# 1.7 Energy, work and power

## 1.7.1 Energy

**FOCUS POINTS**

- ★ Identify different energy stores and describe how energy is transferred from one store to another.
- ★ Use the correct equations for kinetic energy and change in gravitational potential energy.
- ★ Apply the principle of the conservation of energy to simple examples and use it to interpret flow diagrams.
- ★ Apply the principle of the conservation of energy to complex examples represented by Sankey diagrams.

Energy is a theme that appears in all branches of science. It links a wide range of phenomena and enables us to explain them. There are different ways in which energy can be stored and, when something happens, it is likely to be due to energy being transferred from one store to another. Energy transfer is needed to enable people, computers, machines and other devices to work and to enable processes and changes to occur. For example, in Figure 1.7.1, the water skier can be pulled along by the boat only if energy is transferred from the burning petrol to its rotating propeller. Although energy can be transferred to different stores, the total energy of a system remains constant. In this topic you will learn in detail about the potential energy associated with the position of an object in a gravitational field and the kinetic energy which is associated with its motion.

▲ **Figure 1.7.1** Energy transfer in action

## Energy stores

**Energy** can be stored in a number of different ways.

> **Key definition**
>
> **Energy** may be stored as kinetic, gravitational potential, chemical, elastic (strain), nuclear, electrostatic and internal (thermal)

### Chemical energy

Food and fuels, like oil, gas, coal and wood, are concentrated stores of **chemical energy**. The energy of food is released by chemical reactions in our bodies, and during the transfer to other stores we are able to do useful jobs. Fuels cause **energy transfers** when they are burnt in an engine or a boiler. Batteries are compact sources of chemical energy, which in use is transferred by an electric current.

### Gravitational potential energy

This is the energy an object has because of its position. A body above the Earth's surface, like water in a mountain reservoir, has energy stored as **gravitational potential energy**.

### Elastic strain energy

This is energy an object has because of its condition. Work has to be done to compress or stretch a spring or elastic material and energy is transferred to *elastic* **strain energy**. If the bow string in Figure 1.7.3c on the next page were released, the strain energy would be transferred to the arrow.

### Kinetic energy

Any moving object has **kinetic energy** and the faster it moves, the more kinetic energy it has. As a hammer drives a nail into a piece of wood, there is a transfer of energy from the kinetic energy of the moving hammer to other energy stores.

### Electrostatic energy

Energy can be stored by charged objects (see Topic 4.2.1) as **electrostatic energy**. This energy can be transferred by an electric current.

### Nuclear energy

The energy stored in the nucleus of an atom is known as **nuclear energy**. It can be transferred to other energy stores in nuclear reactions such as fission and fusion (Topic 5.1.2).

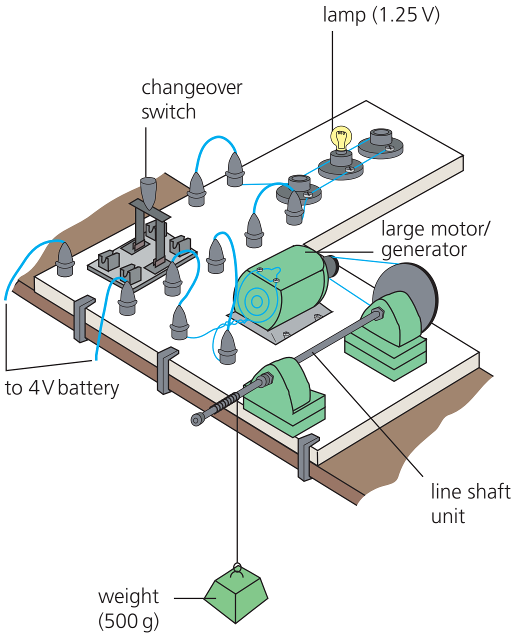
### Internal energy

This is also called **thermal energy** and is the final fate of other energy stores. It is transferred by conduction, convection or radiation.

## Energy transfers

### Demonstration

The apparatus in Figure 1.7.2 can be used to show how energy is transferred between different energy stores. Chemical energy stored in the battery is transferred by an electric current (electrical working) to kinetic energy in the electric motor. The weight is raised when kinetic energy stored in the motor is transferred (by mechanical working) to gravitational potential energy stored in the weight. If the changeover switch is joined to the lamp and the weight allowed to fall, the motor acts as a **generator** of an electric current that transfers (by electrical working) kinetic energy stored in the rotating coil of the generator to internal energy in the lamp. Energy is transferred from the lamp to the environment (by electromagnetic waves and by heating).




▲ **Figure 1.7.2** Demonstrating energy transfers

### Other examples

In addition to electrical working, mechanical working, electromagnetic waves and heating, energy can be transferred between stores by other types of waves, such as sound waves. Sound waves transfer energy from a vibrating source to our eardrums or to a microphone. Heating water in a boiler transfers chemical energy stored in a fuel to internal energy stored in the water.

In summary, energy can be transferred between stores in the following ways:

- mechanical working – by the action of a force (Topic 1.5)
- electrical working – by an electric current (Topic 4.2.2)
- waves – electromagnetic, sound and other waves (Topic 3.3)
- heating – by conduction, convection or radiation (Topic 2.3).

Some energy transfers are shown in Figures 1.7.3a to d:

**a** Potential energy is transferred to kinetic energy by mechanical working (action of a gravitational force).
**b** Thermal energy stored in an electric fire element is transferred by electromagnetic waves and by heating to the environment.
**c** Chemical energy (stored in muscles in the arm) is transferred to elastic energy in the bow by mechanical working.
**d** Gravitational potential energy stored in the water in the upper reservoir is transferred to the kinetic energy of a turbine by mechanical working.


▲ **Figure 1.7.3** Some energy transfers

## Measuring energy transfers

In an energy transfer, work is done. The work done is a measure of the amount of energy transferred. Energy, as well as work, is measured in joules (J).

For example, if you have to exert an upward force of 10 N to raise a stone steadily through a vertical distance of 1.5 m, the mechanical work done is 15 J (see Topic 1.7.2).

work = force × distance moved in the direction of force

This is also the amount of chemical energy transferred from your muscles to the **potential energy** of the stone.

## Principle of conservation of energy

The **principle of conservation of energy** is one of the basic laws of physics and is stated as follows:

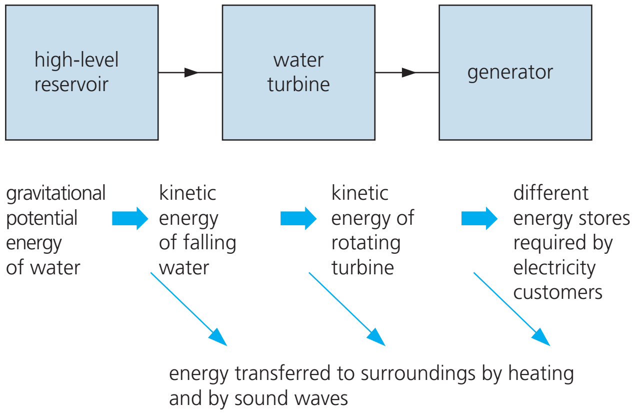
> Energy cannot be created or destroyed; it is always conserved.

However, energy is continually being transferred from one store to another. Some stores, such as those of electrostatic and chemical energy, are easily transferred; for others, such as internal energy, it is hard to arrange a useful transfer.

Ultimately all energy transfers result in the surroundings being heated (as a result of doing work against friction) and the energy is wasted, i.e. spread out and increasingly more difficult to use. For example, when a brick falls, its gravitational potential energy is transferred by mechanical working (gravitational force) to kinetic energy; when the brick hits the ground, kinetic energy is transferred to the surroundings by heating and by sound waves. If it seems in a transfer that some energy has disappeared, the 'lost' energy is often transferred into non-useful thermal energy. This appears to be the fate of all energy in the Universe and is one reason why new sources of useful energy have to be developed.

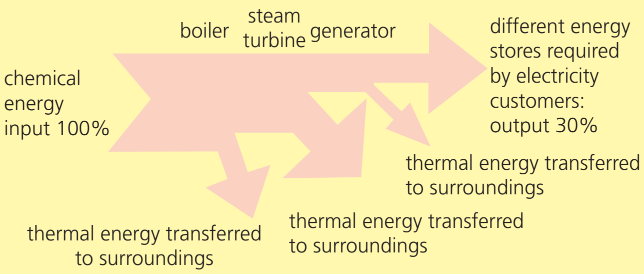
## Representing energy transfers

1 The flow diagram of energy transfers for a hydroelectric scheme like that in Figure 1.7.3d is shown in Figure 1.7.4.




▲ **Figure 1.7.4** Energy transfers in a hydroelectric power station

2 In thermal power stations, thermal energy transferred from burning fossil fuels heats the water in a boiler and turns it into steam. The steam drives turbines which in turn drive the generators that produce electricity as described in Topic 4.5. Figure 1.7.5 shows a **Sankey diagram** for a thermal power station, where the thickness of the bars represents the size of energy transfer at each stage.




▲ **Figure 1.7.5** Sankey diagram depicting energy transfers in a thermal power station

## Kinetic energy ($E_k$)

Kinetic energy is the energy an object has because of its motion.

For an object of mass $m$ travelling with velocity $v$,

$$\text{kinetic energy} = E_k = \frac{1}{2}mv^2$$

If $m$ is in kg and $v$ in m/s, then kinetic energy is in J.

Since $E_k$ depends on $v^2$, a high-speed vehicle travelling at 1000 km/h (Figure 1.7.6), has one hundred times the kinetic energy it has at 100 km/h.

▲ **Figure 1.7.6** Kinetic energy depends on the square of the velocity.

## Worked example

Calculate the kinetic energy of a football of mass 0.4 kg (400 g) moving with a speed of 20 m/s.

$$E_k = \frac{1}{2}mv^2$$
$$= \frac{1}{2} \times 0.4\,\text{kg} \times (20\,\text{m/s})^2$$
$$= 0.2 \times 400\,\text{kg m}^2/\text{s}^2$$
$$= 80\,\text{N m} = 80\,\text{J}$$

### Now put this into practice

1 Calculate the kinetic energy of a ball of mass 0.4 kg moving with a speed of 80 m/s.
2 Calculate the kinetic energy of a ball of mass 50 g moving with a speed of 40 m/s.

## Potential energy ($E_p$)

Potential energy is the energy an object has because of its position or condition.

An object above the Earth's surface is considered to have gained an amount of gravitational potential energy equal to the work that has been done against gravity by the force used to raise it. To lift an object of mass $m$ through a vertical height $\Delta h$ at a place where the Earth's gravitational field strength is $g$ needs a force equal and opposite to the weight $mg$ of the body. Hence

$$\text{work done by force} = \text{force} \times \text{vertical height} = mg \times \Delta h$$

$$\therefore \quad \text{the change in gravitational potential energy} = \Delta E_p = mg\Delta h$$

When $m$ is in kg, $g$ in N/kg (or m/s$^2$) and $\Delta h$ in m, then $\Delta E_p$ is in J.

## Worked example

Taking $g = 9.8$ N/kg, calculate the potential energy gained by a 0.1 kg (100 g) mass raised vertically by 1 m.

$$\Delta E_p = mg\Delta h = 0.1\,\text{kg} \times 9.8\,\text{N/kg} \times 1\,\text{m} = 1\,\text{N m} = 1\,\text{J}$$

### Now put this into practice

1 Calculate the gravitational potential energy gained by a 0.2 kg mass raised vertically by 2 m.
2 Calculate the gravitational potential energy lost by a 0.4 kg mass which falls vertically by 3 m.

## Practical work

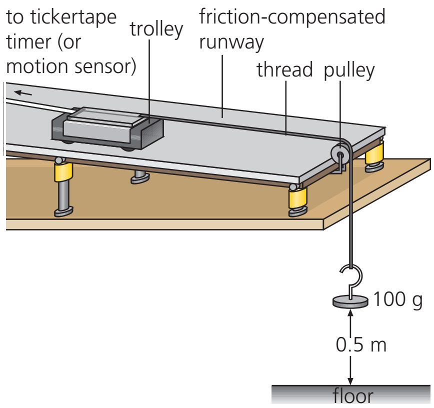
### Transfer of gravitational potential energy to kinetic energy

#### Safety

- Place something soft on the floor to absorb the impact of the masses.
- Take care to keep feet well away from the falling masses.

Friction-compensate a runway by raising the start point slightly so that the trolley maintains a constant speed on the slope when no weight is attached. Arrange the apparatus as in Figure 1.7.7 with the bottom of the 0.1 kg (100 g) mass 0.5 m from the floor.

Start the timer and release the trolley. It will accelerate until the falling mass reaches the floor; after that it moves with *constant* velocity $v$.




▲ **Figure 1.7.7**

1 From your results calculate $v$ in m/s (on the tickertape 50 ticks = 1 s). Find the mass of the trolley in kg. Work out:
Kinetic energy gained by trolley and 0.1 kg mass = ___J
Potential energy lost by 0.1 kg mass = ___J
Compare and comment on the results.
2 Explain why
  a the runway should be friction-compensated
  b the trolley in the experiment will move at a constant speed when the mass hits the floor.
3 Calculate the change in gravitational potential energy of a mass of 300 g falling through a distance of 80 cm.
4 Calculate the kinetic energy of a mass of 300 g travelling at a speed of 4.0 m/s.

## Conservation of energy

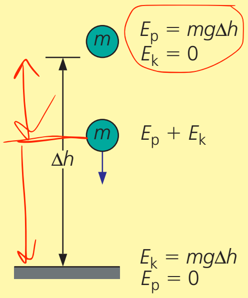
A mass $m$ at height $\Delta h$ above the ground has gravitational potential energy $= mg\Delta h$ (Figure 1.7.8). When an object falls, its speed increases and it gains kinetic energy at the expense of its gravitational potential energy. If it starts from rest and air resistance is negligible, the kinetic energy it has gained on reaching the ground equals the gravitational potential energy lost by the mass

$$E_k = \Delta E_p$$

or

$$\frac{1}{2}mv^2 = mg\Delta h$$

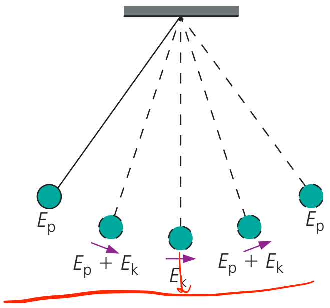
where $v$ is the speed of the mass when it reaches the ground.




▲ **Figure 1.7.8** Loss of gravitational potential energy = gain of kinetic energy

This is an example of the principle of conservation of energy which was discussed earlier.

In the case of a pendulum (Figure 1.7.9), kinetic and gravitational potential energy are interchanged continually. The energy of the bob is all gravitational potential energy at the end of the swing and all kinetic energy as it passes through its central position. In other positions it has both gravitational potential and kinetic energy. Eventually all the energy is transferred to thermal energy as a result of overcoming air resistance.




▲ **Figure 1.7.9** Interchange of potential and kinetic energy for a simple pendulum

## ? Worked example

A boulder of mass 4 kg rolls over a cliff and reaches the beach below with a velocity of 20 m/s. Find:

**a** the kinetic energy of the boulder as it lands
**b** the potential energy of the boulder when it was at the top of the cliff
**c** the height of the cliff.

**a** mass of boulder $= m = 4\,\text{kg}$

velocity of boulder as it lands $= v = 20\,\text{m/s}$

$$\therefore \text{ kinetic energy of boulder as it lands } E_k = \frac{1}{2}mv^2$$
$$= \frac{1}{2} \times 4\,\text{kg} \times (20)^2\,\text{m}^2/\text{s}^2$$
$$= 800\,\text{kg m}^2/\text{s}^2$$
$$= 800\,\text{N m}$$
$$= 800\,\text{J}$$

**b** Applying the principle of conservation of energy (and neglecting energy lost in overcoming air resistance)

change in potential energy = kinetic energy of boulder as it lands

$$\therefore \quad \Delta E_p = E_k = 800\,\text{J}$$

**c** If $\Delta h$ is the height of the cliff

$$\Delta E_p = mg\Delta h$$

$$\therefore \quad \Delta h = \frac{\Delta E_p}{mg} = \frac{800\,\text{J}}{4\,\text{kg} \times 10\,\text{m/s}^2} = \frac{800\,\text{N m}}{40\,\text{kg m/s}^2} = 20\,\text{m}$$

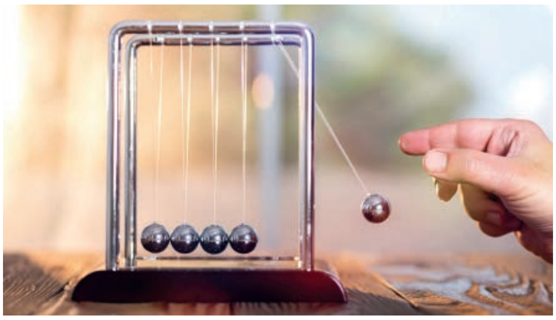
### Now put this into practice

1. A stone of mass 2 kg rolls off the flat roof of a building and reaches the ground with a speed of 10 m/s. Find
   - **a** the kinetic energy of the stone when it reaches the ground
   - **b** the gravitational potential energy of the stone when it was on the roof
   - **c** the height of the roof. Neglect air resistance.
2. A football of mass 0.4 kg rolls off a 30 m high cliff. Calculate the speed of the football when it lands on the beach (neglecting air resistance).

## Going further

### Elastic and inelastic collisions

In all collisions (where no external force acts) some kinetic energy is usually transferred to thermal energy and, to a small extent, to sound. The greater the proportion of kinetic energy transferred, the less *elastic* is the collision, i.e. the more inelastic it is. In a perfectly elastic collision, kinetic energy is conserved.



▲ **Figure 1.7.10** Newton's cradle is an instructive toy for studying collisions and conservation of energy.

### Driving and car safety

#### Braking distance and speed

For a car moving with speed $v$, the brakes must be applied over a braking distance $s$ to bring the car to rest. The *braking distance is directly proportional to the square of the speed*, i.e. if $v$ is doubled, $s$ is quadrupled. The thinking distance (i.e. the distance travelled while the driver is reacting before applying the brakes) has to be added to the braking distance to obtain the overall stopping distance, in other words

$$\text{stopping distance} = \text{thinking distance} + \text{braking distance}$$

Typical values taken from the Highway Code are given in Table 1.7.1 for different speeds. The greater the speed, the greater the stopping distance for a given braking force. (To stop the car in a given distance, a greater braking force is needed for higher speeds.)

▼ **Table 1.7.1**

| **Speed/km/h** | 30 | 60 | 90 | 120 |
|---|---|---|---|---|
| **Thinking distance/metres** | 6 | 12 | 18 | 24 |
| **Braking distance/metres** | 6 | 24 | 54 | 96 |
| **Total stopping distance/metres** | 12 | 36 | 72 | 120 |

Thinking distance depends on the driver's reaction time – this will vary with factors such as the driver's degree of tiredness, use of alcohol or drugs, eyesight and the visibility of the hazard. Braking distance varies with both the road conditions and the state of the car; it is longer when the road is wet or icy, when friction between the tyres and the road is low, than when conditions are dry. Efficient brakes and deep tyre tread help to reduce the braking distance.

#### Car design and safety

When a car stops rapidly in a collision, large forces are produced on the car and its passengers, and their kinetic energy has to be dissipated.

Crumple zones at the front and rear collapse in such a way that the kinetic energy is absorbed gradually (Figure 1.7.11). As we saw in Topic 1.6, this extends the collision time and reduces the decelerating force and hence the potential for injury to the passengers.


▲ **Figure 1.7.11** Cars in an impact test showing the collapse of the front crumple zone

Extensible seat belts exert a backwards force (of 10 000 N or so) over about 0.5 m, which is roughly the distance between the front seat occupants and the windscreen. In a car travelling at 15 m/s (54 km/h), the effect felt by anyone *not* using a seat belt is the same as that, for example, produced by jumping off a building 12 m high.

Air bags in most cars inflate and protect the driver from injury by the steering wheel.

Head restraints ensure that if the car is hit from behind, the head goes forwards with the body and not backwards over the top of the seat. This prevents damage to the top of the spine.

All these are secondary safety devices which aid *survival* in the event of an accident. Primary safety factors help to *prevent* accidents and depend on the car's roadholding, brakes, steering, handling and above all on the driver since most accidents are due to driver error.

The chance of being killed in an accident is about *five times less* if seat belts are worn and head restraints are installed.

## Test yourself

1 Name the way by which energy is transferred in the following processes
   a a battery is used to light a lamp
   b a ball is thrown upwards
   c water is heated in a boiler.
2 State how energy is stored in the following
   a fossil fuels
   b hot water
   c a rotating turbine
   d a stretched spring.

3 Calculate the kinetic energy of a
   a 1 kg trolley travelling at 2 m/s
   b 2 g (0.002 kg) bullet travelling at 400 m/s
   c 500 kg car travelling at 72 km/h.
4 a What is the velocity of an object of mass 1 kg which has 200 J of kinetic energy?
   b Calculate the potential energy of a 5 kg mass when it is i 3 m and ii 6 m, above the ground. ($g = 9.8$ N/kg)
5 It is estimated that $7 \times 10^6$ kg of water pours over the Niagara Falls every second.
   If the falls are 50 m high, and if all the energy of the falling water could be harnessed, what power would be available? ($g = 9.8$ N/kg)

# 1.7.2 Work

**FOCUS POINTS**

★ Understand that when mechanical or electrical work is done, energy is transferred.
★ Use the correct equation to calculate mechanical work.

In science the word work has a different meaning from its everyday use. Here work is associated with the motion of a force. When you lift and move a heavy box upstairs you will have done work in either sense! In the absence of heat being generated, the work done is a measure of the amount of energy transferred. When moving the heavy box, chemical energy from your muscles is transferred to gravitational potential energy. If an electric motor is used to move the box, an equal amount of electrical work will be done. In this topic you will learn how to calculate the mechanical work done in different situations.

## Work

In an energy transfer, work is done. *The work done is a measure of the amount of energy transferred.* The same amount of mechanical or electrical work is done in transferring equal amounts of energy.

Mechanical **work** is done when a force moves. No work is done in the scientific sense by someone standing still holding a heavy pile of books: an upward force is exerted, but no motion results.

If a building worker carries ten bricks up to the first floor of a building, they do more work than if they carry only one brick because they have to exert a larger force. Even more work is required if they carry the ten bricks to the second floor.

The amount of work done $W$ depends on the size of the force $F$ applied and the distance $d$ it moves. We therefore measure work by

$$\text{work} = \text{force} \times \text{distance moved in direction of force}$$

or $$W = Fd = \Delta E$$

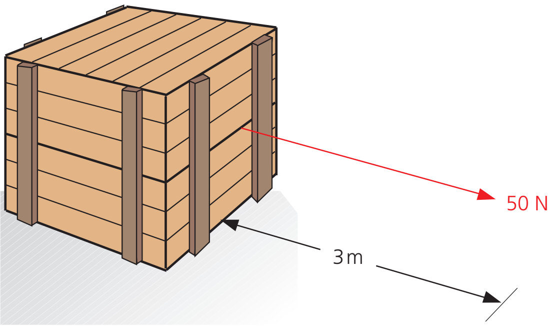
where $\Delta E$ is the energy transferred.

The unit of work is the **joule** (J); it is the work done when a force of 1 newton (N) moves through 1 metre (m). For example, if you have to pull with a force of 50 N to move a crate steadily 3 m in the direction of the force (Figure 1.7.12a), the work done is 50 N × 3 m = 150 N m = 150 J. That is

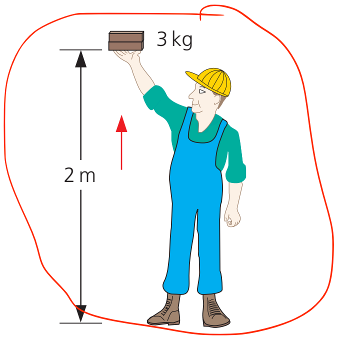
$$\text{joules} = \text{newtons} \times \text{metres}$$

If you lift a mass of 3 kg vertically through 2 m (Figure 1.7.12b), you have to exert a vertically upward force equal to the weight of the body, i.e. 30 N (approximately), and the work done is 30 N × 2 m = 60 N m = 60 J.

Note that you must always take the distance in the direction in which the force acts.




▲ **Figure 1.7.12a**




▲ **Figure 1.7.12b**

## Test yourself

6 How much work is done when a mass of 3 kg ($g$ = 9.8 N/kg) is lifted vertically through 6 m?

7 A hiker climbs a hill 300 m high. If she has a mass of 51 kg, calculate the work she does in lifting her body to the top of the hill.

8 An electric motor does 80 J of work in lifting a box vertically upwards through 5 m. Calculate the weight of the box.

# 1.7.3 Energy resources

## FOCUS POINTS

★ Understand the various ways that useful energy may be obtained or electrical power generated and give advantages and disadvantages of each method.
★ Understand efficiency of energy transfer.

★ Know that energy is released by nuclear fusion in the Sun and that research is being carried out into how energy released from nuclear fusion could produce large-scale electrical energy.
★ Define efficiency and use the correct equations to calculate it.

Energy is needed to heat buildings, to make cars move, to provide artificial light, to make computers work, and so on. The list is endless. This useful energy needs to be produced in controllable energy transfers. For example, in power stations a supply of useful energy is transferred by electric currents to different energy stores required by electricity customers. The raw materials for energy production are energy sources. These may be non-renewable or renewable.

In this topic you will learn that, apart from nuclear, geothermal, hydroelectric or tidal energy, energy released by nuclear fusion in the Sun (Topic 5.1) is the source for all our energy resources. Although energy cannot be destroyed, as you learnt in the previous section, it can be transferred into non-useful stores, such as internal energy. The efficiency of a device measures the useful energy as a percentage of the total energy supplied.

You will be able to recognise many different types of **energy sources**. Such sources may be **renewable** or **non-renewable**; non-renewable sources represent previously stored energy. Much of the energy used in everyday life is ultimately derived from the release of energy in the Sun by nuclear fusion. Sunlight is used in biological processes to store chemical energy and can be harnessed to generate electricity directly in solar cells.

## Non-renewable energy sources

Once used up these cannot be replaced.

Two advantages of all non-renewable fuels are

(i) their high **energy density** (i.e. they are concentrated sources) and the relatively small size of the energy transfer device (e.g. a furnace) which releases their energy, and

(ii) their ready **availability** when energy demand increases suddenly or fluctuates seasonally.

### Fossil fuels

**Fossil fuels** include coal, oil and natural gas, formed from the remains of plants and animals which lived millions of years ago and obtained energy originally from the Sun. Their energy is stored as chemical energy and at present they are our main energy source. Predictions vary as to how long they will last since this depends on what reserves are recoverable and on the future demands of a world population expected to increase from about 7700 million in 2019 to about 9700 million by the year 2050. Some estimates say oil and gas will run low early in the present century but coal should last for 200 years or so.

Burning fossil fuels in power stations and in cars pollutes the atmosphere with harmful gases such as carbon dioxide and sulfur dioxide. Carbon dioxide emission aggravates the greenhouse effect (Topic 2.3) and increases global warming. It is not immediately feasible to prevent large amounts of carbon dioxide entering the atmosphere, but less is produced by burning natural gas than by burning oil or coal; burning coal produces most carbon dioxide for each unit of energy produced. When coal and oil are burnt they also produce sulfur dioxide which causes acid rain. The sulfur dioxide can be extracted from the waste gases so it does not enter the atmosphere or the sulfur can be removed from the fuel before combustion, but these are both costly processes which increase the price of electricity produced using these measures.

### Nuclear fuels

The energy released in a nuclear reactor (Topic 5.1) from the fission of uranium, found as an ore in the ground, can be used to produce electricity. **Nuclear fuels** do not pollute the atmosphere with carbon dioxide or sulfur dioxide but they do generate **radioactive** waste materials with very long half-lives (Topic 5.2); safe ways of storing this waste for perhaps thousands of years must be found. As long as a reactor is operating normally it does not pose a radiation risk, but if an accident occurs, dangerous radioactive material can leak from the reactor and spread over a large area.

## Renewable energy sources

These cannot be exhausted and are generally non-polluting.

### Solar energy

The energy falling on the Earth from the Sun is transferred mostly by visible light and infrared radiation and in an hour equals the total energy used by the world in a year. Unfortunately, its low energy density requires large collecting devices and its availability varies. The greatest potential use of **solar energy** is as an energy source for low-temperature water heating. The energy transferred by electromagnetic waves from the Sun is stored as internal energy in **solar panels** and can be transferred by heating to produce domestic hot water at about 70°C and to heat swimming pools.

Solar energy can also be used to produce high-temperature heating, up to 3000°C or so, if a large curved mirror (a solar furnace) focuses the Sun's rays onto a small area. The energy can then be used to turn water to steam for driving the turbine of an electric generator in a power station.

Solar cells, made from semiconducting materials, convert sunlight into electricity directly. A number of cells connected together can be used to supply electricity to homes (Figure 1.7.13) and to the electronic equipment in communication and other satellites. They are also used for small-scale power generation in remote areas where there is no electricity supply. The energy generated by solar cells can be stored in batteries for later use. Recent developments have made large-scale generation more cost effective and large solar power plants are becoming more common. There are many designs for prototype light vehicles run on solar power (Figure 1.7.14).

▲ **Figure 1.7.13** Solar cells on a house provide electricity.

▲ **Figure 1.7.14** Solar-powered car

## Wind energy

Infrared radiation from the Sun is also responsible for generating wind energy. Giant windmills called **wind turbines** with two or three blades each up to 30 m long drive electrical generators. Wind farms of 20 to 100 turbines spaced about 400 m apart (Figure 1.7.15) supply about 400 MW (enough electricity for 250 000 homes) in the UK and provide a useful 'top-up' to the National Grid.

Wind turbines can be noisy and are considered unsightly by some people so there is some environmental objection to wind farms, especially as the best sites are often in coastal or upland areas of great natural beauty.

▲ **Figure 1.7.15** Wind farm turbines

## Wave energy

The rise and fall of sea waves have to be transferred by some kind of **wave energy** converter into the rotary motion required to drive a generator. It is a difficult problem and the large-scale production of electricity by this means is unlikely in the near future. However, small systems are being developed to supply island communities with power.

## Tidal and hydroelectric energy

The flow of water from a higher to a lower level from behind a **tidal barrage** (barrier) or a hydroelectric dam (**tidal energy**) is used to drive a water turbine (water wheel) connected to a generator.

One of the largest working tidal schemes is the La Grande I project in Canada (Figure 1.7.16). Such schemes have significant implications for the environment, as they may destroy wildlife habitats of wading birds for example, and also for shipping routes.

Over 100 years ago, India was one of the first countries to develop hydroelectric power; today such power provides about 14% of the country's electricity supply. China is the world's largest producer of hydroelectricity, generating around 20% of the country's needs. With good management, **hydroelectric energy** is a reliable energy source, but there are risks connected with the construction of dams, and a variety of problems may result from the impact of a dam on the environment. Land previously used for forestry or farming may have to be flooded.

▲ **Figure 1.7.16** Tidal barrage in Canada

## Geothermal energy

If cold water is pumped down a shaft into hot rocks below the Earth's surface, it may be forced up another shaft as steam. This can be used to drive a turbine and generate electricity or to heat buildings. The **geothermal energy** that heats the rocks is constantly being released by radioactive elements deep in the Earth as they decay (Topic 5.2).

Geothermal power stations are in operation in the USA, New Zealand and Iceland. A disadvantage is that they can only be built in very specific locations where the underlying rocks are hot enough for the process to be viable.

## Biofuels (vegetable fuels)

Biomass includes cultivated crops (e.g. oilseed rape), crop residues (e.g. cereal straw), natural vegetation (e.g. gorse), trees grown for their wood (e.g. spruce), animal dung and sewage. Chemical energy can be stored in **biofuels** such as alcohol (ethanol) and methane gas can be obtained from them by fermentation using enzymes or by decomposition by bacterial action in the absence of air. Liquid biofuels can replace petrol (Figure 1.7.17); although they have up to 50% less energy per litre, they are lead- and sulfur-free and so do not pollute the atmosphere with lead or sulfur dioxide when they are burned. **Biogas** is a mix of methane and carbon dioxide with an energy content about two-thirds that of natural gas. It is produced from animal and human waste in digesters (Figure 1.7.18) and used for heating and cooking. Biogas is cheap to produce on a small scale but not economically viable for large-scale production. It reduces landfills but due to its methane content it is unstable and may explode.


▲ **Figure 1.7.17** Filling up with biofuel in Brazil

▲ **Figure 1.7.18** Methane generator in India

## The Sun as an energy source

The Sun is the main source of energy for many of the energy sources described above. The exceptions are geothermal, nuclear and tidal sources. Fossil fuels such as oil, coal and gas are derived from plants which grew millions of years ago in biological processes requiring light from the Sun. Sunlight is also needed by the plants used in biomass energy production today. Energy from the Sun drives the weather systems which enable wind and hydroelectric power to be harnessed. Solar energy is used directly in solar cells for electricity generation.

The source of the Sun's energy is nuclear fusion in the Sun. You will learn more about the fusion process which produces large amounts of energy in Topic 5.1. At present it is not possible to reproduce the fusion process on Earth for the large-scale production of electricity but much research is being directed towards that goal.

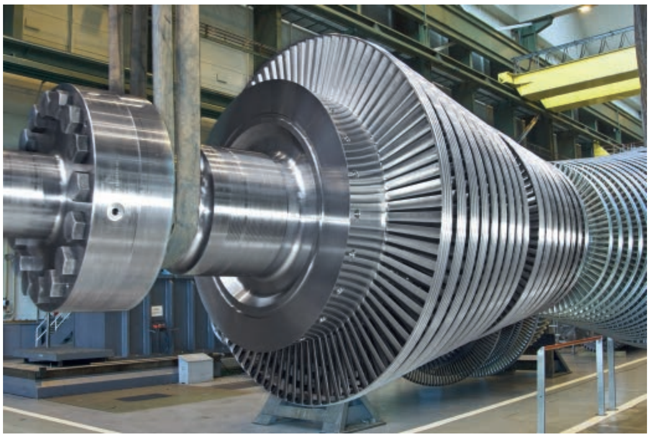
## Power stations

The processes involved in the production of electricity at power stations depend on the energy source being used.

### Non-renewable sources

Fossil fuels and nuclear fuels are used in **thermal power stations** to provide thermal energy that turns water into steam. The steam drives turbines which in turn drive the generators that produce electricity as described in Topic 4.5. If fossil fuels are the energy source (usually coal but natural gas is favoured in new stations), the steam is obtained from a boiler. If nuclear fuel is used, such as uranium or plutonium, the steam is produced in a heat exchanger as explained in Topic 5.1.

The action of a **steam turbine** resembles that of a water wheel but moving steam, not moving water, causes the motion. Steam enters the turbine and is directed by the **stator** or diaphragm (sets of fixed blades) onto the **rotor** (sets of blades on a shaft that can rotate) (Figure 1.7.19). The rotor revolves and drives the electrical generator. The steam expands as it passes through the turbine and the size of the blades increases along the turbine to allow for this.



▲ **Figure 1.7.19** The rotor of a steam turbine

The overall efficiency of thermal power stations is only about 30%. They require cooling towers to condense steam from the turbine to water and this is a waste of energy.

A Sankey diagram (Figure 1.7.5) shows the energy transfers that occur in a thermal power station.

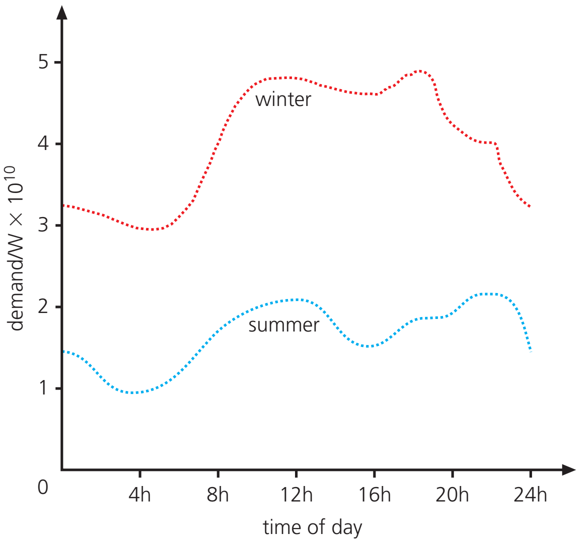
In gas-fired power stations, natural gas is burnt in a **gas turbine** linked directly to an electricity generator. The hot exhaust gases from the turbine are not released into the atmosphere but used to produce steam in a boiler. The steam is then used to generate more electricity from a steam turbine driving another generator. The efficiency is claimed to be over 50% without any extra fuel consumption. Furthermore, the gas turbines have a near 100% combustion efficiency, so very little harmful exhaust gas (i.e. unburnt methane) is produced, and natural gas is almost sulfur-free, so the environmental pollution caused is much less than for coal.

### Renewable sources

In most cases the renewable energy source is used to drive turbines directly, as explained earlier in the cases of hydroelectric, wind, wave, tidal and geothermal schemes.

The efficiency of a large installation can be as high as 85–90% since many of the causes of loss in thermal power stations (e.g. water-cooling towers) are absent. In some cases, the generating costs are half those of thermal stations.

A feature of some hydroelectric stations is **pumped storage**. Electricity cannot be stored on a large scale but must be used as it is generated. The demand varies with the time of day and the season (Figure 1.7.20), so in a pumped-storage system electricity generated at off-peak periods is used to pump water back up from a low-level reservoir to a higher-level one. It is easier to do this than to reduce the output of the generator. At peak times the potential energy of the water in the high-level reservoir is converted back into electricity; three-quarters of the electricity that was used to pump the water is generated.




▲ **Figure 1.7.20** Variation in power demand

## Economic, environmental and social issues

When considering the large-scale generation of electricity, the economic and environmental costs of using various energy sources have to be weighed against the benefits that electricity brings to society as a clean, convenient and fairly cheap energy supply.

Environmental problems such as polluting emissions that arise with different energy sources were outlined when each was discussed previously. Apart from people using less energy, how far pollution can be reduced by, for example, installing desulfurisation processes in coal-fired power stations, is often a matter of cost.

Although there are no fuel costs associated with electricity generation from renewable energy sources such as wind power, the energy is so dilute that the capital costs of setting up the generating installation are high. Similarly, although fuel costs for nuclear power stations are relatively low, the costs of building the stations and of dismantling them at the end of their useful lives is higher than for gas- or coal-fired stations.

It has been estimated that currently it costs between 9 USc and 22 USc to produce a unit of electricity in a gas- or coal-fired power station in the UK. Wind energy costs vary, depending upon location, but are in the range 7 USc to 16 USc per unit. In the most favourable locations wind competes with coal and gas generation. The cost for a nuclear power station is in excess of 10 USc per unit. After the Tohoku earthquake and tsunami disaster which led to the damage and closure of the Fukushima nuclear reactor in Japan, several countries have reduced their dependence on nuclear energy and Germany plans to phase out nuclear power completely by 2022.

The reliability of a source has also to be considered, as well as how easily production can be started up and shut down as demand for electricity varies. Natural gas power stations have a short start-up time, while coal and then oil power stations take successively longer to start up; nuclear power stations take longest. They are all reliable in that they can produce electricity at any time of day and in any season of the year as long as fuel is available. Hydroelectric power stations are also very reliable and have a very short start-up time, which means they can be switched on when the demand for electricity peaks. The electricity output of a tidal power station, although predictable, is not as reliable because it depends on the height of the tide which varies over daily, monthly and seasonal time scales. The wind and the Sun are even less reliable sources of energy since the output of a wind turbine changes with the strength of the wind and that of a solar cell with the intensity of light falling on it; the output may not be able to match the demand for electricity at a particular time.

Renewable sources are still only being used on a small scale globally. The contribution of the main energy sources to the world's total energy consumption at present is given in Table 1.7.2. (The use of biofuels is not well documented.) The great dependence on fossil fuels worldwide is evident. It is clear the world has an energy problem and new solutions to energy production need to be found.

▼ **Table 1.7.2** World use of energy sources

| Oil | Coal | Gas | Nuclear | Hydroelectric |
|---|---|---|---|---|
| 34% | 27% | 24% | 4% | 7% |

Consumption varies from one country to another; North America and Europe are responsible for about 42% of the world's energy consumption each year. Table 1.7.3 shows approximate values for the annual consumption per head of population for different areas. These figures include the hidden consumption in the manufacturing and transporting of goods. The world average consumption is $76 \times 10^9$ J per head per year.

▼ **Table 1.7.3** Energy consumption per head per year/J $\times 10^9$

| N. America | UK | Japan | S. America | China | Africa | India | Malaysia |
|---|---|---|---|---|---|---|---|
| 240 | 121 | 150 | 56 | 97 | 15 | 25 | 130 |

## Efficiency of energy transfers

1 The **efficiency** of a device is the percentage of the energy supplied to it that is usefully transferred.

2 Efficiency is calculated from the expression

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

For example, for the lever shown in Figure 1.5.22 (p. 45)

$$\text{efficiency} = \frac{\text{work done on load}}{\text{work done by effort}} \times 100\%$$

This will be less than 100% if there is friction in the fulcrum.

**Key definition**

**Efficiency** (%) efficiency $= \frac{\text{(useful energy output)}}{\text{(total energy input)}}$ (× 100%)

Table 1.7.4 lists the efficiencies of some devices.

▼ **Table 1.7.4**

| Device | % efficiency |
|---|---|
| large electric motor | 90 |
| large electric generator | 90 |
| domestic gas boiler | 75 |
| compact **fluorescent** lamp | 50 |
| steam turbine | 45 |
| car engine | 25 |
| filament lamp | 10 |

A device is efficient if it transfers energy mainly to useful stores and the lost energy is small.

The efficiency of a device can also be defined in terms of power output and input

$$\text{efficiency} = \frac{\text{(useful power output)}}{\text{(total power input)}} \times 100\%$$

**Key definition**

**Efficiency** (%) efficiency $= \frac{\text{(useful power output)}}{\text{(total power input)}}$ (× 100%)

### Worked example

**a** The energy input to an electric motor is 400 J when raising a load of 200 N through a vertical distance of 1.5 m. Calculate the efficiency of the motor.

work done on load = force × distance
= 200 N × 1.5 m
= 300 N m = 300 J

useful energy output 300 J

total energy input = 400 J

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

$$= \frac{300\,\text{J}}{400\,\text{J}} \times 100\% = 75\%$$

**b** If the energy input to an electric drill is 300 J/s and it transfers 100 J/s of energy to thermal energy when in use, calculate its efficiency.

power supplied to the drill = 300 J/s

useful power output = (300 – 100) J/s
= 200 J/s

$$\text{efficiency} = \frac{\text{(useful power output)}}{\text{(total power input)}} \times 100\%$$

$$= \frac{200}{300} \times 100\% = 67\%$$

#### Now put this into practice

1 A robot is used to lift a load. If the energy input to the robot is 8000 J in the time it takes to lift a load of 500 N through 12 m, calculate the efficiency of the robot.

2 If the energy input to an electric motor is 560 J/s and 170 J/s of energy is transferred to thermal energy when in use, calculate its efficiency.

### Test yourself

9 List six properties which you think the ideal energy source should have for generating electricity in a power station.

10 **a** List six social everyday benefits for which electricity generation is responsible.
**b** Draw up two lists of suggestions for saving energy
**i** in the home, and
**ii** globally.

11 Calculate the efficiency of a compact fluorescent light if a power input of 20 J/s gives an output power of 9 J/s.

# 1.7.4 Power

## FOCUS POINT

★ Define power and use the correct equations to calculate power in terms of the rate at which work is done or energy transferred.

**To heat up a frozen dinner in a microwave oven you need to know the power of the oven, if over- or under-cooking is to be avoided. Similarly, one needs to check the power rating of a light bulb before inserting it into a socket to ensure over-heating does not occur. Most electrical appliances have their power rating marked on them, usually at the rear or base of the device. The power of a device is the rate at which it does work and so is equal to the rate at which it transfers energy to different stores.**

## Power

The more powerful a car is, the faster it can accelerate or climb a hill, i.e. the more rapidly it does work. The **power** of a device is the work it does per second, i.e. the rate at which it does work. This is *the same as the rate at which it transfers energy from one store to another.*

$$\text{power} = \frac{\text{work done}}{\text{time taken}} = \frac{\text{energy transferred}}{\text{time taken}}$$

$$\text{power } P = \frac{W}{t}$$

where $W$ is the work done in time $t$

$$\text{also } P = \frac{\Delta E}{t}$$

where $\Delta E$ is the energy transferred in time $t$.

### Key definition

**Power** the work done per unit time and the energy transferred per unit time

The unit of power is the **watt** (W) and is *a rate of working of 1 joule per second*, i.e. 1 W = 1 J/s. Larger units are the **kilowatt** (kW) and the **megawatt** (MW):

$$1\,\text{kW} = 1000\,\text{W} = 10^3\,\text{W}$$

$$1\,\text{MW} = 1\,000\,000\,\text{W} = 10^6\,\text{W}$$

If a machine does 500 J of work in 10 s, its power is 500 J/10 s = 50 J/s = 50 W. A small car develops a maximum power of about 25 kW.

### Test yourself

12 A boy whose weight is 600 N runs up a flight of stairs 10 m high in 12 s. What is his average power?

13 Calculate the power of a lamp that transfers 2400 J to thermal energy in 1 minute.

14 An escalator carries 60 people of average mass 70 kg to a height of 5 m in one minute. Find the power needed to do this.

### Practical work

#### Measuring your own power

##### Safety

- You should only volunteer for this if you feel able to. No one should pressure you into taking part.

Get someone with a stopwatch to time you running up a flight of stairs; the more steps the better. Find your weight (in newtons). Calculate the total vertical height (in metres) you have climbed by measuring the height of one step and counting the number of steps.

The work you do (in joules) in lifting your weight to the top of the stairs is (your weight) × (vertical height of stairs). Calculate your power (in watts).

5 Name the stores between which energy is transferred as you run up the stairs.

6 How is energy transferred when you run up the stairs?

## Revision checklist

After studying Topic 1.7 you should know and understand the following:

✓ work is done when energy is transferred

✓ the Sun is the main source of energy for all our energy resources except geothermal, nuclear and tidal

✓ energy is released by nuclear fusion in the Sun

✓ the different ways of harnessing solar, wind, wave, tidal, hydroelectric, geothermal and biofuel energy

✓ the difference between renewable and non-renewable energy sources

✓ how nuclear fuel and the chemical energy stored in fuel are used to generate electricity in power stations

✓ the meaning of efficiency in energy transfers and that power is the rate of energy transfer.

After studying Topic 1.7 you should be able to:

✓ recall different stores of energy and describe energy transfers in given examples

✓ recall the principle of conservation of energy and apply it to simple systems including the interpretation of flow diagrams

✓ define kinetic energy and perform calculations using $E_k = \frac{1}{2}mv^2$

✓ define gravitational potential energy and perform calculations using $\Delta E_p = mgh$

✓ apply the principle of conservation of energy to complex systems and interpret Sankey diagrams

✓ relate work done to the magnitude of a force and the distance moved, and recall the units of work, energy and power

✓ recall and use the equation $W = F \times d = \Delta E$ to calculate energy transfer

✓ compare and contrast the advantages and disadvantages of using different energy sources to generate electricity

✓ define efficiency in relation to the transfer of energy and power.

# Exam-style questions

**1** State how energy is transferred from
- **a** a toaster [2]
- **b** a refrigerator [2]
- **c** an audio system. [2]

[Total: 6]

**2** A 100 g steel ball falls from a height of 1.8 m onto a metal plate and rebounds to a height of 1.25 m. Calculate the
- **a** potential energy of the ball before the fall ($g = 9.8\,\text{m/s}^2$) [2]
- **b** kinetic energy of the ball as it hits the plate [1]
- **c** velocity of the ball on hitting the plate [3]
- **d** kinetic energy of the ball as it leaves the plate on the rebound [2]
- **e** velocity of rebound. [3]

[Total: 11]

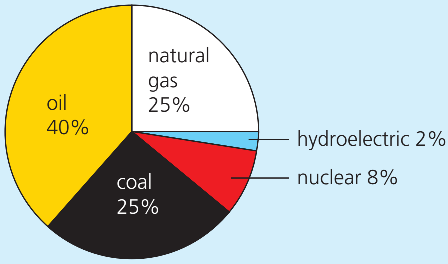
**3** A ball of mass 0.5 kg is thrown vertically upwards with a kinetic energy of 100 J. Neglecting air resistance calculate
- **a** the initial speed of the ball [3]
- **b** the potential energy of the ball at its highest point [1]
- **c** the maximum height to which the ball rises. [3]

[Total: 7]

**4** In loading a lorry a man lifts boxes each of weight 100 N through a height of 1.5 m.
- **a** Calculate the work done in lifting one box. [2]
- **b** Calculate how much energy is transferred when one box is lifted. [1]
- **c** If he lifts four boxes per minute, at what power is he working? [3]

[Total: 6]

**5** The pie chart in Figure 1.7.21 shows the percentages of the main energy sources used by a certain country.




▲ **Figure 1.7.21**

- **a** Give the percentage supplied by water. [1]
- **b** Name any of the sources that are renewable. [1]
- **c** Explain what is meant by a renewable source. [1]
- **d** Name two other renewable sources. [2]
- **e** If energy is always conserved, explain the importance of developing renewable sources. [2]

[Total: 7]

**6**
- **a** Give
  - **i** two advantages and
  - **ii** two disadvantages

  of using fossil fuels in electricity generating stations. [4]
- **b** Give
  - **i** two advantages and
  - **ii** two disadvantages

  of using solar energy in electricity generating stations. [4]

[Total: 8]

**7** When the energy input to a gas-fired power station is 1000 MJ, the energy output is 300 MJ.
- **a** Calculate the efficiency of the power station. [3]
- **b** Calculate how much energy is lost and name the energy store to which it is moved. [2]
- **c** Describe where the lost energy goes. [2]

[Total: 7]