mv^2$
 $= \frac{1}{2} (vA\rho)v^2$
 $= \frac{1}{2} A\rho v^3$

In other words, power available $= \frac{1}{2} A\rho v^3$

In practice, the kinetic energy of the incoming wind is easy to calculate, but it cannot all be harnessed as the air must continue to move – in other words the wind turbine cannot be one hundred per cent efficient. A doubling of the wind speed would mean that the available power would increase by a factor of eight.

ADVANTAGES AND DISADVANTAGES

Advantages

- Very 'clean' production – no harmful chemical by-products.
- Renewable source of energy.
- Source of energy is free.

Disadvantages

- Source of energy is unreliable – could be a day without wind.
- A very large area would need to be covered for a significant amount of energy.

- Some consider large wind generators to spoil the countryside.
- Can be noisy.
- Best positions for wind generators are often far from centres of population.

SECONDARY ENERGY SOURCES

By far the most common primary energy sources in use worldwide are the three main fossil fuels: oil, coal and natural gas. With the inclusion of uranium, at the time of writing this guide, this accounts for 90% of the world's energy consumption. Other primary fuels include the renewables: solar, wind, tidal, biomass and geothermal.

With global energy demand expected to rise in the future, the hope is that developments with renewable energy can help to reduce the dependence on fossil fuels.

Primary energy sources are not convenient for individual users and typically a conversion process takes place that results in a

secondary energy source that can be widely used in society.

The most common secondary sources are electrical energy (a very versatile secondary source) or refined fuels (e.g. petrol).

The storage of electrical energy is a challenge, with everyday devices (e.g. batteries or capacitors) having a very limited capability when compared with typical everyday demands. Power companies need to vary the generation of electrical energy to match consumer demand. Currently pumped storage hydroelectric systems are the only viable large-scale method of storing spare electrical energy capacity for future use. The efficiency of a typical system is approximately 75% meaning that one quarter of the energy supplied is wasted.

NEW AND DEVELOPING TECHNOLOGIES

It is impossible to predict technological developments that are going to take place over the coming years. Current models, however, predict a continuing dependence on the use of fossil fuels for many years to come. The hope is that we will be able to decrease this dependency over time. It is important to be

aware of the development of new technologies particularly those associated with:

- renewable energy sources
- improving the efficiency of our energy conversion process.