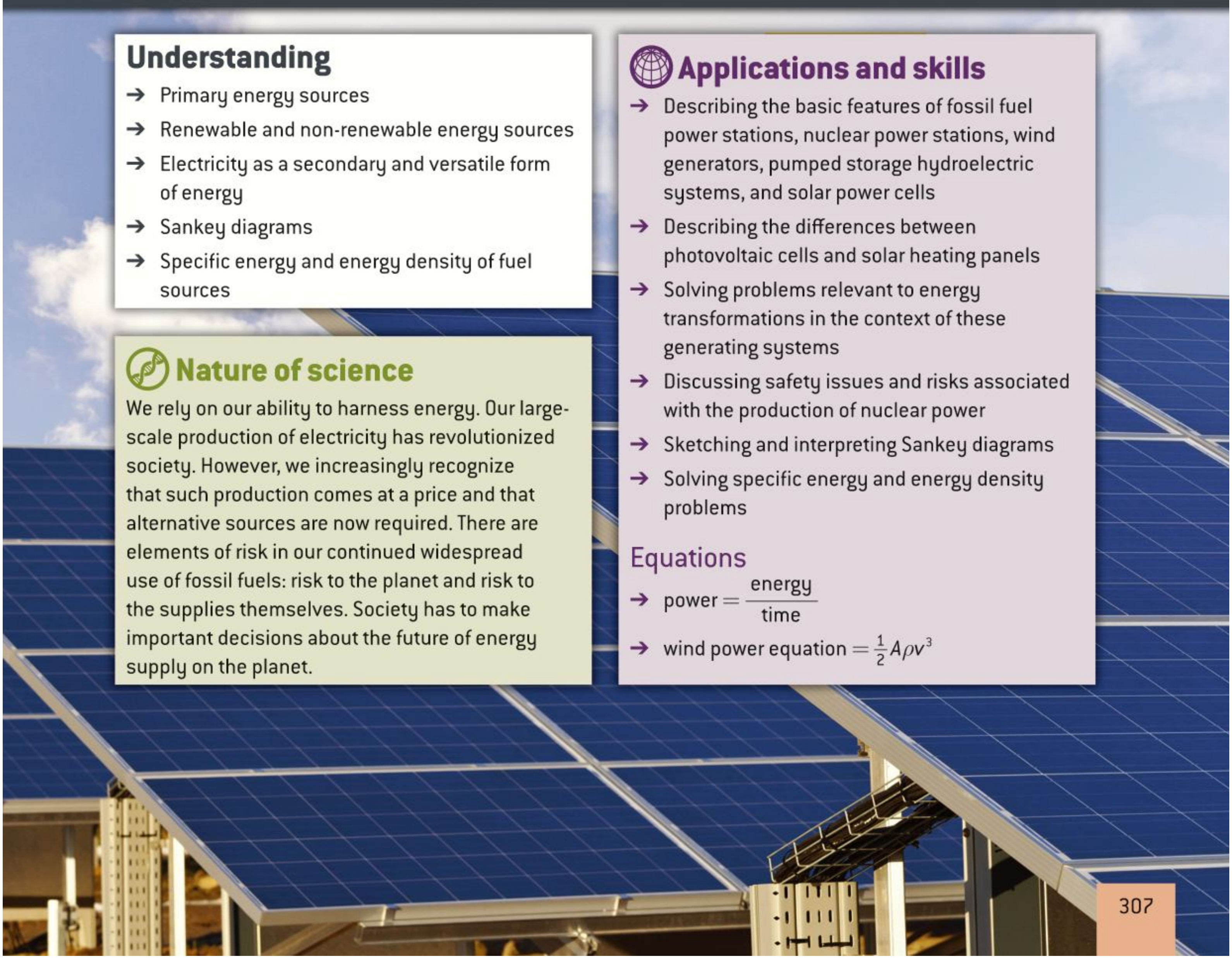
# 8 ENERGY PRODUCTION

## Introduction

In Topic 2 we looked at the principles behind the transfer of energy from one form to another. We now look in detail at sources that provide the energy we use every day. The provision of energy is a global issue. On the one hand, fossil fuel reserves are limited and these fuels can be a source of pollution and greenhouse gases, yet they are a convenient and energy-rich resource. The development of renewable energy sources continues but they are not yet at a point where they can provide all that we require. Political rhetoric and emotion often obscure scientific assessments about energy resources. Everyone – not just scientists – needs a clear understanding of the issues involved in order to make sound judgements about the future of our energy provision.

# 8.1 Energy sources



### Understanding

- Primary energy sources
- Renewable and non-renewable energy sources
- Electricity as a secondary and versatile form of energy
- Sankey diagrams
- Specific energy and energy density of fuel sources

### Nature of science

We rely on our ability to harness energy. Our large-scale production of electricity has revolutionized society. However, we increasingly recognize that such production comes at a price and that alternative sources are now required. There are elements of risk in our continued widespread use of fossil fuels: risk to the planet and risk to the supplies themselves. Society has to make important decisions about the future of energy supply on the planet.

### Applications and skills

- Describing the basic features of fossil fuel power stations, nuclear power stations, wind generators, pumped storage hydroelectric systems, and solar power cells
- Describing the differences between photovoltaic cells and solar heating panels
- Solving problems relevant to energy transformations in the context of these generating systems
- Discussing safety issues and risks associated with the production of nuclear power
- Sketching and interpreting Sankey diagrams
- Solving specific energy and energy density problems

### Equations

- $\text{power} = \frac{\text{energy}}{\text{time}}$
- $\text{wind power equation} = \frac{1}{2}A\rho v^3$

## Primary and secondary energy

We use many different types of energy and energy source for our heating and cooking, transport, and for the myriad other tasks we undertake in our daily lives. There is a distinction between two basic types of energy source we use: primary sources and secondary sources.

A **primary source** is one that has not been transformed or converted before use by the consumer, so a fossil fuel – coal, for example – burnt directly in a furnace to convert chemical potential energy into the internal energy of the water and surroundings is an example of a primary source. Another example is the kinetic energy in the wind that can be used to generate electricity (a secondary source) or to do mechanical work such as in a windmill (a device used, for example, to grind corn or to pump up water from underground).

The definition of a **secondary source** of energy is one that results from the transformation of a primary source. The electrical energy we use is generated from the conversion of a primary source of energy. This makes electrical energy our most important secondary source. Another developing secondary source is hydrogen, although this is, at the moment, much less important than electricity. Hydrogen makes a useful fuel because it burns with oxygen releasing relatively large amounts of energy (you will know this if you have ever observed hydrogen exploding with oxygen in the lab). The product of this reaction (water) has the advantage that it is not a pollutant. However, hydrogen does not exist in large quantities in the atmosphere. So energy from a primary source would have to be used to form hydrogen from hydrocarbons, or by separating water into hydrogen and oxygen. The hydrogen could then be transported to wherever it is to be used as a source of energy.

## Renewable and non-renewable energy sources

The primary sources can themselves be further divided into two groups: **renewable** and **non-renewable**. Renewable sources, such as biomass, can be replenished in relatively short times (on the scale of a human lifetime), whereas others such as wind and water sources are continually generated from the Sun's energy. Non-renewable sources, on the other hand, can be replaced but only over very long geological times.

A good way to classify renewable and non-renewable resources is by the rates at which they are being consumed and replaced. Coal and oil, both non-renewable, are produced when vegetable matter buried deep below ground is converted through the effects of pressure and high temperature. The time scale for production is hundreds of millions of years (the deposits of coal on Earth were formed from vegetation that lived and died during the Carboniferous geological period, roughly 300 million years ago). There are mechanisms active today that are beginning the process of creating fossil fuels in suitable wetland areas of the planet, but our present rate of usage of these fossil fuels is far greater than the rate at which they are being formed.

On the other hand, renewable fuels such as biomass use biological materials such as trees that were only recently alive. Such sources can be grown to maturity relatively quickly and then used for energy conversion. The rate of usage of the fuels can be similar to the rate at which they are being grown.

There are further advantages in the use of biomass and other renewable sources, where the material has been produced recently. When these renewable resources are converted, they will release carbon dioxide (one of the greenhouse gases) back into the atmosphere. But this is "new carbon" that was taken from the atmosphere and trapped in the biomass material relatively recently. The conversion of fossil fuels releases carbon dioxide into the atmosphere that was fixed in the fossil fuels hundreds of millions of years ago. The carbon dioxide content of the atmosphere was more than 150% greater in the Carboniferous period than it is today, and thus the burning of fossil fuels increases the overall amount of this greenhouse gas in the present-day atmosphere.

## Types of energy sources

In Topic 2 there was a list of some of the important energies available to us. Some were mechanical in origin. Other energies were related to the properties of bulk materials and atomic nuclei. Of particular importance are the nuclear reactions, both fission and fusion, that you met in Topic 7.

### Primary sources

The table below gives an indication of many of the primary sources that are used in the world today – although not all sources can be found in all locations. The use of geothermal energy, for example, requires that the geology of the location has hot rocks suitably placed below the surface.

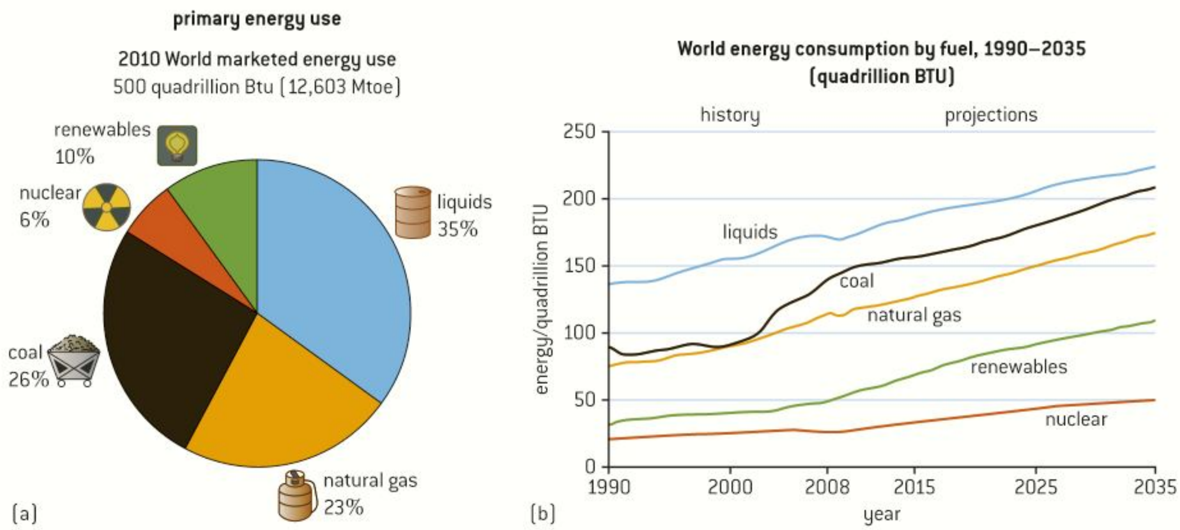
| Energy sources | | | |
|---|---|---|---|
| | | **source** | **Energy form** |
| Non-renewable sources | Nuclear fuels | uranium-235 | nuclear |
| | Fossil fuels | crude oil | chemical potential |
| | | coal | |
| | | natural gas | |
| Renewable sources | | Sun | radiant (solar) |
| | | water | kinetic |
| | | wind | kinetic |
| | | biomass | chemical potential |
| | | geothermal | internal |

Not all the primary sources in the table are necessarily used to provide electricity as a secondary source, it depends on local circumstances. A water wheel using flowing water in a river can be used to grind corn in a farming community rather than be harnessed to an electrical generator. A solar furnace may be used in an African village to boil water or to cook, while photovoltaic cells may produce the electrical energy required by the community. In some situations, this is often a better solution than that of changing all the solar energy to an electrical form that has to be reconverted subsequently.

Some energy is always degraded into an internal form in a conversion. Nevertheless, many of the world's primary sources are used to provide electricity using a power station where the secondary source output is in the form of electrical energy.

## Primary energy use

Data for the present usage of various energy sources are readily available from various sources on the Internet. Figure 1 shows two examples of data released by the US Department of Energy.




▲ Figure 1 Total world energy usage (US Energy Information Administration, report #DOE/EIA-0484 (2010)).

The first example (figure 1(a)) is a chart that shows the various energy sectors that account for the total world usage of energy sold on the open market in 2010. There are two units here that are common in energy data. When you carry out your own investigations of global energy usage, you will almost certainly come across these non-SI units.

- The British Thermal Unit (BTU) is still used in energy resource work; it was historically very important. The BTU is defined as the energy required to raise one British pound of water (about 0.5 kg) through 1 °F (a change of roughly 0.6 K) and is equivalent to about 1000 J.
- Mtoe stands for "million tonnes of oil equivalent". One tonne of oil equivalent is the energy released when one tonne (1000 kg) of crude oil is burnt; this is roughly 42 GJ, leading to a value of $5 \times 10^{20}$ J for 2010 usage total.

The US chart uses an unusual multiplier – the energy total for 2010 is given as 500 quadrillion. The quadrillion is either $10^{15}$ or $10^{24}$ depending on the definition used. In this particular case it is $10^{15}$ and the total world energy usage in 2010 was about $5 \times 10^{17}$ BTU, which also leads to about $5 \times 10^{20}$ J.

The second chart (figure 1(b)) gives a projection from 1990 up to the year 2035 for world energy usage. Adding the various contributions to the total indicates that the US Department of Energy predicts a world total energy usage in 2035 of about $7.5 \times 10^{20}$ J; a 50% increase on the 2010 figure. One feature of this graph (in the light of the enhanced greenhouse effect that we shall discuss later) is that the relative proportions of the various energy sources do not appear to be changing greatly over the timescale of the prediction.

## Investigate!

### Where are we today?

- Textbooks are of necessity out-of-date! They represent the position on the day that part of the book was completed. So the examples here are to give you some insight into the type and quantity of data that are available to you. But they are not to be regarded either as the last word or information that you must memorize for the examination. All the resources shown here were accessed on the Internet without difficulty.
- You should search for the latest tables and graphs using the source information printed with the graphs. (This is known as a bibliographic reference and it is essential to quote this when you use other people's data.) Search for the latest data and discuss it in class. Divide up the jobs so that students bring different pieces of data to the discussion. Ask yourselves: What are the trends now? Has the position changed significantly since this book was written?
- Science does not stand still, and this area of environmental science is moving as quickly as any other discipline. You need to have accurate data if you are to make informed judgments.
- Predictions are based on assumptions. They cannot predict  critical events that might alter the situation e.g. a disaster triggered by a tsunami.

## Specific energy and energy density

Much of the extraction of fossil fuels involves hard and dangerous work in mines or on oilrigs whether at sea or on land. On the face of it, the effort and risk of mining fossil fuels does not seem to be justified when there are other sources of energy available. So why are fossil fuels still extracted? The answer becomes more obvious when we look at the energy available from the fossil fuel itself. There are two ways to measure this: specific energy and energy density.

The word "specific" has the clear scientific meaning of "per unit mass", or (in SI) "per kg". So, **specific energy** indicates the number of joules that can be released by each kilogram of the fuel. Typical values for a particular fuel can vary widely, coal, for example, has a different composition and density depending on where it comes from, and even depending on the location of the sample in the mining seam.

Density is a familiar concept; it is the amount of quantity possessed by one cubic metre of a substance. **Energy density** is the number of joules that can be released from 1 $m^3$ of a fuel.

| Fuel | Specific energy/ $MJ\ kg^{-1}$ | Energy density/ $MJ\ m^{-3}$ |
|---|---|---|
| Wood | 16 | $1 \times 10^4$ |
| Coal | 20–60 | $(20-60) \times 10^6$ |
| Gasoline (petrol) | 45 | $35 \times 10^6$ |
| Natural gas at atmospheric pressure | 55 | $3.5 \times 10^4$ |
| Uranium (nuclear fission) | $8 \times 10^7$ | $1.5 \times 10^{15}$ |
| Deuterium/tritium (nuclear fusion) | $3 \times 10^8$ | $6 \times 10^{15}$ |
| Water falling through 100 m in a hydroelectric plant | $10^{-3}$ | $10^3$ |

The table shows comparisons between some common fuels (and in the case of fusion, the possible energy yields if fusion should become commercially viable). You should look at these and other values in detail for yourself. Notice the wide range of values that appear in this table. Explore data for other common fuels. As you learn about different fuels, find out data for their specific energy and energy density and add these values to your own table.

## Worked examples

**1** A fossil-fuel power station has an efficiency of 25% and generates 1200 MW of useful electrical power. The specific energy of the fossil fuel is 52 MJ kg$^{-1}$. Calculate the mass of fuel consumed each second.

### Solution

If 1200 MW of power is developed then, including the efficiency figure, $\frac{1200 \times 100}{25} = 4800$ MW of energy needs to be supplied by the fossil fuel.

The specific energy is 52 MJ kg$^{-1}$, so the mass of fuel required is $\frac{4800}{52} = 92$ kg s$^{-1}$. (That is roughly 1 tonne every 10 s, or one railcar full of coal every 2 minutes.)

**2** When a camping stove that burns gasoline (petrol) is used, 70% of the energy from the fuel reaches the cooking pot. The energy density of the gasoline is 35 GJ m$^{-3}$.

**a)** Calculate the volume of gasoline needed to raise the temperature of 1 litre of water from 10 °C to 100 °C. Assume that the heat capacity of the pot is negligible. The specific heat capacity of the water is 4.2 kJ kg$^{-1}$ K$^{-1}$.

**b)** Estimate the volume of fuel that a student should purchase for a weekend camping expedition.

### Solution

**a)** 1 litre of water has a mass of 1 kg so the energy required to heat the water is 4200 × 1 × 90 which is 0.38 MJ.

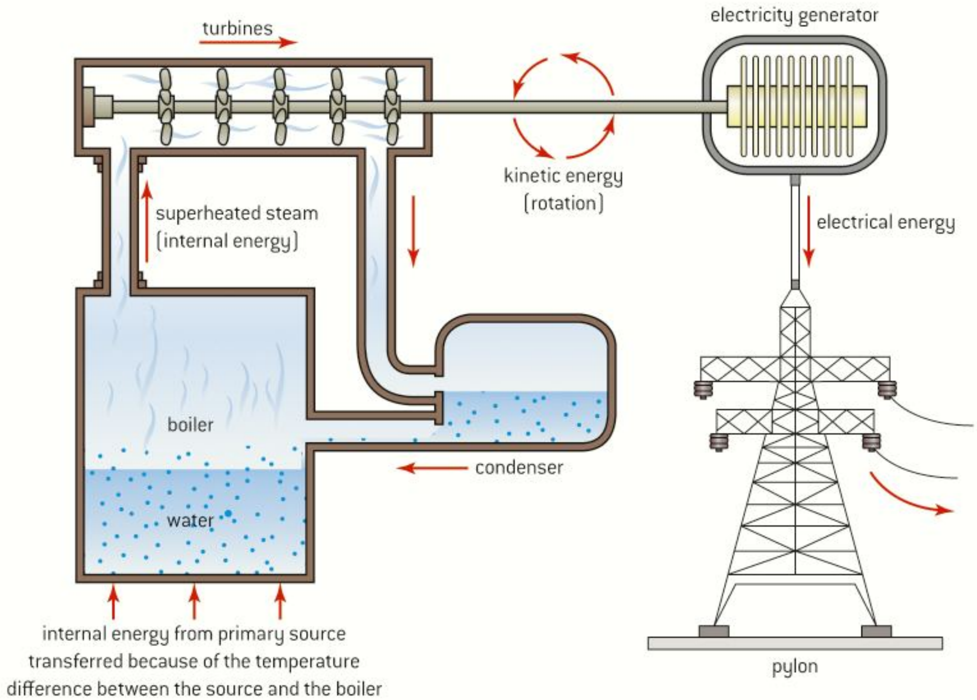
Allowing for the inefficiency, 0.54 MJ of energy is required and this is a volume of fuel of $\frac{0.54 \times 10^6}{35 \times 10^9} = 1.6 \times 10^{-4}$ m$^3$ or about 200 ml.

**b)** Assume that 2 litres of water are required for each meal, and that there will be 5 cooked meals during the weekend. So 2 litres of fuel should be more than enough.

## Thermal power stations

A thermal power station is one in which a primary source of energy is converted first into internal energy and then to electrical energy. The primary fuel can include nuclear fuel, fossil fuel, biomass or other fuel that can produce internal energy. (In principle, a secondary source could be used to provide the initial internal energy, but this would not be sensible as it incurs substantial extra losses.) We will discuss the different types of primary conversion later. However, once the primary energy has been converted to internal energy, all thermal power stations use a common approach to the conversion of internal into electrical energy: the energy is used to heat water producing steam at high temperatures and high pressures. Figure 2 shows what happens.

Energy from the primary fuel heats water in a pressure vessel to create steam. This steam is superheated. This means that its temperature is well above the familiar 100 °C boiling point that we are used to at atmospheric pressure. To attain such high temperatures the steam has to be at high pressure, hundreds of times more than atmospheric pressure. At these high pressures the water in the vessel does not boil in the




▲ Figure 2 Energy conversions inside a power station.

way that is familiar to us, it goes straight into the steam phase without forming the bubbles in the liquid that you see in a cooking pot on a stove. However, we will continue to use the term "boiler" for the vessel where the water is converted to steam even though the idea of boiling is technically incorrect.

The high-pressure steam is then directed to a turbine. Turbines can be thought of as "reverse" fans where steam blows the blades around (whereas in a fan the blades turn to move the gas). There is usually more than one set of blades and each set is mounted on a common axle connected to an alternating current (ac) electricity generator. In the generator, the electrical energy is produced when coils of wire, turned by the turbine, rotate in a magnetic field. The energy that is generated is sent, via a network of electrical cables, to the consumers. You can find the details of the physics of electrical energy generation and its subsequent transmission in Topic 11.

There are really three energy transfers going on in this process: primary energy to the internal energy of water, this internal energy to the kinetic energy of the turbine, and kinetic energy of the turbine to electrical energy in the generator. It is easy to forget the kinetic energy phase and to say that the internal energy goes straight to electrical.

Of course, the original internal energy is produced in different ways in different types of thermal power station. In fossil and biomass stations, there is a straightforward combustion process where material is set alight and burnt. In nuclear stations, the process has to be more complicated. We shall look at the differences between stations in the initial conversion of the energy later.

### Tip

Do not confuse the roles of turbine and dynamo in a power station. The energy conversions they carry out are quite different.

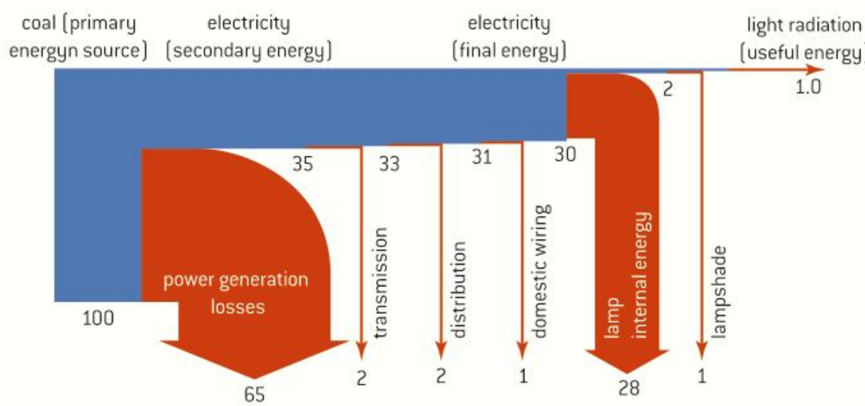
## Sankey diagrams

Different types of thermal power station have different energy losses in their processes and different overall efficiencies. The **Sankey diagram** is a visual representation of the flow of the energy in a device or in a process (although in other subjects outside the sciences, the Sankey diagram is also used to show the flow of material).

There are some rules to remember about the Sankey diagram:

- Each energy source and loss in the process is represented by an arrow.
- The diagram is drawn to scale with the width of an arrow being proportional to the amount of energy it represents.
- The energy flow is drawn from left to right.
- When energy is lost from the system it moves to the top or bottom of the diagram.
- Power transfers as well as energy flows can be represented.

Here is an example to demonstrate the use of a Sankey diagram.

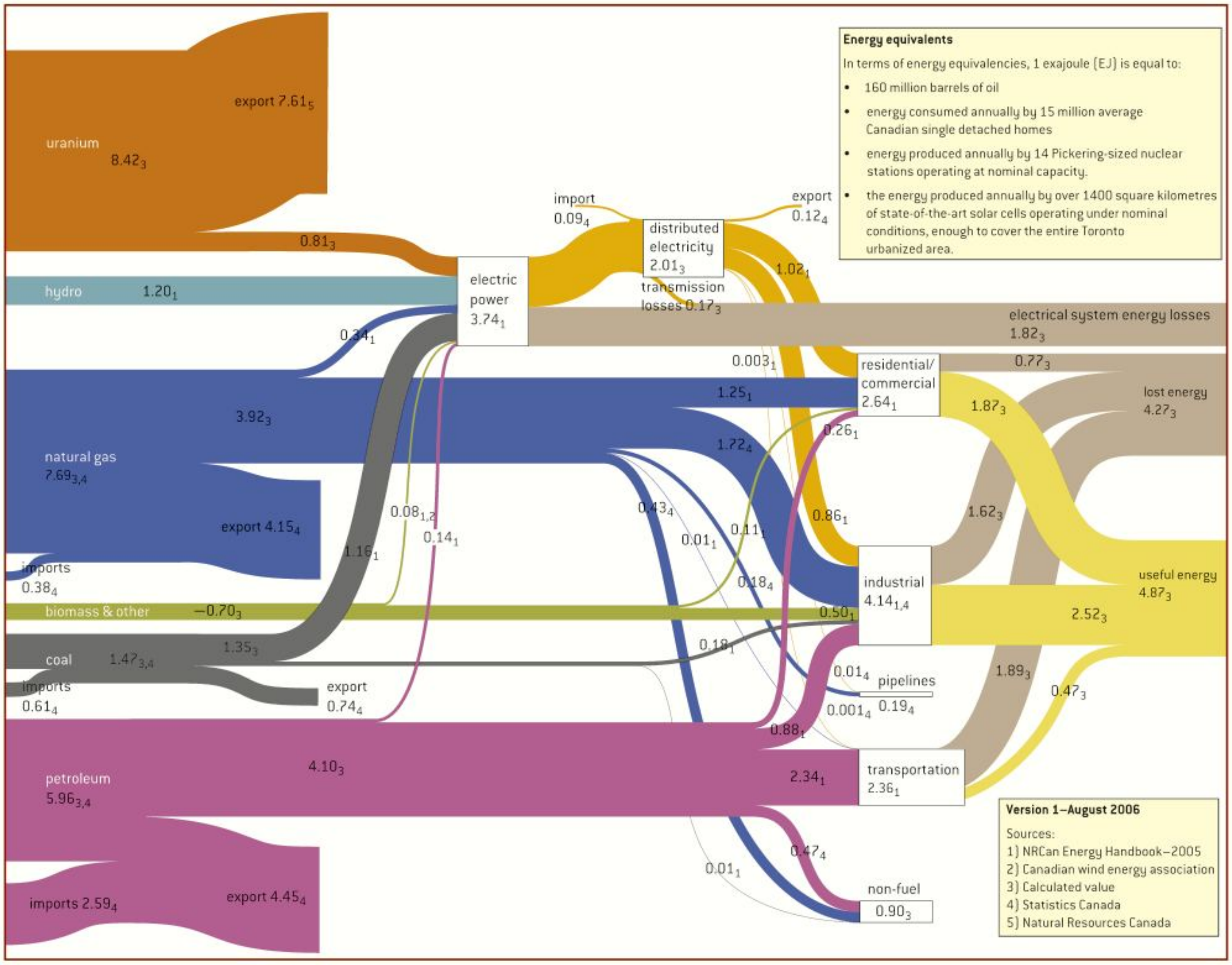



▲ Figure 3 Sankey diagram for a lamp.

It shows the flows of energy that begin with the conversion of chemical energy from fossil fuels and end with light energy emitted from a filament lamp. The red arrows represent energy that is transferred from the system in the form of energy as a result of temperature differences. It is important to recognize that in any process where there is an energy transformation, this energy is "lost" and is no longer available to perform a useful job. This is **degraded energy** and there is always a loss of energy like this in all energy transfers.

Of the original primary energy (100% shown in blue at the bottom of the diagram), only 35% appears as useful secondary energy. The remaining 65% (shown in red) is lost to the surroundings in the process, shown by an arrow that points downwards off the chart. The secondary energy is then shown with the losses involved in the transmission and distribution of the electricity, and to losses in the house wiring. In the lamp itself, most of the energy (28% of the original) is transferred to the internal energy of the surroundings. Finally only 1% of the original primary energy is left as light energy for illumination.

A Sankey diagram is a useful way to visualize the energy consumption of nations. There are many examples of this available on the Internet. Figure 4 shows the energy flows associated with the Canadian economy. Look on the Internet and you will probably find the Sankey diagram for your own national energy demand.

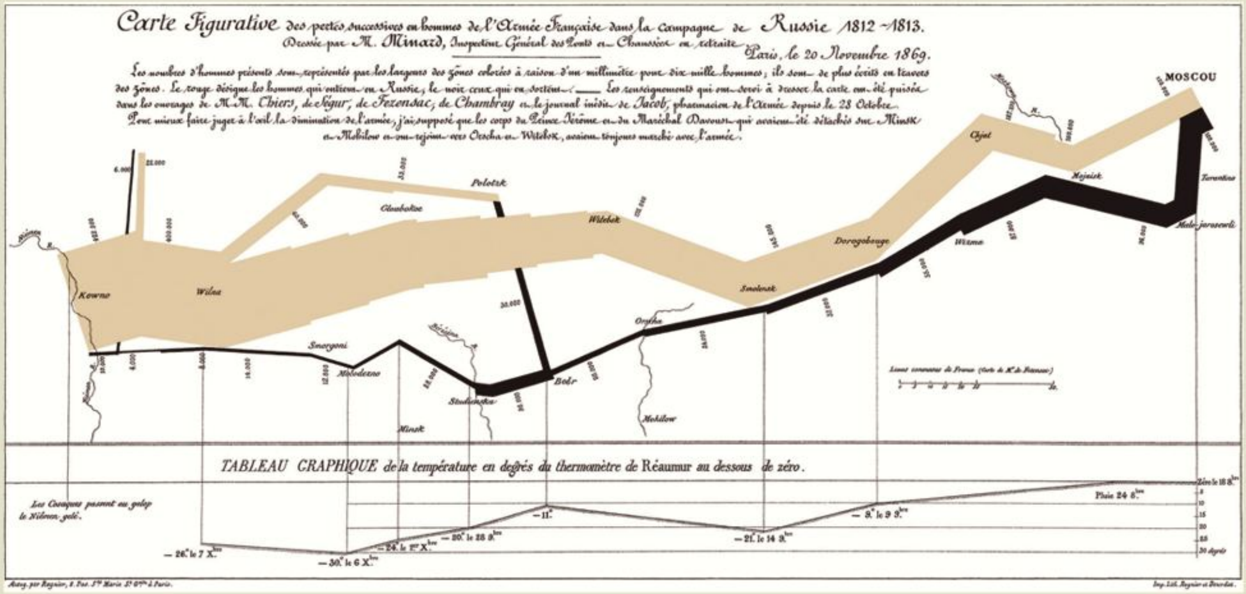



▲ Figure 4 The energy flow in Canada in 2003. The values are in exajoule. (http://ww2.nrcan.ge.ca/es/oerd).

## Nature of science

### Sankey diagram in another context

Here is a completely different use of the Sankey diagram constructed in a historical context. It shows the progress of Napoleon's army to and from his Russian campaign 1812–1813. The width of the strips gives the number of men in the army: brown in the journey to Moscow, black on the return. The graph below the diagram gives the average temperature experienced by the army on its return journey in Réaumur degrees. The Réaumur temperature scale is named after the French scientist who suggested a scale that had fixed points of 0 at the freezing point of water and 80 at the boiling point of water.




▲ Figure 5 A Sankey diagram showing the change in size of Napoleon's army during his Russian campaign.

## Worked examples

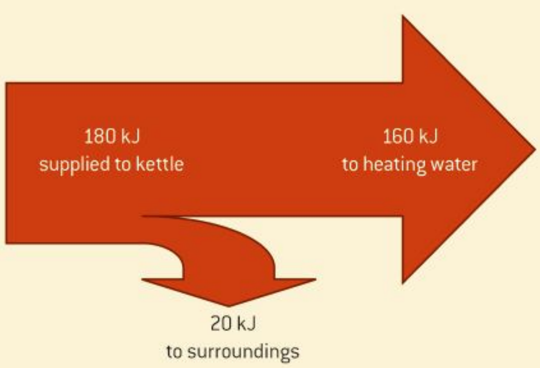
1 An electric kettle of rating 2.0 kW is switched on for 90 s. During this time 20 kJ of energy is lost to the surroundings from the kettle.

Draw a Sankey diagram for this energy transfer.

### Solution

The energy supplied in 90 s is
$2 \times 1000 \times 90 = 180$ kJ.

20 000 J is lost to the surroundings; this is 11% of the total.



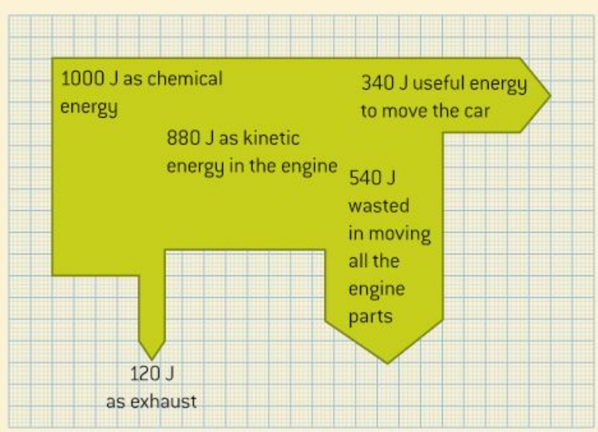

2 In a petrol-powered car 34% of the energy in the fuel is converted into the kinetic energy of the car. Heating the exhaust gases accounts for 12% of the energy lost from the fuel. The remainder of the energy is wasted in the engine, the gearbox and the wheels.

Use these data to sketch a Sankey diagram for the car.

### Solution

Of the 100% of the original fuel energy, 12% is lost in the exhaust, and 34% is useful energy. This leaves 54% energy lost in the engine and the transmission.

A convenient way to draw the diagram is on squared paper. Use a convenient scale: $10\% \equiv 1$ large square is a reasonable scale here.



## Primary sources used in power stations

This section compares the different ways in which the initial energy required by a thermal power station can be generated.

### Fossil fuels

Modern fossil-fuel power stations can be very large and can convert significant amounts of power. The largest in the world at the time of writing has a maximum power output of about 6 GW.

The exact process required before the fuel is burnt differs slightly depending on the fuel used, whether coal, oil, or natural gas. The gas and oil can be burnt readily in a combustion chamber that is thermally connected to the boiler. In the case of coal, some pre-treatment is normally required. Often the coal is crushed into a fine powder before being blown into the furnace where it is burnt.

There are obvious disadvantages to the burning of fossil fuels. Some of these are environmental, but other disadvantages can be seen as a misuse of these special materials:

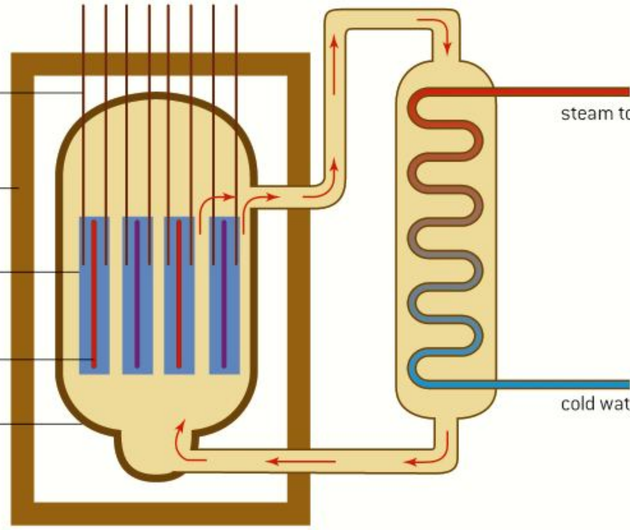
- The materials have taken a very large time to accumulate and will not be replaced for equally long times.
- The burning of the fuels releases into the atmosphere large quantities of carbon dioxide that have been locked in the coal, oil, and gas for millions of years. This has a major impact on the response of the atmospheric system to the radiation incident on it from the Sun (the greenhouse and enhanced greenhouse effects).
- Fossil fuels have significant uses in the chemical industry for the production of plastics, medicines, and other important products.
- It makes sense to locate power stations as close as possible to places where fossil fuels are recovered; however, this is not always possible and, in some locations, large-scale transportation of the fuels is still required. A need for transport leads to an overall reduction in the efficiency of the process because energy has to be expended in moving the fuels to the power stations.

## Nuclear fuel

Sub-topic 7.2 dealt with the principles that lie behind nuclear fission. It explained the origin of the energy released from the nucleus when fission occurs and showed you how to calculate the energy available per fission.

In this course we will only consider so-called "thermal fission reactors", but there are other types in frequent use. A particularly common variety of the thermal reactors is the pressurized water reactor (PWR). Uranium-235 is the nuclide used in these reactors. As with all our other examples of power stations, the aim is to take the energy released in the nuclear fission and use this to create high-pressure steam to turn turbines connected to an electrical generator. However, the energy is not gained quite so easily as in the case of the fossil fuels.

Figure 6 shows a schematic of a PWR with the final output of steam to, and the return pipe from, the turbines on the right-hand side of the diagram. The remainder of the power station is as in figure 2 on p313.




▲ Figure 6 Basic features of a pressurised water reactor (PWR).

Uranium is mined as an ore in various parts of the world, including Australia, Canada, and Kazakhstan (which together produce about 60% of the world's ore every year). The US, Russia, and parts of Africa also produce smaller amounts of uranium ore. About 99% of the ore as it comes directly from the ground is made up of uranium-238, with the remainder being U-235; it is the U-235 not U-238 that is required for the fission process. This means that an initial extraction process is required to boost the ratio of U-235 : U-238. The fuel needs to contain about 3% U-235 before it can be used in a reactor. This is because U-238 is a good absorber of neutrons and too much U-238 in the fuel will prevent the fission reaction becoming self-sustaining. The fuel with its boosted proportions of U-235 is said to be **enriched**.

| Fission product | energy/MeV |
|---|---|
| fission fragments | 160 |
| decay of fission fragments | 21 |
| emitted gamma rays | 7 |
| emitted neutrons | 5 |

The enriched material is then formed into fuel rods – long cylinders of uranium that are inserted into the core of the reactor. Most of the energy (about 200 MeV or $3 \times 10^{-11}$ J per fission) is released in the form of kinetic energy of the fission fragments and neutrons emitted during the fission. Immediately after emission, the neutrons are moving at very high speeds of the order of $10^4$ km $s^{-1}$. However, in order for them to be as effective as possible in causing further fissions to sustain the reaction they need to be moving with kinetic energies much lower than this, of the order of 0.025 eV (with a speed of about 2 km $s^{-1}$). This slower speed is typical of the speeds that neutrons have when they are in equilibrium with matter at about room temperatures. Neutrons with these typical speeds are known as **thermal neutrons**.

The requirement of removing the kinetic energy from the neutrons is not only that the neutrons can stimulate further fissions effectively, but that their energy can be efficiently transferred to the later stages of the power station. The removal of energy is achieved through the use of a **moderator**, so-called because it moderates (slows down) the speeds of the neutrons.

Typical moderators for the PWR type include water and carbon in the form of graphite. The transfer of energy is achieved when a fast-moving neutron strikes a moderator atom inelastically, transferring energy to the atom and losing energy itself. After a series of such collisions the neutron will have lost enough kinetic energy for it to be moving at thermal speeds and to have a high chance of causing further fission.

A further problem is that U-238 is very effective at absorbing high-speed neutrons, so if the slowing down is carried out in the presence of the U-238 then few free neutrons will remain at the end of it. So reactor designers have moderators close to, but not part of, the fuel rods; the neutrons slow down in the presence of moderator but away from the U-238. The fuel rods and the moderating material are kept separate and neutrons move from one to the other at random. The reactor vessel and its contents are designed to facilitate this.

The criteria for a material to be a good moderator include not being a good absorber of neutrons (absorption would lower the reaction rate and possibly stop the reaction altogether) and being inert in the extreme conditions of the reactor. Some reactor types, for example, use deuterium ($^{2}_{1}H$) in the form of deuterium oxide ($D_2O$, called "heavy water") rather than graphite.

You should be able to recognize that the best moderator of all ought to be a hydrogen atom (a single proton in the nucleus) because the maximum energy can be transferred when a neutron strikes a proton. However, hydrogen is a very good absorber of neutrons and it cannot be used as a moderator in this way.

There is a need to regulate the power output from the reactor and to shut down its operation if necessary. This is achieved through the use of **control rods**. These are rods, often made of boron or some other element that absorbs neutrons very well, that can be lowered into the reactor. When the control rods are inserted a long way into the reactor, many neutrons are absorbed in the rods and fewer neutrons will be available for subsequent fissions; the rate of the reaction will drop. By raising and lowering the rods, the reactor operators can keep the energy output of the reactor (and therefore the power station) under control.

The last part of the nuclear power station that needs consideration is the mechanism for conveying the internal energy from inside the reactor to the turbines. This is known as the **heat exchanger**. The energy exchange cannot be carried out directly as in the fossil-fuel stations. There needs to be a closed-system heat exchanger that collects energy from the moderator and other hot regions of the reactor, and delivers it to the water. The turbine steam cannot be piped directly through the reactor vessel because there is a chance that radioactive material could be transferred outside the reactor vessel. Using a closed system prevents this.

The pressurized water reactor is given its name because it transfers the energy from moderator and fuel rods to the boiler using a closed water system under pressure. Water is not the only substance available for this. In the Advanced Gas-cooled Reactors (AGR) used in the UK, carbon dioxide gas is used rather than water, but the principle of transferring energy safely through a closed system is the same.

## Nature of science

### Fast breeder reactors

A remarkable design for nuclear reactors comes with the development of the fast breeder reactor. Plutonium-239 (Pu-239) is the fissionable material in this case just as uranium-235 is used in PWRs. However, a blanket of uranium-238 surrounds the plutonium core. Uranium-238 does not easily fission and is a good absorber of neutrons (remember that its presence is undesirable in a PWR). This U-238 absorbs neutrons lost from the reactor core and is transmuted into Pu-239 – the fuel of the fast breeder reactor! The reactor is making its own fuel and generating energy at the same time. It has been reported that, under the right conditions, a fast breeder reactor can produce 5 kg of fissionable plutonium for every 4 kg used in fission. This is a good way to convert the large stockpiles of virtually useless uranium-238 into something of value.

There are drawbacks of course: large amounts of high-level radioactive waste from the fast breeder reactor need to be dealt with and, in the wrong hands, the plutonium can be used for nuclear weapons.

## Investigate!

### Running your own reactor

- No schools are likely to have their own nuclear reactor for students to use! However you can still investigate the operation of a nuclear power station.
- There are a number of simulations available on the Internet that will give you virtual control of the station. A suitable starting point is to enter "nuclear reactor applet" into a search engine.

### Worked examples

**1** When one uranium-235 nucleus undergoes fission, $3.2 \times 10^{-11}$ J of energy is released. The density of uranium-235 is $1.9 \times 10^4$ kg m$^{-3}$.

Calculate, for uranium-235:

**a)** the specific energy

**b)** the energy density.

### Solution

**a)** The mass of the atom is 235u (ignoring the mass of the electrons in the atom).

This is equivalent to a mass of $1.7 \times 10^{-27} \times 235 = 4.0 \times 10^{-25}$ kg.

So the specific energy of uranium-235 is $\frac{3.2 \times 10^{-11}}{4.0 \times 10^{-25}} = 8.0 \times 10^{13}$ J kg$^{-1}$

**b)** 1 kg of uranium-235 has a volume of $\frac{1}{1.9 \times 10^4} \approx 5 \times 10^{-5}$ m$^3$. Therefore the energy density of pure uranium-235 $= 8.0 \times 10^{13} \div 5 \times 10^{-5} = 1.6 \times 10^{18}$ J m$^{-3}$

**2** Explain what will happen in a pressured water reactor if the moderator is removed.

### Solution

The role of the moderator is to remove kinetic energy from neutrons so that there is a high probability that further fissions will occur. When neutrons are moving at high speeds, there is a very high probability that uranium-238 nuclei will absorb them without fission occurring. So the removal of the moderator will mean that neutrons are no longer slowed down, and will be absorbed by U-238. The fission reaction will either stop or its rate will be reduced.

**3** When a moving neutron strikes a stationary carbon-12 atom head-on, the neutron loses about 30% of its kinetic energy. Estimate the number of collisions that would be required for a 1 MeV neutron to be slowed down to 0.1 eV.

### Solution

After one collision the remaining kinetic energy of the neutron will be $0.7 \times 1$ MeV.

After two collisions the energy of the neutron will be $0.7 \times 0.7 \times 1$ MeV

$= 0.7^2 \times 1$ MeV

After $n$ collisions the energy of the neutron will be $0.7^n \times 1$ MeV.

So $0.7^n = 0.1 \times 10^{-6}$,

or $n = \frac{-7}{\log_{10} 0.7} = 45.2$

So 46 collisions are required to reduce the neutron speed by this factor of $10^7$.

(In practice, about 100 are required; you might want to consider why the actual number is larger than the estimate.)

## Safety issues in nuclear power

There needs to be a range of safety measures provided at the site of a nuclear reactor to protect the work force, the community beyond the power station, and the environment.

- The reactor vessel is made of thick steel to withstand the high temperatures and pressures present in the reactor. This has the benefit of also absorbing alpha and beta radiations together with some of the gamma rays and stray neutrons.
- The vessel itself is encased in layers of very thick reinforced concrete that also absorb neutrons and gamma rays.
- There are emergency safety mechanisms that operate quickly to shut the reactor down in the event of an accident.
- The fuel rods are inserted into and removed from the core using robots so that human operators do not come into contact with the spent fuel rods, which become highly radioactive during their time in the reactor.

The issue of the disposal of the waste produced in the nuclear industry is much debated in many parts of the world. Some of the waste will remain radioactive for a very long time – but, as you know from Topic 7, this implies that its activity will be quite low during this long period. There are however other problems involving the chemical toxicity of this waste material which mean that it is vital to keep it separate from biological material and thus the food chain. The technology required to achieve this is still developing.

At the end of the life of a reactor (of the order of 25–50 years at the moment), the reactor plant has to be decommissioned. This involves removing all the fuel rods and other high-activity waste products and enclosing the reactor vessel and its concrete shield in a larger shell of concrete. It is then necessary to leave the structure alone for up to a century to allow the activity of the structure to drop to a level similar to that of the local background. Such long-term treatment is expensive and it is important to factor these major costs into the price of the electricity as it is being produced during the lifetime of the power station.

### TOK

Of all the scientific issues of our time, perhaps nuclear energy invokes the greatest emotional response in both scientists and non-scientists alike. It is vital to carry out accurate risk assessments for all energy sources, not just nuclear. Is it possible we could forget the location of the waste sites in 50, 100, or 1000 years? Are human errors part of the equation? How can such assessments be carried out in an emotionally charged debate?

## Nature of science

### Society and nuclear power

The use of nuclear power has been growing throughout the world since the late 1940s. However, society has never been truly comfortable with its presence and use. There are many reasons for this, including a lack of public understanding of the fission process (both advantages and disadvantages), public reaction to accidents that have occurred periodically over the years, and a fear of radioactive materials. Major accidents have included the Chernobyl incident, the event at Three Mile Island, and the Fukushima accident of 2011 that was triggered by a tsunami and possibly also an associated earthquake.

At the time of writing there has been a withdrawal of approval for nuclear plans by some governments as a result of public opinion changes after the Fukushima accident. Continuing decisions about how we generate energy will be required by society as time goes on, and as our energy-generation technology improves.

When you debate these issues, ensure that you understand the scientific facts and statistics that surround the issue of nuclear power.

It is important also to understand the meaning of risk, not just in the context of the nuclear power industry, but also in relation to things we do every day. Do some research for yourself. Find out the risks to your health of:

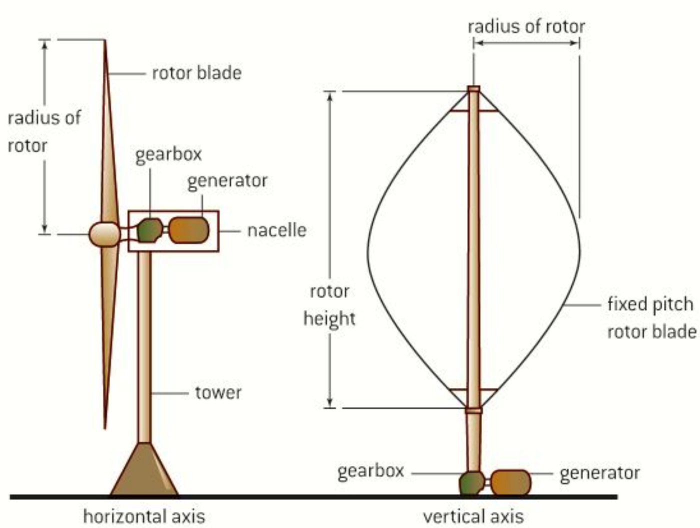
- living within 20 km of a nuclear power station
- flying once from Europe to a country on the Pacific Rim
- smoking 20 cigarettes every day
- driving 1000 km in a car.

Try to find numerical estimates of the risk, not just written statements.

## Wind generators

Wind generators can be used successfully in many parts of the world. Even though the wind blows erratically at most locations, this can be countered by the provision of separate wind farms, each with large numbers of individual turbines all connected to the electrical power grid.

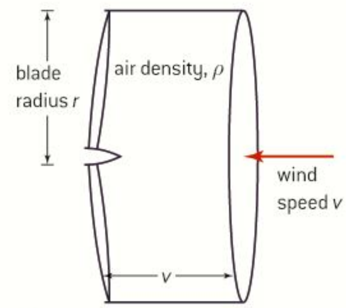
There are two principal designs of generator: horizontal-axis and vertical-axis. In both cases a rotor is mounted on an axle that is either horizontal or vertical, hence the names. The rotor is rotated by the wind and, through a gearbox, this turns an electrical generator. The electrical energy is fed either to a storage system (but this increases the expense) or to the electrical grid.




▲ Figure 7 Wind turbine configurations.

The horizontal-axis machine can be steered into the wind. The vertical-axis type does not have to be steered into the wind and therefore its generator can be placed off-axis.

It is possible to estimate the maximum power available from a horizontal-axis wind turbine of blade area $A$. In one second, the volume of air moving through the turbine is $vA$ when the speed of the wind is $v$ (figure 8).




▲ Figure 8 Volume of air entering a wind turbine in one second.

The mass of air moving through the turbine every second is $\rho vA$ where $\rho$ is the density of the air, and the kinetic energy of the air arriving at the turbine in one second is

$$\frac{1}{2}(mass) \times (speed)^2 = \frac{1}{2}(\rho vA)v^2 = \frac{1}{2}\rho Av^3$$

If a wind turbine has a blade radius $r$ then the area $A$ swept out by the blades is $\pi r^2$ and the maximum theoretical kinetic energy arriving at the turbine every second (and hence the maximum theoretical power) is

$$\frac{1}{2}\rho\pi r^2 v^3$$

This is a *maximum theoretical value of the available power* as there are a number of assumptions in the proof. In particular, it is assumed that *all* the kinetic energy of the wind can be used. Of course, the wind has to move out of the back of the turbine and so must have some kinetic energy remaining after being slowed down. Also, if the turbine is part of a wind farm then the presence of other nearby turbines disturbs the flow of the air and leads to a reduction in the energy from turbines at the rear of the array.

The turbine power equation suggests that a high wind speed and a long blade (large $A$ or $r$) will give the best energy yields. However, increasing the radius of the blade also increases its mass and this means that the rotors will not rotate at low wind speeds. The blade radius has to be a compromise that depends on the exact location of the wind farm.

Many wind farms are placed off-shore; the wind speeds are higher than over land. This is because the sea is relatively smooth compared with the buildings, hills and so on that are found on land. However, installation and subsequent maintenance for off-shore arrays are more expensive because of the access issues.

Another ideal place for wind farms is at the top of a hill. The effect of the land shape is to constrict the flow of the wind into a more confined volume so that in consequence the wind speed rises as the air moves up the hill. Wind speeds therefore tend to be greater at the top of hills and, because the power output of the turbine is proportional to $v^3$, even a small increase in average wind speed is advantageous.

Some people object to both on- and off-shore arrays on the grounds of visual pollution. There are also suggestions that wind farms compromise animal habitats in some places and that the turbines are noisy for those who live close by.

The factors for and against wind being used as an energy source are summarized in this table:

| Advantages | Disadvantages |
|---|---|
| No energy costs<br>No chemical pollution<br>Capital costs can be high but reduce with economies of scale<br>Easy to maintain on land; not so easy off-shore | Variable output on a daily or seasonal basis<br>Site availability can be limited in some countries<br>Noise pollution<br>Visual pollution<br>Ecological impact |

## Worked examples

1 A wind turbine produces a power $P$ at a particular wind speed. If the efficiency of the wind turbine remains constant, estimate the power produced by the turbine:

**a)** when the wind speed doubles

**b)** when the radius of the blade length halves.

### Solution

The equation for the kinetic energy arriving at the wind turbine every second is $\frac{1}{2}\rho\pi r^2 v^3$.

**a)** When the wind speed $v$ doubles, $v^3$ increases by a factor of 8, so the power output will be $8P$.

**b)** When the radius of the blade halves, $r^2$ will go down by a factor of 4 and (if nothing else changes) the output will be $\frac{P}{4}$.

2 A wind turbine with blades of length 25 m is situated in a region where the average wind speed is 11 m s$^{-1}$.

**a)** Calculate the maximum possible output of the wind turbine if the density of air is 1.3 kg m$^{-3}$.

**b)** Outline why your estimate will be the maximum possible output of the turbine.

### Solution

**a)** Using the wind turbine equation:

the kinetic energy arriving at the wind turbine every second is $\frac{1}{2}\rho\pi r^2 v^3$,

this will be the maximum power output and is $\frac{1}{2} \times 1.3 \times \pi \times 25^2 \times 11^3 = 1.7$ MW.

**b)** Mechanical and electrical inefficiencies in the wind turbine have not been considered. The calculation assumes that all the kinetic energy of the wind can be utilized; this is not possible as some kinetic energy of the air will remain as it leaves the wind turbine.

## Pumped storage

There are a number of ways in which water can be used as a primary energy resource. These include:

- pumped storage plants
- hydroelectric plants
- tidal barrage
- tidal flow systems
- wave energy.

All these sources use one of two methods:

- The gravitational potential energy of water held at a level above a reservoir is converted to electrical energy as the water is allowed to fall to the lower level (used in hydroelectric (figure 9(a)), pumped storage, and tidal barrage).

- The kinetic energy of moving water is transferred to electrical energy as the water flows or as waves move (river or tidal flow or wave systems). Figure 9(b) shows a picture of the Canadian Beauharnois run-of-the-river power station on the St-Laurent river that can generate 1.9 GW of power.

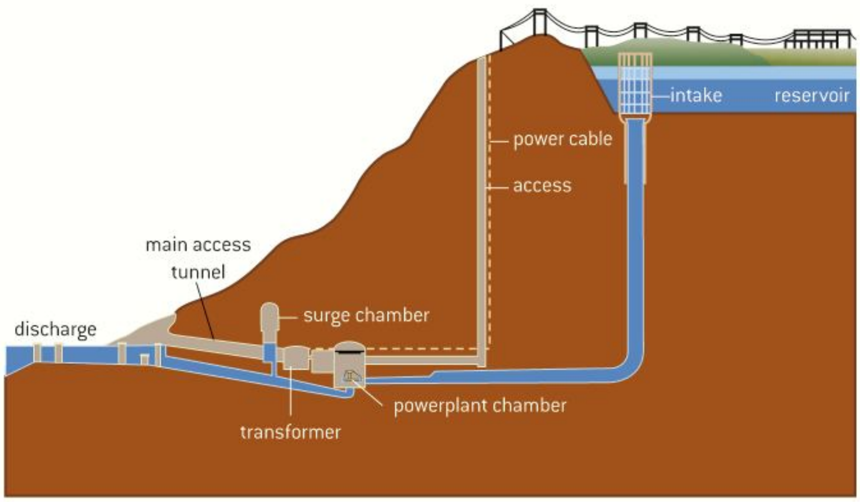
(a)

(b)

▲ Figure 9 Water as a primary energy resource.
(a) A hydroelectric plant in Thailand.
(b) A run-of-the-river plant in Canada.

In this topic we focus on the **pumped storage system**.

The wind farms and nuclear power stations we have discussed so far are known as **baseload** stations. They run 24 hours a day, 7 days a week converting energy all the time. However, the demand that consumers make for energy is variable and cannot always be predicted. From time to time the demand exceeds the output of the baseload stations. Pumped storage is one way to make up for this deficit.




▲ Figure 10 A pumped-storage generating station.

A pumped storage system (Figure 10) involves the use of two water reservoirs – sometimes a natural feature such as a lake, sometimes a man-made lake or an excavated cavern inside a mountain. These reservoirs are connected by pipes. When demand is high, water is allowed to run through the pipes from the upper reservoir to the lower via water turbines. When demand is low, and electrical energy is cheap, the turbines operate in reverse to pump water back from the lower to the upper reservoir.

Some pumped storage systems can go from zero to full output in tens of seconds. The larger systems take longer to come up to full power, however, substantial outputs are usually achieved in only a few minutes from switch on.

For a pumped storage system that operates through a height difference of $\Delta h$, the gravitational potential energy available $= mg\Delta h$ where $m$ is the mass of water that moves through the generator and $g$ is the gravitational field strength.

So the maximum power $P$ available from the water is equal to the rate at which energy is converted in the machine and is

$$P = \frac{m}{t}g\Delta h = \left(\frac{V}{t}\rho\right)g\Delta h$$

where $t$ is the time for mass $m$ to move through the generator, $V$ is the volume of water moving through the generator in time $t$ and $\rho$ is the density of the water.

### Worked examples

**1** Water from a pumped storage system falls through a vertical distance of 260 m to a turbine at a rate of 600 kg s$^{-1}$. The density of water is 1000 kg m$^{-3}$. The overall efficiency of the system is 65%.

Calculate the power output of the system.

### Solution

In one second the gravitational potential energy lost by the system is $mg\Delta h = 600 \times g \times 260 =$ 1.5 MJ.

The efficiency is 65%.

Output power $= 1.5 \times 10^6 \times \dfrac{65}{100} = 0.99$ MW

**2** In a tidal barrage system water is retained behind a dam of height $h$. Show that the gravitational potential energy available from the water stored behind the dam is proportional to $h^2$.

### Solution

Assume that the cross-sectional area of the dam is $A$ and that the cross-section is rectangular.

The volume of water held by the dam is $Ah$.

The mass of the water held by the dam is $\rho Ah$ where $\rho$ is the density of water.

When the dam empties completely the centre of mass of the water falls through a distance $\frac{h}{2}$(because the centre of mass is half way up the height of the dam).

The gravitational potential energy of the water is $mgh = (\rho Ah) \times g \times \frac{h}{2} = \frac{1}{2}\rho Ah^2$.

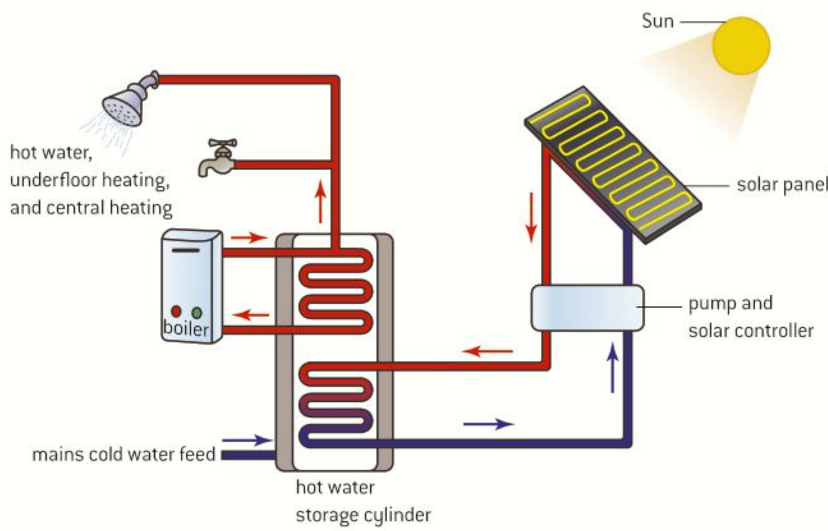
Thus, gpe $\propto h^2$

## Solar energy

Although most energy is ultimately derived from the Sun, two systems use photons emitted by the Sun directly in order to provide energy in both large- and small-scale installations.

### Solar heating panels

Solar heating panels is a technique for heating water using the Sun's energy.



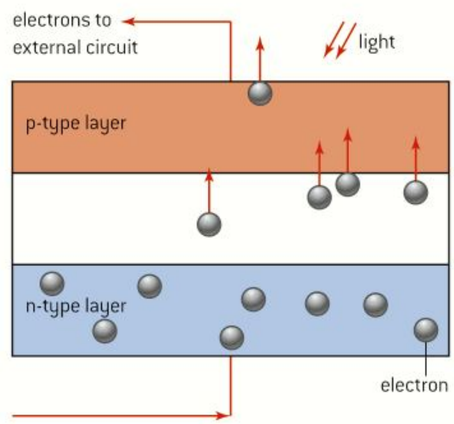

▲ Figure 11 Solar thermal-domestic hot water system.

A **solar heating panel** contains a pipe, embedded in a black plate, through which a glycol–water mixture is circulated by a pump (glycol has a low freezing point, necessary in cold countries). The liquid heats up as infra-red radiation falls on the panel. The pump circulates the liquid to the hot-water storage cylinder in the building. A heat-exchanger system transfers the energy to the water in the storage cylinder. A pump is needed because the glycol–water mixture becomes less dense as it heats up and would therefore move to the top of the panel and not heat the water in the cylinder. A controller unit is required to prevent the system pumping hot water from the cylinder to the panel during the winter when the panel is cold.

▲ Figure 12 A domestic photovoltaic panel system.

## Solar photovoltaic panels

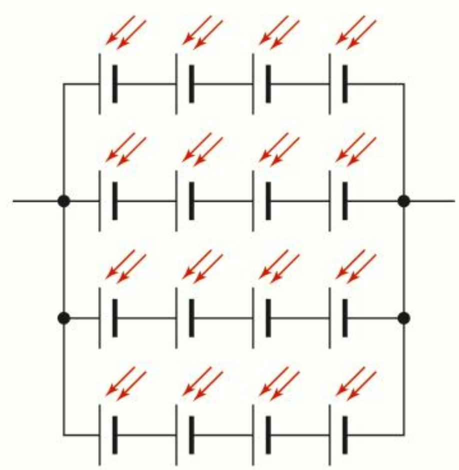
The first solar "photocells" were developed around the middle of the nineteenth century by Alexandre-Edmond Becquerel (the father of Henri the discoverer of radioactivity). For a long time, the use of solar cells, based on the element selenium, was restricted to photography. With the advent of semiconductor technology, it was possible to produce **photovoltaic cells** (as they are properly called, abbreviated to PV) to power everything from calculators to satellites. In many parts of the world, solar panels are mounted on the roofs of houses. These panels not only supply energy to the house, but excess energy converted during sunny days is often sold to the local electricity supply company.




▲ Figure 13 Cross-section of a photovoltaic cell.

The photovoltaic materials in the panel convert electromagnetic radiation from the Sun into electrical energy. A full explanation of the way in which this happens goes beyond the IB syllabus, but a simplified explanation is as follows.

The photovoltaic cell consists of a single crystal of semiconductor that has been doped so that one face is p-type semiconductor and the opposite face is n-type. These terms n-type and p-type indicate the most significant charge carriers in the substance (electrons in n-type, positive "holes" – an absence of electrons – in p-type). Normally there is equilibrium between the charge carriers in both halves of the cell. However, when energy in the form of photons falls on the photovoltaic cell, then the equilibrium is disturbed, electrons are released and gain energy to move from the n-region to the p-region and hence around the external circuit. The electrons transfer this energy to the external circuit in the usual way and do useful work.



▲ Figure 14 Connecting photovoltaic cells together.

One single cell has a small emf of about 1 V (this is determined by the nature of the semiconductor) and so banks of cells are manufactured in order to produce usable currents on both a domestic and commercial scale. Many cells connected in series would give large emfs but also large internal resistances; the compromise usually adopted is to connect the cells in a combination of both series and parallel.

The efficiencies of present-day solar cells are about 20% or a little higher. However, extensive research and development is being carried out in many countries and it is likely that these efficiencies will rise significantly over the next few years.

The advantages of both solar heating panels and photovoltaic cells are that maintenance costs are low, and that there are no fuel costs. Individual households can use them. Disadvantages include high initial cost, and the relatively large inefficiencies (so large areas of cells are needed). It goes without saying that the outputs of both types of cell are variable, and depend on both season and weather. We will look at the reasons for these variations in Sub-topic 8.2.

The mathematics of both photovoltaic cells and solar heating panels is straightforward. At a particular location and time of day, the Sun radiates a certain power per square metre $I$ (also known as the intensity of the radiation) to the panels. Panels have an area $A$, so the power arriving at the surface of the panel will be $IA$. Panels have an efficiency $\eta$ which is the fraction of the energy arriving that is converted into internal energy (of the liquid in the heating panels) or electrical energy (photovoltaics). So the total power converted by the panel is $\eta IA$.

## Worked examples

**1** A house requires an average power of 4.0 kW in order to heat water. The average solar intensity at the Earth's surface at the house is 650 W $m^{-2}$. Calculate the minimum surface area of solar heating panels required to heat the water if the efficiency of conversion of the panel is 22%.

### Solution

4000 W are required, each 1 $m^2$ of panel can produce
$650 \times \frac{22}{100} = 140$ W

$$\text{Area required} = \frac{4000}{140} = 28\ \text{m}^2$$

**2** Identify the energy changes in photovoltaic cells and in solar heating panels.

### Solution

A solar heating cell absorbs radiant energy and converts it to the internal energy of the working fluid.

A photovoltaic cell absorbs photons and converts their energy to electrical energy.