IB Physics DP

YOUR NOTES

8. Energy Production

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8.1 Energy Sources

8.1.1 Specific Energy

Specific Energy

- The amount of energy that a fuel can provide for the amount of fuel used is an important consideration for the modern world
- In order to compare fuels by unit, either mass or volume can be used
  - Comparing by **mass** is known as **specific energy**
  - Comparing by **volume** is known as **energy density**

- Specific energy (E_S) is a measure of the amount of **energy per unit mass** of a fuel
  - It is measured in J kg^{-1}

- Energy density (E_D) is a measure of the amount of **energy per unit volume** of a fuel
  - It is measured in J m^{-3}

- The formula used to calculate **density** from **specific energy** and **energy density** is:

$$density = \frac{Energy\ density}{Specific\ energy}$$

- Energy density is related to specific energy by the **density** of relevant fuel and can be converted between the two quantities this value of density

? Worked Example

Use the values of specific energy for coal: 35 MJ kg^{-1} and energy density for coal: 2 × 10^4 MJ m^{-3}

Estimate the approximate density for coal.

Step 1: List known values

- Specific energy: 35 MJ kg^{-1}
- energy density: 2 × 10^4 MJ m^{-3}

Step 2: Identify relationship needed

- Density has units of kg m^{-3}
- Therefore, energy density must be divided by specific energy

Step 3: Perform the division

$$ED \div SE = (2 \times 10^4) \div 35 \approx 571 \text{ kg m}^{-3}$$

Step 4: State the final answer

- The approximate density of coal is: **571 kg m^{-3}**

Examples of Common Fuels: Energy Density and Specific Energy Table

Fuel	Specific energy (MJ kg^{-1})	Energy density (MJ m^{-3})
Coal	35	2×10^4
Hydrogen	130	10
Kerosene	48	3.3×10^4
Gasoline (petrol)	45	3.4×10^4
Wood	15.5	1×10^4
Uranium–235 (fission)	7.5×10^7	4×10^{13}

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Exam Tip

The term *specific* in physics means per unit mass. For example, in specific heat capacity, the unit is per unit mass (and per degree temperature). Make sure not to confuse specific energy and specific heat capacity which are different concepts though related as they both refer to mass and energy!

8.1.2 Sankey Diagrams

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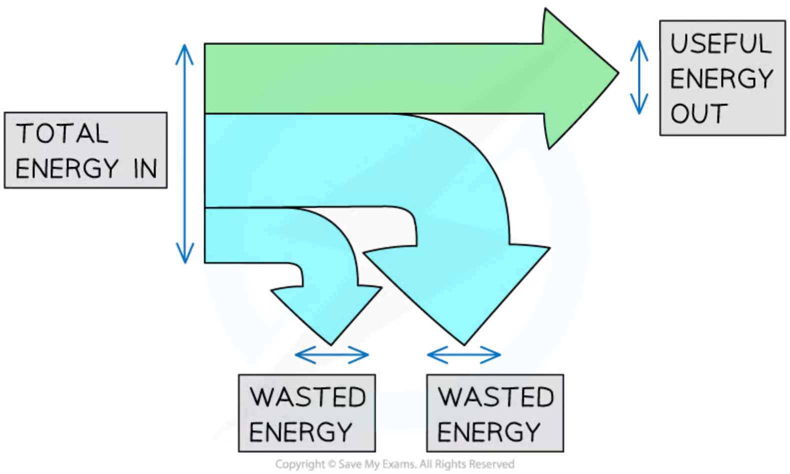
Sankey Diagrams

- Diagrams are used to represent energy transfers
  - These are sometimes called **Sankey diagrams**
- The arrow in a Sankey diagram represents the transfer of energy:
  - The end of the arrow pointing to the right represents the energy that ends up in the desired store (the **useful energy output**)
  - The end(s) that point(s) down represents the **wasted energy**



Total energy in, wasted energy and useful energy out shown on a Sankey diagram

- The width of each arrow is proportional to the amount of energy going to each store
- As a result of the conversation of energy:

Total energy in = Useful energy out + Wasted energy

- A Sankey diagram for a modern efficient light bulb will look very different from that for an old filament light bulb
- A more efficient light bulb has **less** wasted energy
  - This is shown by the smaller arrow downwards representing the heat energy

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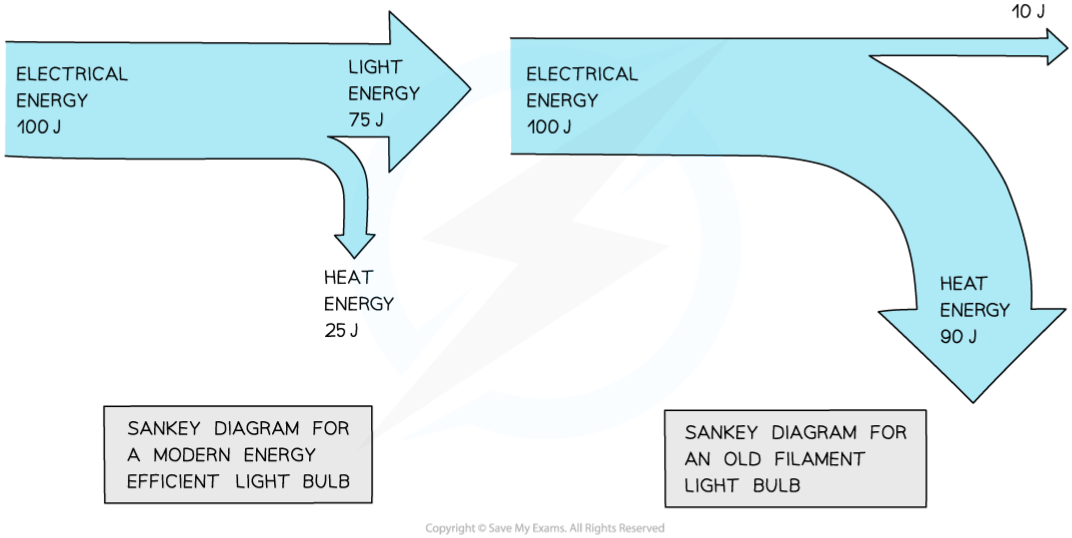
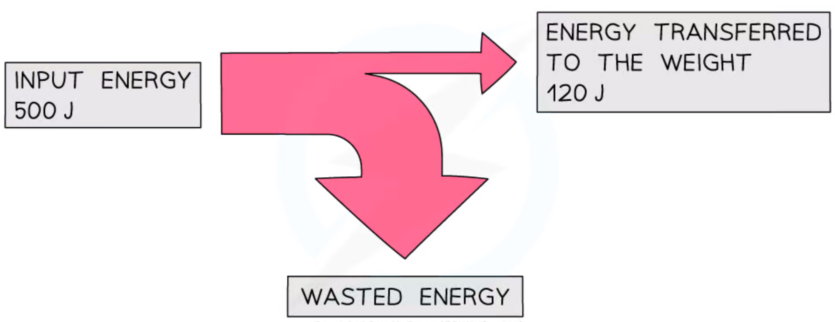


Sankey diagram for modern vs. old filament light bulb

Worked Example

An electric motor is used to lift a weight. The diagram represents the energy transfers in the motor.



How much energy is wasted?

Step 1: State the conservation of energy

- Energy cannot be created or destroyed, it can only be moved from one store to another
- This means that:

Total energy in = Useful energy out + Wasted energy

Step 2: Rearrange the equation for the wasted energy

Wasted energy = Total energy in – Useful energy out

Step 3: Substitute the values from the diagram

500 – 120 = **380 J**

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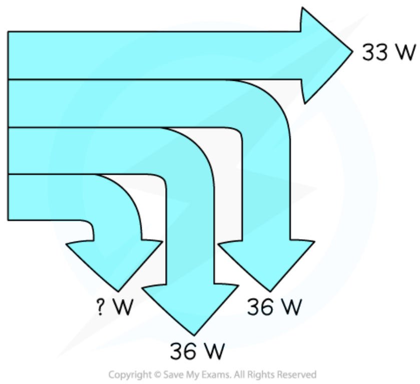
Worked Example

A small electric car is driven by a 120 Watt motor.

The useful power output of the motor is measured to be 33 W. While 36 W of power is wasted on friction losses and a further 36 W is wasted on traction losses.

Further power is lost by the electric car during operation. This situation is shown in the diagram below.



Determine what is the remaining power loss for the electric car when operating?

Step 1: State the conservation of energy

- Energy cannot be created or destroyed, it can only be moved from one store to another
- This also applies to power
- This means that:

Total power in = Useful power out + Friction losses + Traction losses + Wasted power other losses

Step 2: Rearrange the equation for the wasted power

Wasted power other losses = Total power in – (Useful power out + Friction losses + Traction losses)

Step 3: Substitute the values from the diagram

120 – (33 + 36 + 36) = **15 W**

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Exam Tip

- Drawing good Sankey diagrams takes practice.
- Start by planning your diagram:
  - How wide are you going to make the input arrow?
  - How wide will the 'useful energy out' arrow need to be?
  - How wide must the 'wasted energy' arrow be?
- Next, start drawing the diagram one step at a time:
  - Draw the left hand side of the arrow, along with the line going across the top
  - Next add the 'useful energy out' arrow, making sure it is the correct width
  - Now carefully mark the start and end of the wasted arrow – make sure your marks are the correct distance apart!
  - Finally join the markings together, finishing the 'wasted energy' arrow

8.1.3 Primary & Secondary Energy Sources

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Primary Energy Sources

- Primary energy sources are found in nature and have some stored energy capacity
- To be a primary energy source, there must be:
  - No processing or refining
  - Stored energy must occur naturally in the source
- **The definition of a primary energy source is:**

  Energy sources found in the natural environment

- Examples of primary energy sources include fuels such as:
  - oil
  - kerosene
  - coal
  - Nuclear material for fission
- Primary energy sources can also be renewables such as:
  - Geothermal
    - Heat from the Earth's crust
  - Hydroelectric
    - Energy stored in water higher than a set of turbines
  - Solar power
    - Radiation energy from the Sun
  - Wind power
    - Kinetic energy contained within the wind
  - Tidal power
    - Kinetic energy contained within the tides
- In each example listed above, the primary energy source is the focus of the collection
  - Once processing or conversion of energy from one form to another occurs, then it is no longer a primary energy source

Secondary Energy Sources

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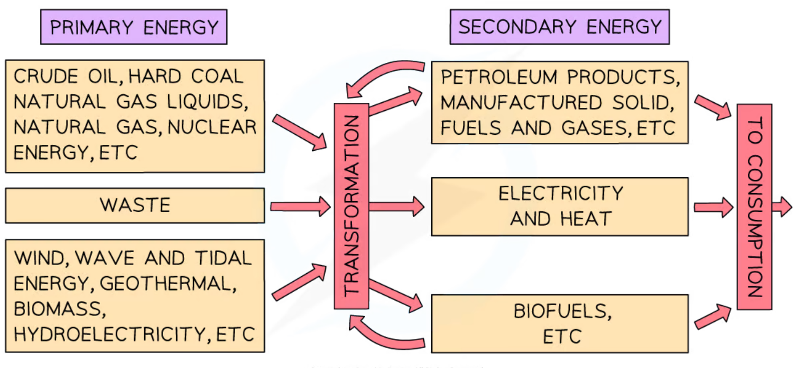
- Secondary energy sources come from the use or processing of primary energy sources
- Often the secondary energy source is electricity
  - It can also be petrol, biofuel and heat
- **The definition of a secondary energy resource is:**

Useful transformations of the primary resources into energy

- Examples include:
  - Stored gravitational energy from water is converted into **electricity** in a hydroelectric plant.
  - Oil is refined to produce **petrol** that can be used to power a car
  - Coal is burnt to produce **heat** on a fire

- The table below shows examples of primary and secondary energy sources as they are used to produce useful energy



8.1.4 Energy Resources

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Energy Resources

- Energy resources are large stores of energy that can be transferred from one form into electrical energy that can be used by society
- Generating energy reliably requires the use of a range of different energy resources

Renewable Energy Resources

- A renewable energy resource is defined as

An energy source that is replenished at a faster rate than the rate at which it is being used

- As a result of this, renewable energy resources cannot run out
- Renewable resources include:
  - Solar energy
  - Wind
  - Bio-fuel
  - Hydroelectricity
  - Geothermal
  - Tidal
  - Bio-fuels

Non-Renewable Energy Resources

- Non-renewable energy resources are those that cannot replenish faster than they are used
- Non-renewable resources include:
  - Petrol (gasoline)
  - Diesel
  - Coal
  - Natural gas
  - Nuclear fission

Energy Resources Table

Energy Resource	Description
Fossil fuels	Burning fossil fuels produces steam, which can turn turbines
Nuclear	Nuclear fuel is reacted, producing heat which creates steam
Bio-fuels	Plant matter, ethanol or methane can be produced and used as a fuel in place of fossil fuels
Wind	Wind turbines can be used to produce electricity
Hydroelectric	Hydroelectric uses the GPE of water stored in reservoirs to turn turbines which generate electricity
Tidal	A dam is used to trap seawater at high tide, which can then be released through a turbine generating electricity
Geothermal	Heat from underground can be used to create steam, which spins turbines producing electricity
Solar	Photovoltaic cells can use light to create electricity or thermal radiation from the sun can be used to warm water passing through black pipes
Water waves	Wave machines use the kinetic energy from the rise and fall of ocean waves to drive electricity generators

Uses of Energy Resources

- The three main uses of energy resources include:
  - Transport
  - Electricity generation
  - Heating

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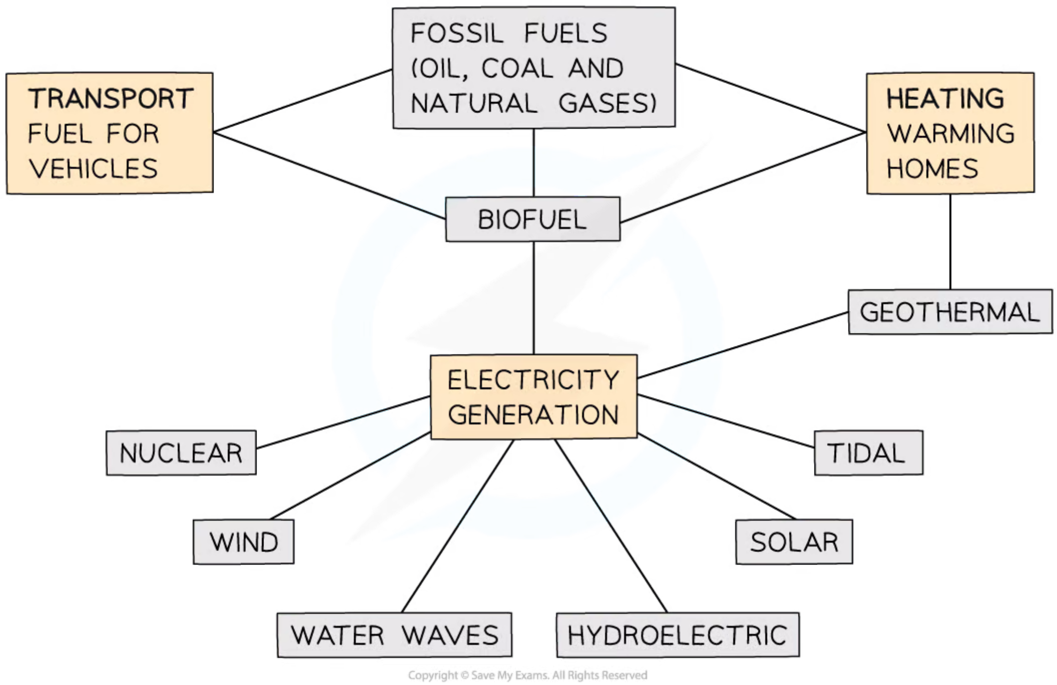

Types of energy resources

Transport

- The majority of vehicles in the world are powered by **petroleum** products such as petrol, diesel and kerosene
    - These resources all originate from crude oil, which is a **fossil fuel**
- A growing number of vehicles are now being powered by **electricity**
    - The advantage of this is that while the vehicle is being driven, it produces **zero carbon emissions**
    - The disadvantage is that when the vehicle is being charged, it is connected to the National Grid, which currently uses a **combination** of renewable and non-renewable energy sources
- Vehicles can also be powered by **biofuel**
    - The advantage of biofuel is that it is a **renewable** resource
    - However, the claim that biofuels are carbon-neutral is largely **controversial**

Electricity Generation

- Electricity plays a bigger role in people's lives than ever before
- With almost 8 billion people in the world, this means the **demand** for electricity is **extremely high**
- To keep up with this demand, a combination of **all** the energy resources available is needed
- On the downside, the majority (84%) of the world's energy is still produced by non-renewable, carbon-emitting sources
    - This has an enormous **negative** impact on the environment
    - Currently, scientists are working hard to develop more and more efficient ways to produce electricity using more carbon-neutral energy resources

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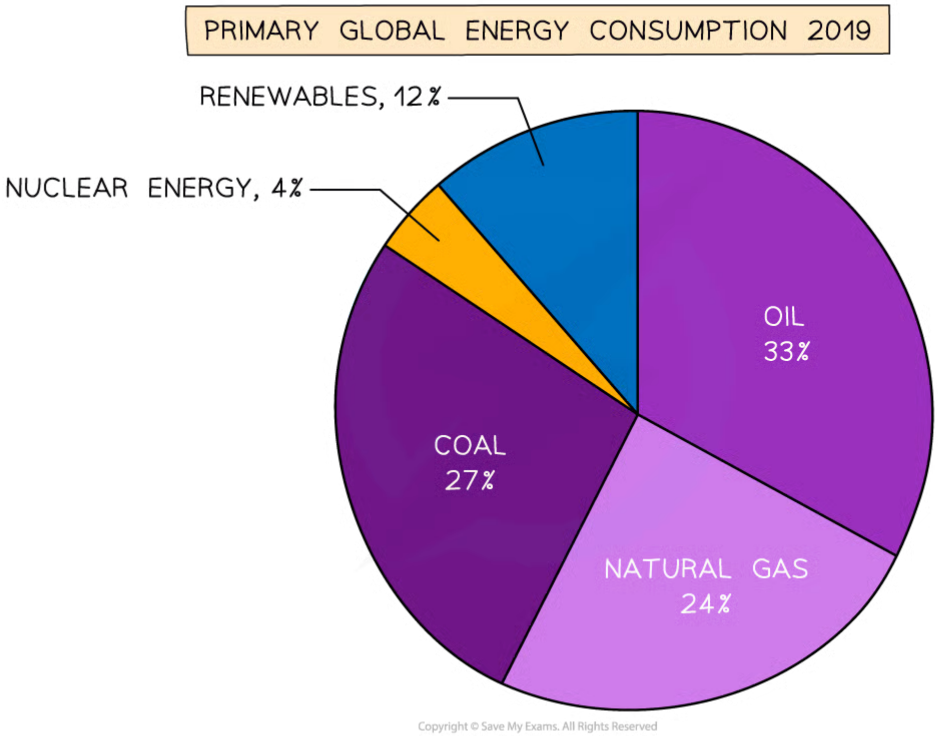

Pie chart of global energy consumption

Heating

- Most homes in cold countries are fitted with **central heating systems**
- These utilize **natural gas** in order to heat up water which can be pumped around radiators throughout the home
  - Unfortunately, gas is a non-renewable energy resource
- In geologically active countries, such as Iceland, they are fortunate to be able to heat their homes using **geothermal** energy

Photovoltaic Cells & Solar Heating Panels

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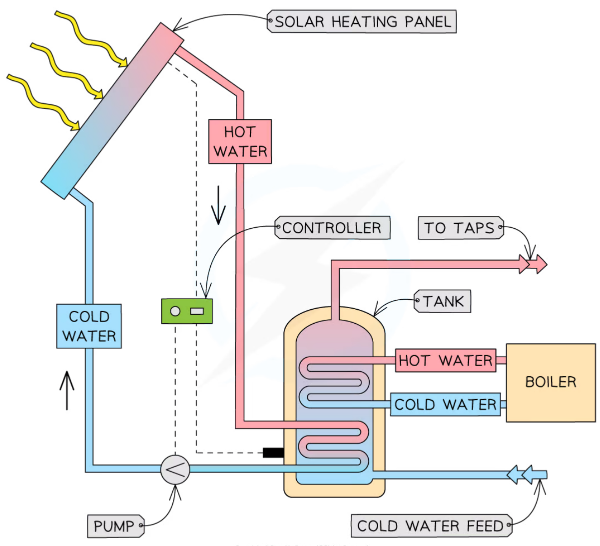
Solar Heating Panels

- Solar heating panels are used to heat tap water (for washing and showers) using the thermal energy of the Sun
- Solar heating panels can contain a water or glycol-water mixture which is pumped around to heat cold water from the main water supply
- The pumped fluid becomes hot within the solar panel and transfers this heat within a hot water storage cylinder
- A solar panel heating system is usually combined with a boiler to produce hot water at all times



A solar heating panel system in a home

Photovoltaic Cells

- Photovoltaic (PV) cells are able to convert light from the Sun directly into electricity
- PV cells contain a single crystal of semiconductor that has been doped to have one side be a p-type semiconductor and the opposite side is an n-type semiconductor
- p-type and n-type relate their names to the majority of charge carriers within them
    - negative electrons for the n-type semiconductor
    - positive 'holes' which is the absence of electrons in the p-type semiconductor

- Photovoltaic cells generate electricity as follows:
    - Light from the sun incident on the PV cell creates a photoelectric effect on the electrode at the surface
    - The reflect-proof film prevents the light from being reflected back into the air
    - Typically, the charge carriers in the semiconductor are in equilibrium, but when radiation is incident upon the PV cell, it enables electrons to move from the n-type layer to the p-type layer
    - The movement of the electrons generates an electrical current

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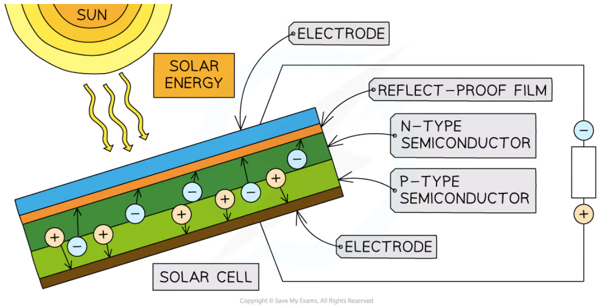

A simple diagram of a PV cell

- A solar panel system is made up of many PV cells in series and parallel within the panel to increase electrical generation
- Typical efficiencies of commercially available PV cell-based solar panels are around 20%

Advantages and disadvantages

- Advantages of using solar power include:
  - Unlimited supply of energy
  - Clean to produce the electricity
  - Freely available everywhere
  - Cheap maintenance
  - No fuel is required for energy

- Disadvantages of using solar power include:
  - Impacted by poor weather
  - Limited efficiency
  - Only available during the day
  - Requires large investment upfront
  - Needs large areas

Worked Example

A small community has solar panels which have an efficiency of 23%. They have arranged 103 m^2 of solar panels to catch the sunlight incident upon them which has an intensity value of: 1.36×10^3 W m^{-2}. Estimate the approximate power these solar panels will produce in 1 hour.

Step 1: List known values

- Solar panel area: 103 m^2
- The average intensity of the Sun: 1.36×10^3 W m^{-2}
- Solar panel efficiency: 23%

Step 2: Identify relationship needed

- The final answer required is power in Watts
- Therefore the quantities must be multiplied together

$$\text{Power} = \text{Area} \times \text{Average Intensity} \times \text{Efficiency}$$

Step 3: Perform the multiplication

$$\text{Power} = 103 \times 1.36 \times 10^3 \times 0.23 = 3.2 \times 10^4 \text{ W}$$

Step 4: State the final answer

- The approximate power the solar panels will produce in 1 hour is: **3.2×10^4 W**

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Exam Tip

An in-depth understanding of how Photovoltaic cells works is not necessary for IB DP Physics, however a basic understanding of the process can be useful for tackling relevant questions.

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8.1.5 Energy Generation

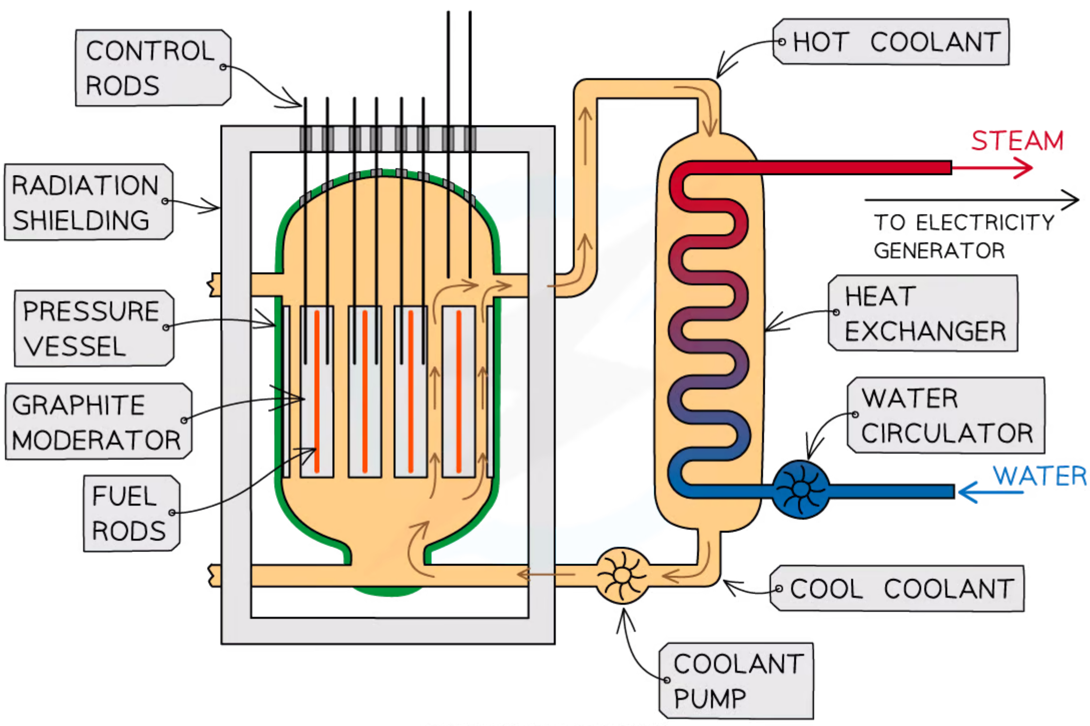
Energy Generation

- You need to know about the main ways of generating electricity:
  - The equipment involved
  - The advantages and disadvantages
  - Calculate power obtained for different setups
- These revision notes cover:
  - Nuclear Power
  - Burning Fossil Fuels
  - Wind Electricity Generators
  - Hydroelectric Power
  - Solar Power

Nuclear Power

Control Rods & Moderators:

- In a nuclear reactor, a chain reaction is required to keep the reactor running
- When the reactor is producing energy at the correct rate, two factors must be controlled:
  - The number of free neutrons in the reactor
  - The energy of the free neutrons
- To do this, nuclear reactors contain **control rods** and **moderators**



The overall purpose of a nuclear reactor is to collect the heat energy produced from nuclear reactions

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Control Rods:

Purpose of a control rod: To absorb neutrons

- Control rods are made of a material which absorb neutrons without becoming dangerously unstable themselves
- The number of neutrons absorbed is controlled by varying the depth of the control rods in the fuel rods
  - Lowering the rods further **decreases** the rate of fission, as more neutrons are absorbed
  - Raising the rods **increases** the rate of fission, as fewer neutrons are absorbed

- This is adjusted automatically so that exactly one fission neutron produced by each fission event goes on to cause another fission
- In the event the nuclear reactor needs to shut down, the control rods can be lowered all the way so no reaction can take place

Moderator:

The purpose of a moderator: To slow down neutrons

- The moderator is a material that surrounds the fuel rods and control rods inside the reactor core
- The fast-moving neutrons produced by the fission reactions slow down by colliding with the molecules of the moderator, causing them to lose some momentum
- The neutrons are slowed down so that they are in **thermal equilibrium** with the moderator, hence the term 'thermal neutron'
  - This ensures neutrons can react efficiently with the uranium fuel

Shielding:

- The entire nuclear reactor is surrounded by **shielding** materials
- The purpose of shielding is to **absorb hazardous radiation**
- The daughter nuclei formed during fission, and the neutrons emitted, are radioactive
- The reactor is surrounded by a **steel** and **concrete** wall that can be nearly 2 metres thick
- This absorbs the emissions from the reactions
  - It ensures that the environment around the reactor is **safe**

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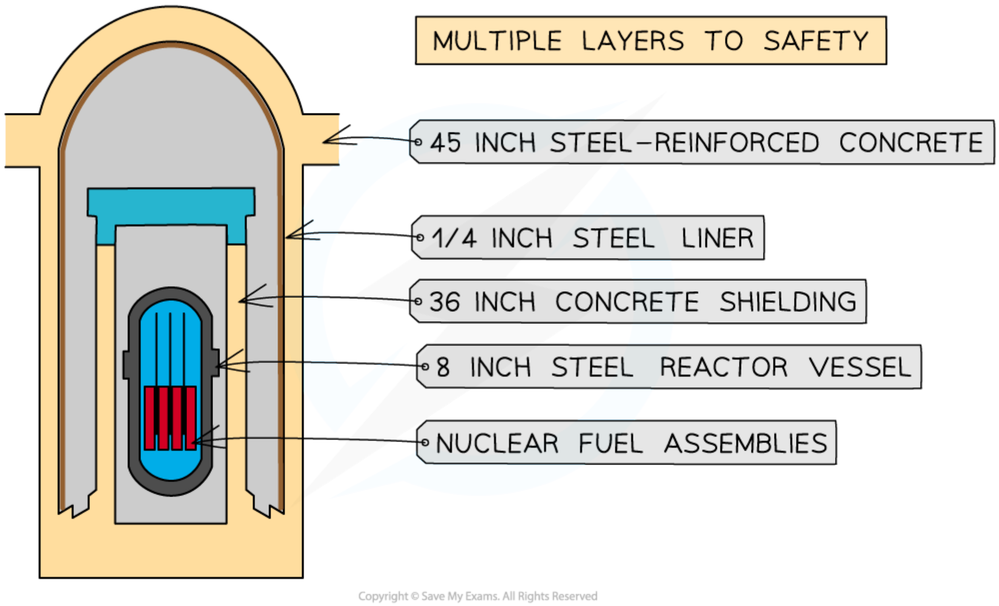

Shielding metals in a nuclear reactor

Advantages & Disadvantages of Nuclear Power

- **Advantages** of using nuclear power include:
  - Extensive reserves of fissionable materials
  - Increasingly refine technology available
  - No greenhouse gases produced
  - A large amount of power is produced
- **Disadvantages** of using nuclear power include:
  - Hazardous radioactive waste materials produced
  - Dangerous if the power plant goes significantly wrong
  - Danger of misuse of nuclear material
  - Problems with mining fuel

Burning Fossil Fuels

- Fossil fuels, such as coal and oil, are used to produce energy **on-demand** when energy is needed
  - This is done by **burning** the materials when the energy is required
- When fossil fuels are burned, it is used to **heat water**
  - This water is heated until it becomes **steam**
- Steam is forced around the system and this turns **a turbine**
- The turbine spins and is connected to a **generator** which generates electricity
  - This electricity is carried out of the system by **electrical lines**
- The steam within the turbine will cool and **condense** and then be pumped back into the boiler to **repeat the process**

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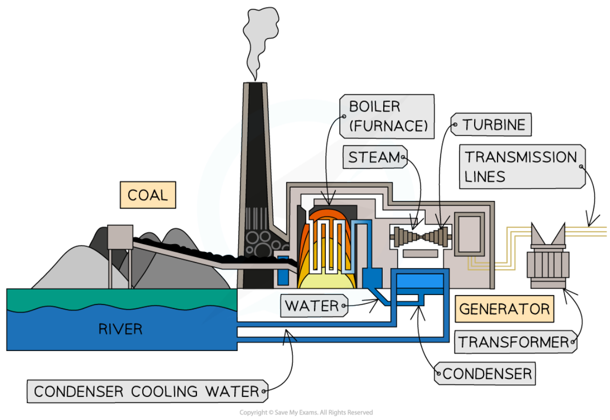


Diagram of a Fossil fuel based Reactor. The overall purpose of the reactor is to collect the heat energy produced from burning fossil fuels

- The approximate **efficiency** of fossil-fuel based power plants is approximately **40%**
  - Energy is **lost** to heat within exhaust gases, heat loss in the condenser process and friction within the system

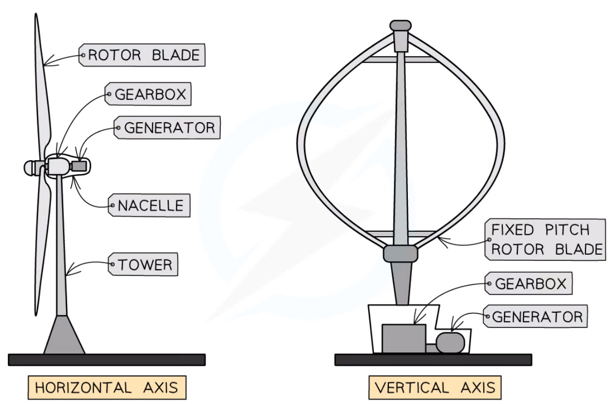
Advantages & Disadvantages of Fossil Fuels

- **Advantages** of using fossil fuel based power plants include:
  - Extensive infrastructure in place
  - High energy density of fuel
  - Available energy at any time
  - Well-known and developed technology

- **Disadvantages** of using fossil fuel based power plants include:
  - Produces greenhouse gases
  - Unsustainable (non-renewable)
  - Produces pollution

Wind Electricity Generators

- Wind generators can be principally horizontally or vertically aligned
  - The majority of modern designs use **horizontally** aligned designs



The two main designs of wind generators: horizontal and vertical alignment

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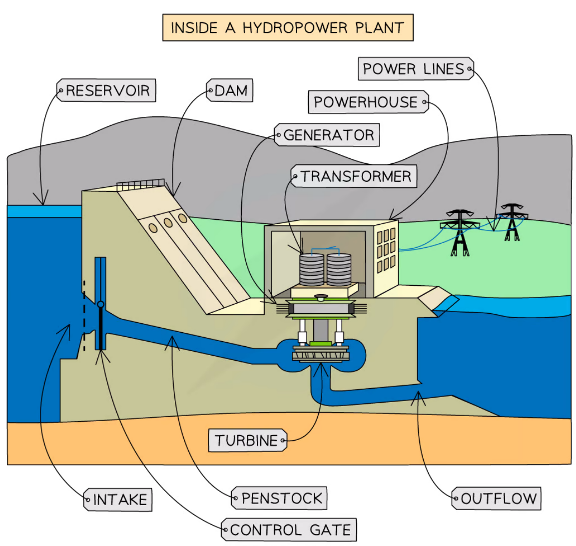
- The approximate **efficiency** of wind generators is approximately **30%**
  - Energy is **lost** to aerodynamic limits, losses transferring the electricity to the grid and friction within the system

Advantages & Disadvantages of Wind Power

- **Advantages** of using wind-powered generators include:
  - Clean (non-polluting) energy generation
  - Freely available
  - Is always sustainable and will never run out
- **Disadvantages** of using wind-powered generators include:
  - Not consistent energy production
  - Needs favourable local conditions to be placed in windy locations
  - Can be visually unappealing

Hydroelectric Power

- Hydroelectric power using water stored at a height ***h***, that mass of water ***m***, is allowed to flow through turbines being pulled down by the acceleration due to gravity ***g***
  - The falling water has **stored gravitational potential energy** which is released when falling and used to **spin turbines** that **generate electricity**
- Energy can be **stored for later** use **by pumping** water back up to a **higher** location to be released to a lower location and spinning the turbines again when needed
- The approximate **efficiency** of hydroelectric power generation is approximately **90%**
  - Energy is **lost** to friction and other resistive forces
- The approximate **maximum power** that can be generated from a hydroelectric generator can be **estimated** by considering the rate of change of potential energy of the water falling through the turbines



A hydroelectric power generation station. In off-peak hours water can be pumped back to the higher reservoir.

Advantages & Disadvantages of Hydroelectric Power

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- **Advantages** of using hydroelectric generators include:
  - Clean (non-polluting) energy generation
  - Is sustainable
  - Can be stored for when needed
- **Disadvantages** of using hydroelectric generators include:
  - Large areas and changes to the environment are needed
  - It relies on suitable locations
  - A large initial investment is required

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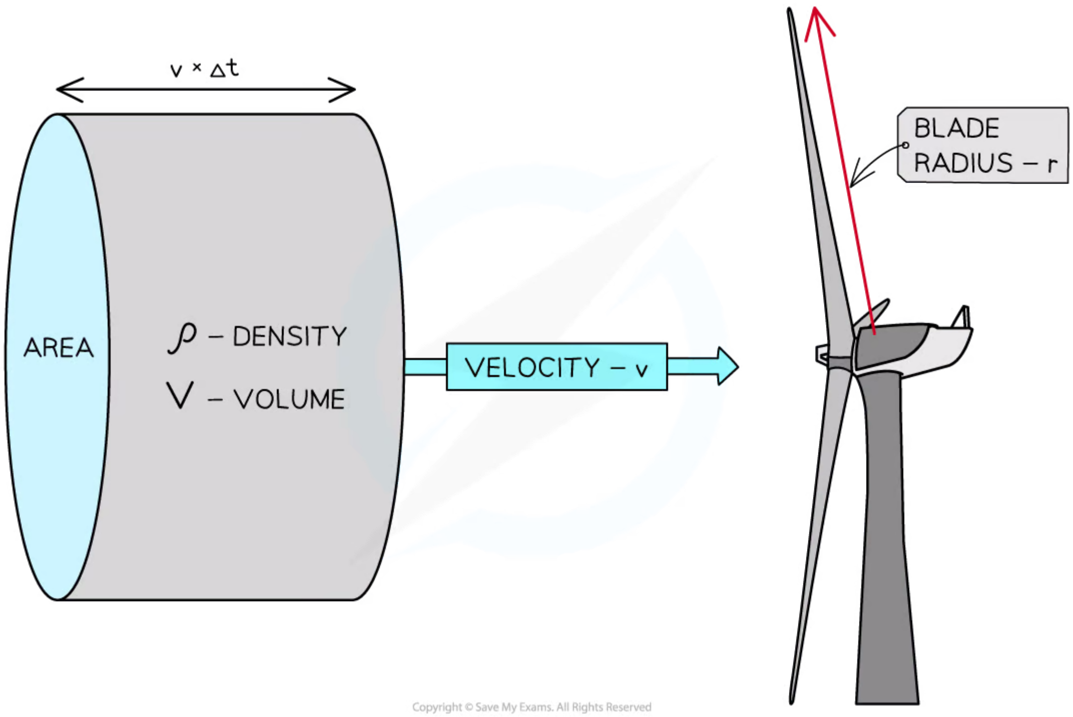
Calculating Energy Transformations

Wind Electricity Generators

- The approximate **maximum power** obtained per second that can be generated from a horizontal wind generator can be **estimated** by considering the blade radius and an incoming column of air



A column of air can provide only a limited amount of energy for a wind generator of blade radius r

- A column of air of density ρ can move through a cross-sectional area ***A*** which is determined by the blade radius ***r***
  - The amount of air that can move through this region is dependent on the velocity of the air ***v*** and the time considered ***t***
- The kinetic energy of the air arriving at the turbine every second can be described by:

$$KE = \tfrac{1}{2} \times mass \times velocity^2$$

- The **mass**, *m*, of the column of air can be described by using the equation

$$m = \rho V = \rho A L$$

- Where:
  - ρ = density of the air (kg m^{-3})
  - V = volume of the column (m^3)
  - A = cross-sectional area of the column (m^2)
  - L = length of the column (m)
- The length of the column can be described by

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$$L = vt$$

- Where:
  - v = velocity of the air ($m\ s^{-1}$)
  - t = time taken to travel the length of the column (s)

- Since the case is being considered for every second, time, t = 1 s
- Therefore, mass, in this case, will be:

$$m = \rho vtA = \rho vA$$

- This means power obtained per second can be described by:

$$P = ½ \times (\rho vA) \times v^2$$

$$P = ½\,\rho Av^3$$

- This equation shows that the main variable that can impact power generated by wind is the wind's velocity
  - If the wind's velocity remains the same, but the area covered by the blades doubles, then the theoretical power will double
  - Yet, if the area covered by the blades remains the same and the wind velocity doubles, then the theoretical power available will increase eight-fold
- Typical values of quantities are useful to be aware of:
  - Density of the air = 1.3 kgm^{-3} at standard temperature and pressure
  - Velocity of the air required to turn the blades = 12 kmh^{-1} to get them turning and then 70 kmh^{-1} at full capacity
  - Radius of the wind turbine blade = 50 - 150 m

Worked Example

Air moving at speed 9.5 $m\ s^{-1}$ with a density of 1.15 $kg\ m^{-3}$ is incident on a wind turbine. The length of the blades in the wind turbine are 14 m. After passing the wind turbine, the air is moving with a speed of 4.5 $m\ s^{-1}$ and has a density of 1.30 $kg\ m^{-3}$. Deduce the maximum power possible every second from this situation.

Step 1: List known values

- Air velocity before passing turbine: 9.5 $m\ s^{-1}$
- Air density: 1.15 $kg\ m^{-3}$
- Blade length: 14 m
- Air velocity after passing turbine: 4.5 $m\ s^{-1}$
- Density: 1.30 $kg\ m^{-3}$

Step 2: Find maximum power available

$$P = 0.5 \times \rho \times A \times v^3 = 0.5 \times 1.15 \times \pi \times 14^2 \times 9.5^3 = 3.04 \times 10^5\ W$$

Step 3: Find the remaining power within the air after passing the turbine

$$P = 0.5 \times \rho \times A \times v^3 = 0.5 \times 1.15 \times \pi \times 14^2 \times 4.5^3 = 3.64 \times 10^4\ W$$

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Step 4: Find the power available for the turbine to use

$$P = (3.04 \times 10^5) - (3.64 \times 10^4) = 2.68 \times 10^5\ W$$

Step 5: State the final answer

- The **maximum power** available to the turbine is: ***2.68 × 10^5 W*** every second

Hydroelectric Power

- Consider water of mass m stored at a height ***h***, that is allowed to flow through turbines being pulled down by the acceleration due to gravity ***g***
  - The gravitational potential energy of the water is ***m × g × h***
- Therefore, the change in energy (the power) will be:

$$P = \frac{m \times g \times h}{\Delta t}$$

- Where Δt = the time taken for the change in energy to occur
- This can be re-written in terms of volume and density rather than mass to consider the equation in terms of the **volume flow rate**

$$\frac{\Delta V}{\Delta t}$$

- Substituting this into the power equation gives:

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

- Therefore, to get large energy from hydroelectric power, large flow rates ***(ΔV ÷ Δt)*** and heights ***h*** are needed to maximise the energy produced

Worked Example

In a hydroelectric dam, water of density 1000 kg m^{-3} flows with a flow rate: 75 × 10^{-3} m^3 s^{-1} goes through a turbine and descends approximately 22 m. Deduce the maximum power this will give if the efficiency of the turbine system is 85%.

Step 1: List the known quantities

- Flow rate, $\Delta V / \Delta t = 75 \times 10^{-3}$ m^3 s^{-1}
- Height of water drop, h = 22 m
- Density of water, ρ = 1000 kg m^{-3}
- Efficiency of turbine system, e = 85%

Step 2: State the relevant equation for hydroelectric power

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

YOUR NOTES
⬇

- P = power (W)
- ρ = density (kg m^{-3})
- g = acceleration due to gravity (m s^{-2})
- h = height of falling water (m)
- $\Delta V / \Delta t$ = the flow rate (m^3 s^{-1})
- e = efficiency [no units]

Step 3: Substitute in the values

$$P = (1000 \times 9.8 \times 22) \times (75 \times 10^{-3}) \times 0.85 = 1.37 \times 10^4 \text{ W}$$

Step 4: State final answer

- The approximate power available for the situation is: **1.37×10^4 W**

YOUR NOTES
⬇

Safety Issues in Nuclear Power

Safety Measures for Workers

- Several measures are in place to reduce the worker's exposure to radiation
  - The fuel rods are **handled remotely** ie. by machines
  - The nuclear reactor is surrounded by a very thick lead or concrete **shielding**, which ensures radiation does not escape
  - In an emergency, the control rods are fully lowered into the reactor core to stop fission reactions by absorbing all the free neutrons in the core, this is known as an **emergency shut-down**

Nuclear Waste

- There are three main types of nuclear waste:
  - Low level
  - Intermediate level
  - High level

- **Low-level waste**
  - This is waste such as clothing, gloves and tools which may be lightly contaminated
  - This type of waste will be radioactive for a few years, so must be encased in concrete and stored a few metres underground until it can be disposed of with regular waste

- **Intermediate-level waste**
  - This is everything between daily used items and the fuel rods themselves
  - Usually, this is the waste produced when a nuclear power station is decommissioned and taken apart
  - This waste will have a longer half-life than the low-level waste, so must be encased in cement in steel drums and stored securely underground

- **High-level waste**
  - This waste comprises of the unusable fission products from the fission of uranium-235 or from spent fuel rods
  - This is by far the **most dangerous** type of waste as it will remain radioactive for thousands of years
  - As well as being highly radioactive, the spent fuel roads are **extremely hot** and must be handled and stored much more carefully than the other types of waste

- How high-level waste is treated:
  - The waste is initially placed in cooling ponds of water close to the reactor for a number of years
  - Isotopes of plutonium and uranium are harvested to be used again
  - Waste is mixed with molten glass and made solid (this is known as **vitrification**)
  - Then it is encased in containers made from steel, lead, or concrete
  - This type of waste must be stored very **deep** underground

Risks & Benefits of Nuclear Power

- **Benefits**

YOUR NOTES
⬇

- Nuclear power stations produce **no polluting gases**
- They are **highly reliable** for the production of electricity
- They require far less fuel as uranium provides far **more energy per kg** compared to coal and other fossil fuels

- **Risks**
  - The production of radioactive waste is very **dangerous** and **expensive** to deal with
  - A **nuclear meltdown**, such as at Chernobyl, could have catastrophic consequences on the environment and to the people living in the surrounding area

Nuclear Energy in Society

- Nuclear power can scare people if they do not understand it
- It is dangerous if not handled properly, yet it is invisible which can be difficult for some people to comprehend
- However, with increased education on nuclear energy, society can use this knowledge to inform their own decisions and opinions

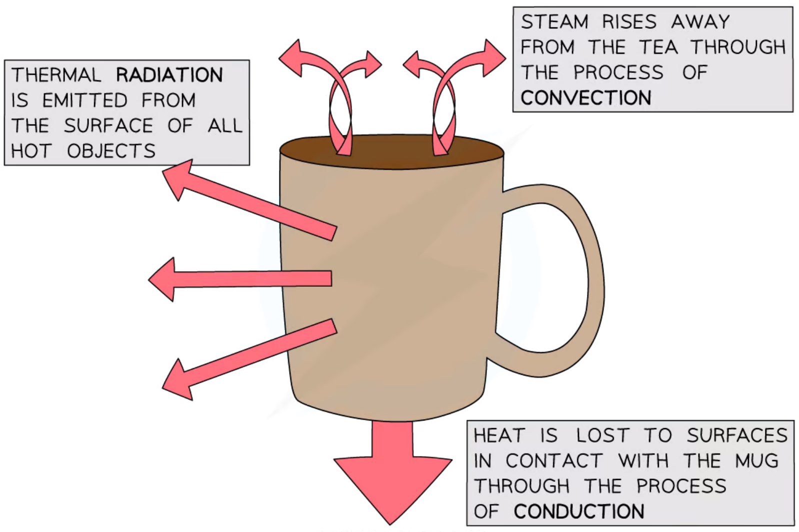
YOUR NOTES
⬇

8.2 Thermal Energy Transfer

8.2.1 Conduction, Convection & Thermal Radiation

Conduction, Convection & Thermal Radiation

- Thermal energy transfers from hotter areas to cooler areas by the processes of:
  - Conduction
  - Convection
  - Radiation



- Objects will **always** lose heat until they are in thermal equilibrium (same temperature) with their surroundings
  - For example, a mug of hot tea will cool down until it reaches room temperature

Conduction

- Conduction is the main method of thermal energy transfer in **solids**
- Conduction occurs when:

  Two solids of different temperatures come in contact with one another, thermal energy is transferred from the hotter object to the cooler object

- Metals are the best thermal **conductors**
  - This is because they have a high number of **free electrons**

- Non-metals, such as plastic or glass, are poor at conducting heat
  - Poor conductors of heat tend to be poor conductors of electricity
  - This suggests a link between the mechanisms behind both types of conduction

- Liquids and gases are even poorer thermal conductors
  - This is because the atoms are further apart, hence, the intermolecular forces are weaker

YOUR NOTES
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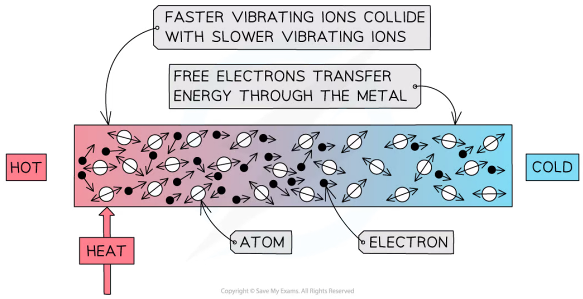


Conduction: the atoms in a solid vibrate and bump into each other

- Conduction can occur through two mechanisms:
  - Atomic vibrations
  - Free electron collisions

- When a substance is heated, the atoms, or ions, **start to move around (vibrate) more**
  - The atoms at the hotter end of the solid will vibrate more than the atoms at the cooler end
  - As they do so they **bump into each other**, transferring energy from atom to atom
  - These collisions transfer internal energy until **thermal equilibrium** is achieved throughout the substance
  - This occurs in **all solids**, metals and non-metals alike

- Metals are especially good at conducting heat due to their high number of **delocalised electrons**
  - These can collide with the atoms, helping to transfer the **vibrations** through the material
  - This, therefore, allows metals to achieve thermal equilibrium **faster** than non-metals

Worked Example

Determine which of the following metals is likely to be the best thermal conductor, and which is likely to be the worst.

Metal	Density / g cm^{-3}	Relative atomic mass
Copper	8.96	63.55
Steel	7.85	55.85
Aluminium	2.71	26.98

You may take Avogadro's number to be 6.02×10^{23} mol^{-1} and you can assume each metal contributes one free electron per atom.

Step 1: Use dimensional analysis to determine the equation for the number of free electrons

- Units for number of free electrons per cubic centimetre, $[n] = \text{cm}^{-3}$
- Units for density, $[\rho] = \text{g cm}^{-3}$

YOUR NOTES
⬇

- Units for Avogadro's number, $[N_A] = mol^{-1}$
- Units for relative atomic mass, $[A] = g\ mol^{-1}$

$$[n]^a = [\rho]^b [N_A]^c [A]^d$$

$$(cm^{-3})^a = (g\ cm^{-3})^b (mol^{-1})^c (g\ mol^{-1})^d$$

- The only unit present on both sides is cm^{-3}, therefore:

$$a = b = 1$$

- No other units are present on both sides, so:

$$c + d = 0$$

$$b + d = 0$$

$$\therefore d = -1, c = 1$$

Step 2: Write out the equation for the number of free electrons per cubic centimetre

$$[n]^1 = [\rho]^1 [N_A]^1 [A]^{-1}$$

$$n = \frac{\rho N_A}{A}$$

Step 3: Calculate the number of free electrons in each metal

- Copper:

$$n = \frac{8.96 \times (6.02 \times 10^{23})}{63.55} = 8.49 \times 10^{22}\ cm^{-3}$$

- Steel:

$$n = \frac{7.85 \times (6.02 \times 10^{23})}{55.85} = 8.46 \times 10^{22}\ cm^{-3}$$

- Aluminium:

$$n = \frac{2.71 \times (6.02 \times 10^{23})}{26.98} = 6.05 \times 10^{22}\ cm^{-3}$$

Step 4: Rank the metals from best thermal conductor to worst

- Best thermal conductor = **copper** (highest number of free electrons)
- Worst thermal conductor = **aluminium** (lowest number of free electrons)

Convection

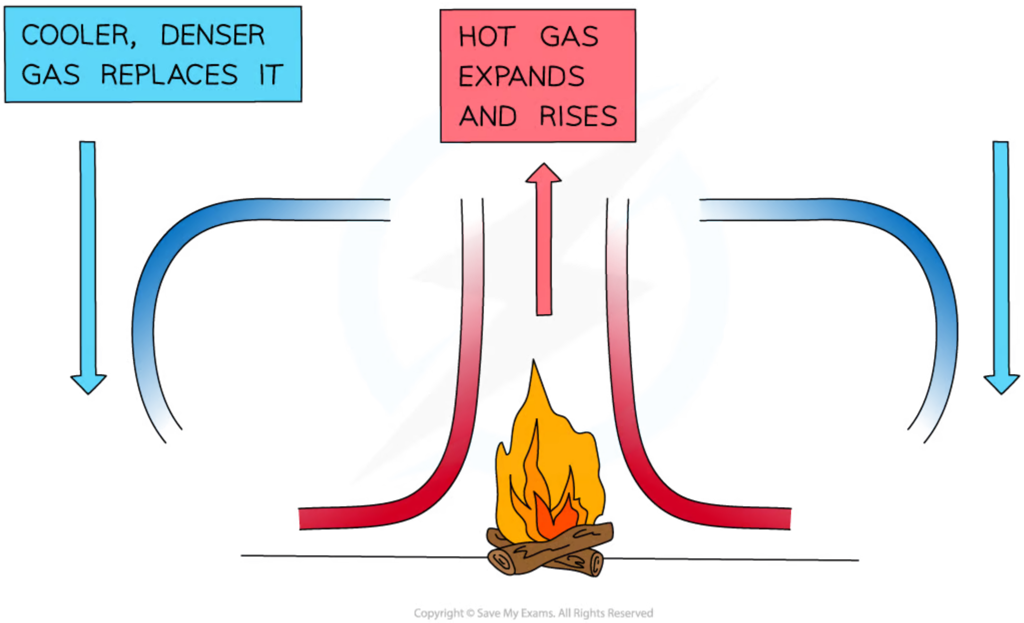
- Convection occurs when:

    A fluid is heated causing the movement of groups of atoms or molecules due to variations in density

- Convection is the main way that heat travels through **liquids** and **gases**
    - Convection **cannot occur in solids**

YOUR NOTES
⬇

- When a fluid (a liquid or a gas) is heated from below:
  - The heated molecules gain kinetic energy and push each other apart, making the fluid **expand**
  - This makes the hot part of the fluid **less dense** than the surrounding fluid
  - The **hot fluid rises**, and the cooler (surrounding) fluid moves in to take its place
  - Eventually, the hot fluid cools, contracts and sinks back down again
  - The resulting motion is called a **convection current**

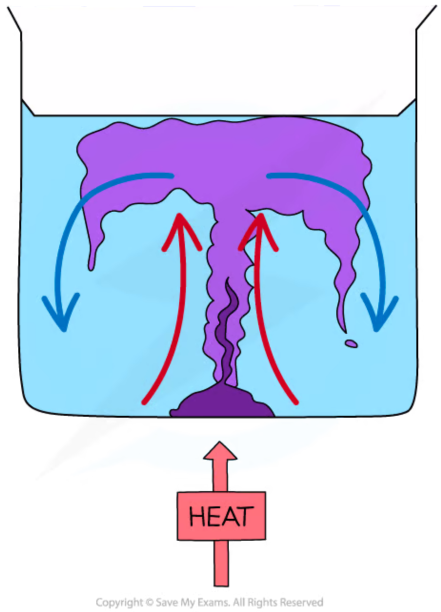


A convection current caused by the heat transfer from the fire

Worked Example

Discuss **one** example, in nature or in the lab, in which convection takes place.

Step 1: Draw a diagram to illustrate the convection currents



YOUR NOTES
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Step 2: Describe the situation

- One method of observing a convection current is by heating a beaker of water containing potassium permanganate crystals
- Heat is initially transferred through the glass wall of the beaker by conduction
- The water in the region of the Bunsen flame is heated and expands, becomes **less dense** and **rises**
  - This causes the dissolved purple crystal to flow up with the water
- Meanwhile, when the water at the top of the beaker cools, it becomes **denser** again and falls
- The process continues which leads to a **convection current** where heat is transferred through the liquid
  - The dissolved purple crystal follows this current which is what is observed during this experiment
- Other examples of convection include:
  - Atmospheric convection / winds / sea breezes
  - Thunderheads (a cloud that appears before a thunderstorm)
  - Convection currents in the Earth's mantle (which can lead to continental drift)
  - Ocean currents
  - Solar conventions / sunspots / flares

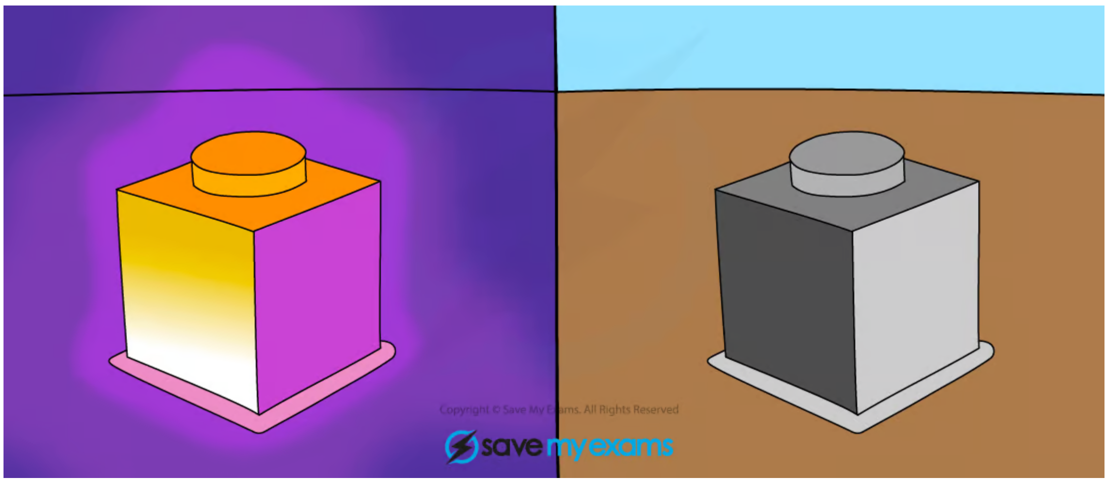
Thermal Radiation

- All bodies (objects), no matter what temperature, emit a spectrum of thermal radiation in the form of electromagnetic waves
- These electromagnetic waves usually lie in the **infrared** region of the spectrum
  - Black-body radiation can also be emitted in the form of visible light or other wavelengths, depending on the temperature
- Thermal radiation is defined as:

Heat transfer by means of electromagnetic radiation normally in the infrared region

- The **hotter** the object, the **more** infrared radiation it radiates in a given time
  - This is because atoms and molecules above absolute zero are in constant motion
  - Electric charges within the atoms in a material vibrate causing **electromagnetic radiation** to be emitted
  - Therefore, the higher the **temperature**, the greater the **thermal motion** of the atoms and the greater the **rate** of emission of **radiation**

- Thermal radiation is the **only** method of thermal energy transfer that does not require **matter** in order to **move or propagate**
  - Therefore, thermal radiation is the only way heat can travel through a **vacuum**



All objects above absolute zero emit infrared radiation

Worked Example

A hot meteorite hits the surface of the Moon.

Identify and discuss the principle means by which the meteorite can dissipate thermal energy.

Step 1: Identify the types of thermal energy transfer

- An object can lose energy through conduction, convection or radiation
- In this case, the hot meteorite will only be able to lose energy via **conduction** and **radiation**

Step 2: Explain these choices

- The meteorite can lose heat energy through conduction because it is in contact with the surface of the Moon
- The Moon does not have an atmosphere, so convection is **not** possible
- Infrared photons emitted by the meteorite are able to travel through a vacuum, so heat loss via radiation **is** possible

YOUR NOTES
⬇

Exam Tip

If a question...

...mentions thermal energy transfers and **metals**, the answer will probably have something to do with conduction!

...refers to thermal energy transfers and a **liquid or gas** (that isn't trapped) then make sure your answer mentions that convection currents will probably form!

...refers to the colour of something (**black, white or shiny**) then the answer will probably have something to do with thermal radiation!

...involves a **vacuum** (empty space) then mention **radiation** as it is the **only** way in which heat can travel through a vacuum as conduction and convection require particles to transfer heat!

8.2.2 Black-Body Radiation

YOUR NOTES
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Black-Body Radiation

- Black body radiation is the name given to the **thermal radiation** emitted by all bodies (objects)
- All objects, no matter what temperature, emit black body radiation in the form of electromagnetic waves
- These electromagnetic waves usually lie in the **infrared** region of the spectrum
  - Black-body radiation can also be emitted in the form of visible light or other wavelengths, depending on the temperature

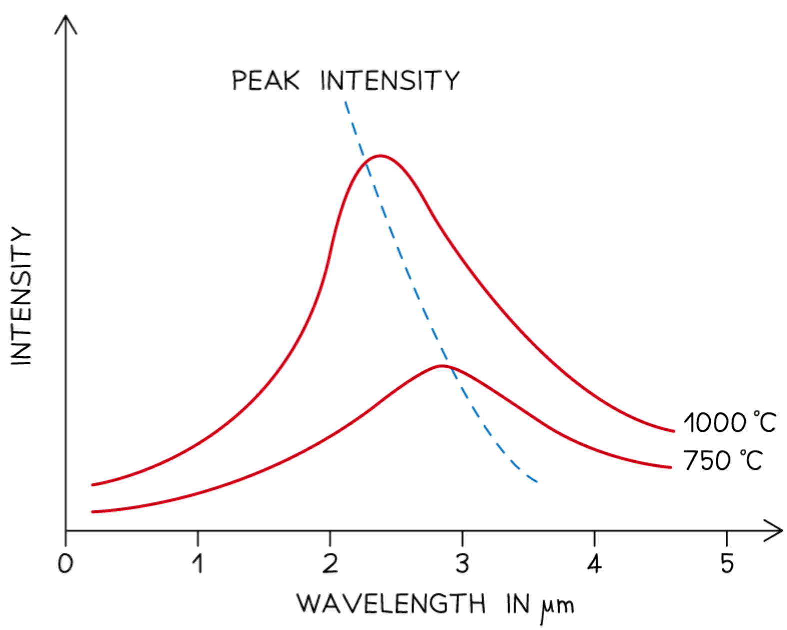
- The **hotter** object, the **more** infrared radiation it radiates in a given time

- A perfect black body is defined as:

  An object that absorbs all of the radiation incident on it and does not reflect or transmit any radiation

- Since a good absorber is also a good emitter, a perfect black body would be the best possible emitter too
- As a result, an object which perfectly absorbs all radiation will be black
  - This is because the colour black is what is seen when **all** colours from the visible light spectrum are absorbed

- The **intensity** and **wavelength** distribution of any emitted waves depends on the **temperature** of the body
- This is represented on a black body radiation curve
  - As the temperature increases, the peak of the curve moves
  - This moves to a **lower** wavelength and a **higher** intensity



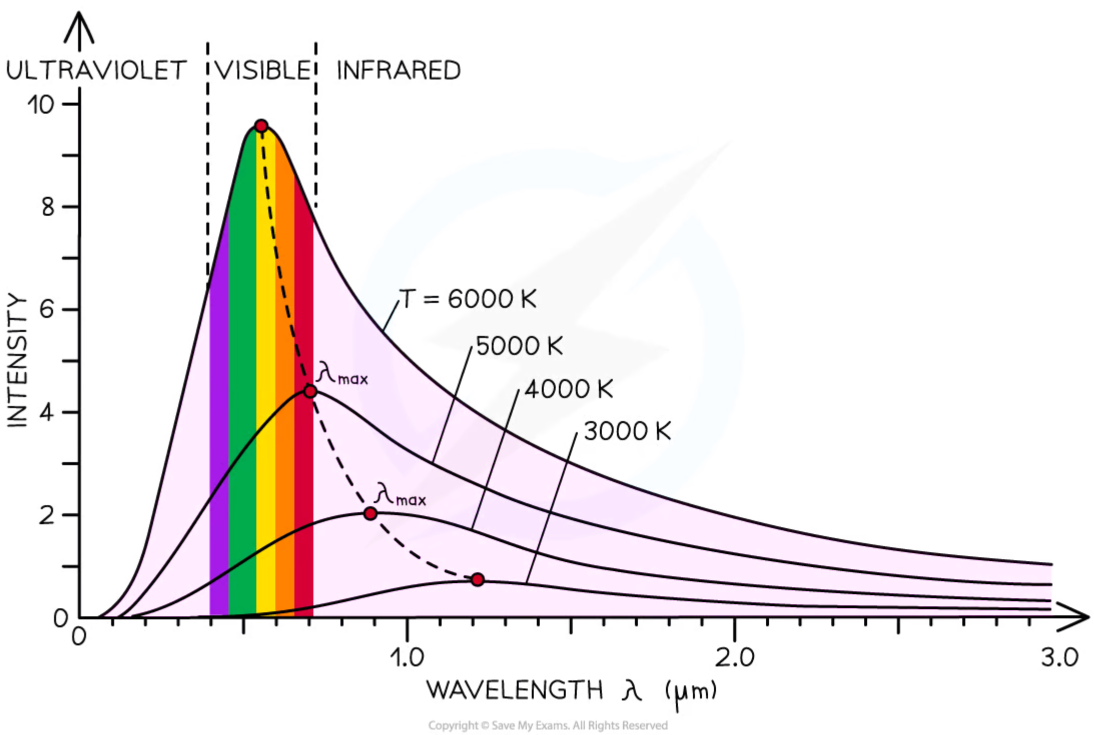
Black body spectrum for objects of different temperatures

YOUR NOTES

- From the electromagnetic spectrum, waves with a **smaller** wavelength have **higher** energy (e.g. UV rays, X-rays)
- When an object gets hotter, the amount of **thermal radiation** it emits increases
- This increases the thermal energy emitted and therefore the **wavelength** of the emitted radiation **decreases**
  - At room temperature objects emit thermal radiation in the infrared region of the spectrum
  - At around 1000 °C an object will emit a significant amount of **red light**
  - At 6000 °C an object will mainly emit **white** or **blue light** (and some ultraviolet)
  - At even higher temperatures objects will emit **ultraviolet** or even **X-rays**

- A black body is an object which:
  - Absorbs all the radiation that falls on it, and is also a good emitter
  - Does not reflect or transmit any radiation

- A black body is a theoretical object, however, stars are the best approximation there is
- The radiation emitted from a black body has a **characteristic spectrum** that is determined by the temperature alone



The intensity-wavelength graph shows how thermodynamic temperature links to the peak wavelength for four different bodies

Stefan–Boltzmann Law & Wien's Displacement Law

YOUR NOTES
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Wien's Displacement Law

- Wien's displacement law relates the wavelength emitted by a body to its surface temperature, it states:

 The black body radiation curve for different temperatures peaks at a wavelength which is inversely proportional to the temperature

- This relation can be written as:

$$\lambda_{max} \propto \frac{1}{T}$$

- The full equation for Wien's Law is given by

$$\lambda_{max}T = 2.9 \times 10^{-3} \text{ m K}$$

- Where:
  - λ_{max} = peak wavelength emitted by the body (m)
  - T = temperature of the body (K)

- This equation shows:
  - The **higher** the **temperature** of a body, the **shorter** the **wavelength** it emits at the peak intensity
  - The **higher** the **temperature** of a body, the **greater** the **intensity** of the radiation at each wavelength

Stefan–Boltzmann Law

- The power output of a black body depends on two factors:
  - Its surface temperature
  - Its radius

- The relationship between these is known as the **Stefan-Boltzmann Law**, which states:

 The total energy emitted by a black body per unit area per second is proportional to the fourth power of the absolute temperature of the body

- It is equal to:

$$P = \sigma A T^4$$

- Where:
  - P = total power emitted by the black body (W)
  - σ = the Stefan-Boltzmann constant
  - A = total surface area of the black body (m^2)
  - T = absolute temperature of the body (K)

- When considering a sphere (such as a star) the surface area is equal to $4\pi r^2$
- In this case, the Stefan-Boltzmann law can be written as:

$$P = 4\pi r^2 \sigma T^4$$

YOUR NOTES
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Worked Example

Betelguese is our nearest red giant star. It has a power output of 4.49×10^{31} W and emits radiation with a peak wavelength of 850 nm.

Calculate the ratio of the radius of Betelgeuse r_B to the radius of the Sun r_S.

Radius of the sun $r_s = 6.95 \times 10^8$ m.

Step 1: Write down Wien's displacement law

$$\lambda_{max} T = 2.9 \times 10^{-3} \text{ m K}$$

Step 2: Rearrange Wien's displacement law to find the surface temperature of Betelguese

$$T = \frac{2.9 \times 10^{-3}}{\lambda_{max}} = \frac{2.9 \times 10^{-3}}{850 \times 10^{-9}} = 3410 \text{ K}$$

Step 3: Write down the Stefan-Boltzmann law

$$P = \sigma A T^4$$

$$P = 4\pi r^2 \sigma T^4$$

Step 4: Rearrange for r and calculate the stellar radius of Betelguese

$$r_B = \sqrt{\frac{L}{4\pi\sigma T^4}} = \sqrt{\frac{(4.49 \times 10^{31})}{4\pi \times (5.67 \times 10^{-8}) \times (3410)^4}} = 6.83 \times 10^{11} \text{ m}$$

Step 5: Calculate the ratio r_B / r_s

$$\frac{r_B}{r_s} = \frac{6.83 \times 10^{11}}{6.95 \times 10^8} = \mathbf{983}$$

- Therefore, the radius of Betelguese is about 1000 times larger than the Sun's radius

8.2.3 The Solar Constant, Albedo & Emissivity

YOUR NOTES
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The Solar Constant

- Since life on Earth is entirely dependant on the Sun's energy, it is useful to quantify how much of its energy reaches the top of the atmosphere
  - This is known as the solar constant
- The solar constant is defined as:

  The amount of solar radiation across all wavelengths that is incident in one second on one square metre at the mean distance of the Earth from the Sun

- The value of the solar constant varies year-round because:
  - The Earth's is in an **elliptical orbit** around the Sun, meaning at certain times of year the Earth is closer to the Sun, and other times of year it is further away
  - The **Sun's output varies** by about 0.1% during its 11-year sunspot cycle
- Calculations of the solar constant assume that:
  - This radiation is incident on a **plane perpendicular** to the Earth's surface
  - The Earth is at its **mean distance** from the Sun

Worked Example

The Sun emits 4×10^{26} J in one second. The mean distance of the Earth from the Sun is 1.5×10^{11} m.

Using this data, calculate the solar constant.

Step 1: List the known quantities

- Power output of Sun, $P = 4 \times 10^{26}$ W
- Distance between the Earth and Sun, $r = 1.5 \times 10^{11}$ m

Step 2: Model the scenario using geometry

- As light leaves the surface of the Sun, it begins to spread out uniformly through a spherical shell
- The surface area of a sphere = $4\pi r^2$
- The radius r of this sphere is equal to the distance between the Sun and the Earth

YOUR NOTES
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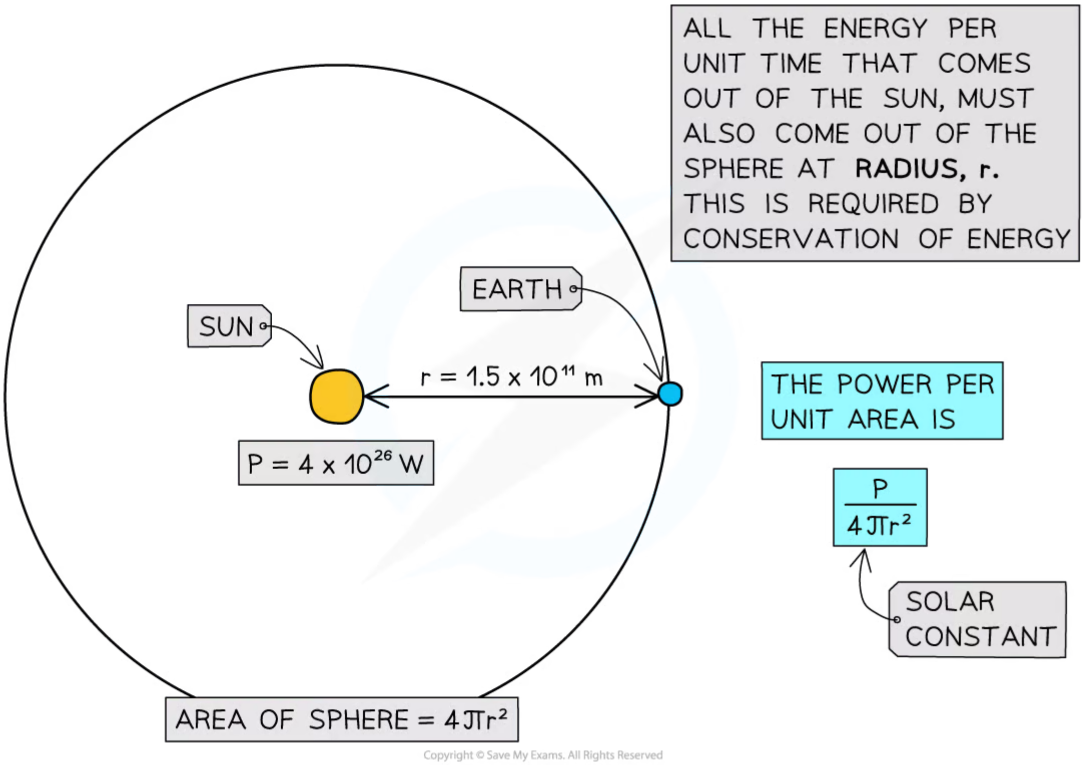

Step 3: Write an equation to calculate the solar constant

$$\text{Solar constant} = \frac{P}{4\pi r^2}$$

Step 4: Calculate the solar constant

$$\text{Solar constant} = \frac{4 \times 10^{26}}{4\pi(1.5 \times 10^{11})^2} = 1415\ \text{W m}^{-2}$$

Solar constant = **1.4 kW m^{-2}** (2 s.f)

YOUR NOTES
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Albedo & Emissivity

Albedo

- Albedo, a, is defined as

The proportion of light that is reflected by a given surface

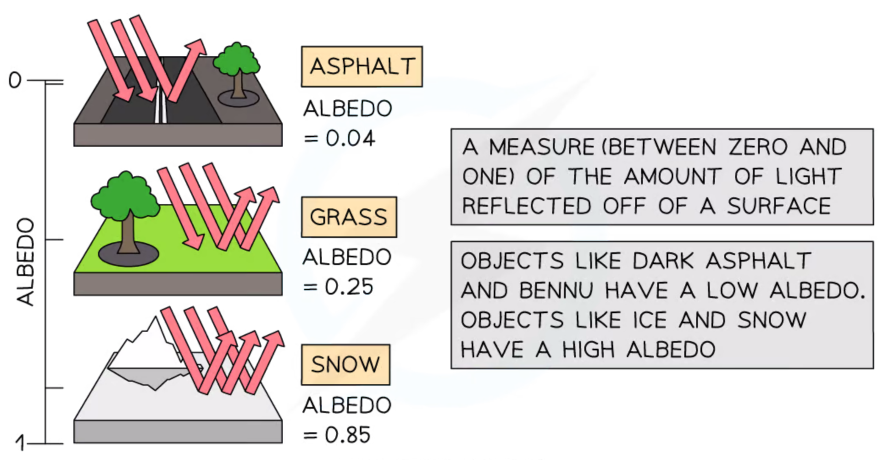
- It can be calculated using the equation

$$a = \frac{\text{total scattered power}}{\text{total incident power}}$$

- More specifically, the albedo of a **planet** is defined as

The ratio between the total scattered, or reflected, radiation and the total incident radiation of that planet

- Earth's albedo is generally taken to be 0.3, which means 30% of the Sun's rays that reach the ground are reflected, or scattered, back into the atmosphere
- Earth's albedo varies daily and depends on:
  - **Cloud formations** and **season** – the thicker the cloud cover, the higher the degree of reflection
  - **Latitude**
  - **Terrain** – different materials reflect light to different degrees
- It is useful to know the albedo of common materials:
  - Fresh asphalt = 0.04
  - Bare soil = 0.17
  - Green grass = 0.25
  - Desert sand = 0.40
  - New concrete = 0.55
  - Ocean ice = 0.50 - 0.70
  - Fresh snow = 0.85
- Albedo has no units because it is a **ratio** (or fraction) of power



Emissivity

- Stars are good approximations to a black body, whereas planets are not

YOUR NOTES
⬇

- This can be quantified using the emissivity
- Emissivity, e, is defined as

The power radiated by a surface divided by the power radiated from a black body of the same surface area and temperature

- It can be calculated using the equation

$$e = \frac{\text{power radiated by an object}}{\text{power emitted by a black body}}$$

- Calculations of the emissivity assume that the black body:
  - Is at the same temperature as the object
  - Has the same dimensions as the object
- For a perfect black body, emissivity is equal to 1
- When using the Stefan-Boltzmann law for an object which is not a black body, the equation becomes:

$$P = e\sigma A T^4$$

- Where:
  - P = total power emitted by the object (W)
  - e = emissivity of the object
  - σ = the Stefan-Boltzmann constant
  - A = total surface area of the object black body (m^2)
  - T = absolute temperature of the body (K)

Worked Example

The average albedo of fresh snow is 0.85

Calculate the ratio $\frac{\text{energy absorbed by fresh snow}}{\text{energy reflected by fresh snow}}$

Step 1: Define albedo
- Albedo = the proportion of radiation that is reflected
- Therefore, the energy reflected by fresh snow = 0.85

Step 2: Identify the proportion of radiation that is absorbed
- If 85% of the radiation is reflected, we can assume that 15% is absorbed
- Therefore, the energy absorbed by fresh snow = 1 – 0.85 = 0.15

Step 3: Calculate the ratio

$$\frac{\text{energy absorbed by fresh snow}}{\text{energy reflected by fresh snow}} = \frac{0.15}{0.85} = 0.18$$

YOUR NOTES
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Exam Tip

You will be expected to remember that a perfect black body has an emissivity of 1 - this information is **not** included in the data booklet!

8.2.4 The Greenhouse Effect

YOUR NOTES

Greenhouse Gases

- When radiation from the Sun hits the Earth, it is radiated back from the Earth's surface as long-wave radiation
- A greenhouse gas is a gas that absorbs this re-radiated radiation, trapping it in the Earth's atmosphere so that it is not lost to space
  - Greenhouse gases in the atmosphere have a similar effect to the glass in a greenhouse, hence the term greenhouse gas
- There are many greenhouse gases, and those that contribute most to the greenhouse effect are:
  - Carbon dioxide (CO_2)
  - Water vapour (H_2O)
- These have the most significant impact on the greenhouse effect
- There are other greenhouse gases which have a lesser effect, such as:
  - Ozone (O_2 and O_3)
  - Methane
  - Nitrous oxides

YOUR NOTES
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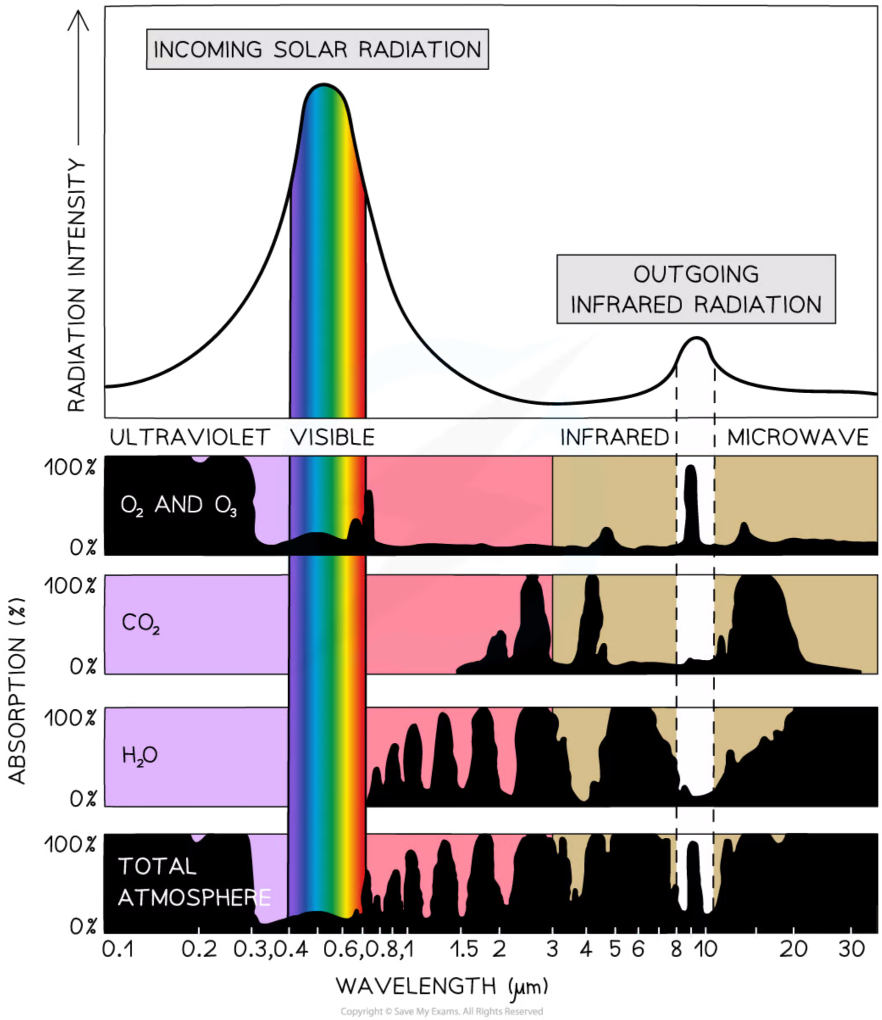

Greenhouse Gas Absorption Spectrum: Ozone absorbs nearly 100% ultraviolet rays, carbon dioxide absorbs radiation with wavelengths between 1.5 – 30 μm and water vapour from 0.8 – 35 μm. Most of the ultraviolet, visible, infrared and microwave radiation is absorbed by the atmosphere. The dark parts show radiation that is absorbed by each type of greenhouse gas. It is the ozone that restricts most of the outgoing infrared radiation from leaving the Earth's atmosphere.

Molecular Mechanisms

- The greenhouse effect occurs due to the particular molecular structure of greenhouse gases
  - High-frequency UV light is energetic and able to break bonds within molecules
  - Infrared light, on the other hand, causes atoms to vibrate
- The greenhouse gases have a **natural frequency** that falls in the infrared region
  - This means when they absorb infrared light, they begin to resonate, causing the molecules to heat up
  - They absorb the infrared radiation and subsequently emit it back towards the Earth's surface

YOUR NOTES
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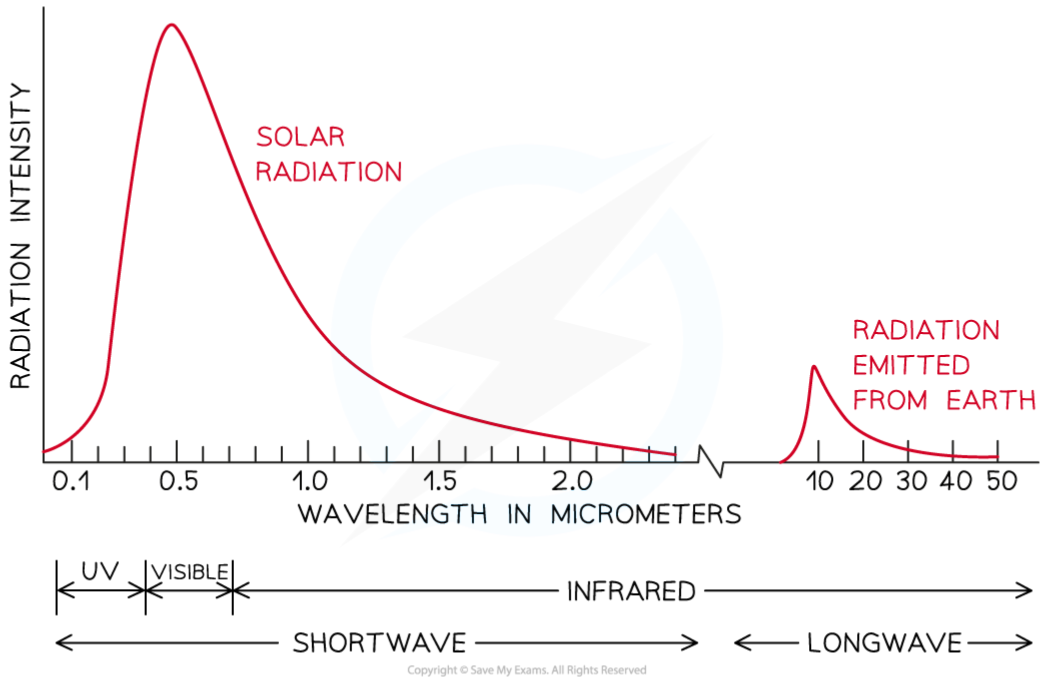

Solar radiation is primarily short-wave, while the radiation that is re-emitted by earth is long-wave radiation

Exam Tip

You may have heard of a separate environmental concern, described as the 'hole in the ozone layer'; this is **not** something that you need to know about. Ozone is an atmospheric gas that absorbs harmful UV radiation before it reaches earth, but any concerns about ozone depletion have nothing to do with the greenhouse effect. The problem of ozone depletion is one that has improved significantly due to measures taken to reduce certain types of emissions; humans can get it right sometimes!

You do not need to know the specific sources of each type of greenhouse gas – all you need to know is that each greenhouse gas has both natural and man-made origins

YOUR NOTES
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The Greenhouse Effect

- While only around 25% of the (primarily short wavelength) solar radiation is absorbed by the atmosphere on its way to Earth, around 80% of the (long wavelength) re-emitted radiation from Earth is absorbed on its way back into the atmosphere
  - For example, incoming UV radiation is absorbed by ozone
  - Re-emitted infrared radiation is absorbed by greenhouse gases
- This absorbed radiation keeps Earth at a habitable temperature
  - However, if there is an imbalance in the chemical composition of the atmosphere, this can lead to fluctuations in the Earth's mean surface temperature

Process of Global Warming

- Incoming radiation from the Sun predominantly takes the form of ultraviolet and visible radiation
- Visible light is not absorbed by the atmosphere, instead, it is absorbed by the Earth's surface
- At night, the Earth re-radiates this radiation as infrared
- Some of this radiation is absorbed by the Earth's atmosphere and some of the radiation is reflected back into space
- The greenhouse gases present in the atmosphere absorb infrared radiation and reflect it back towards the Earth's surface
  - The higher the concentration of greenhouse gases present, the more infrared radiation that remains in the Earth's surface-atmosphere system
- Therefore, heat energy becomes trapped inside Earth's atmosphere and accumulates
  - This leads to the greenhouse effect and an increase in average mean temperatures on Earth

YOUR NOTES
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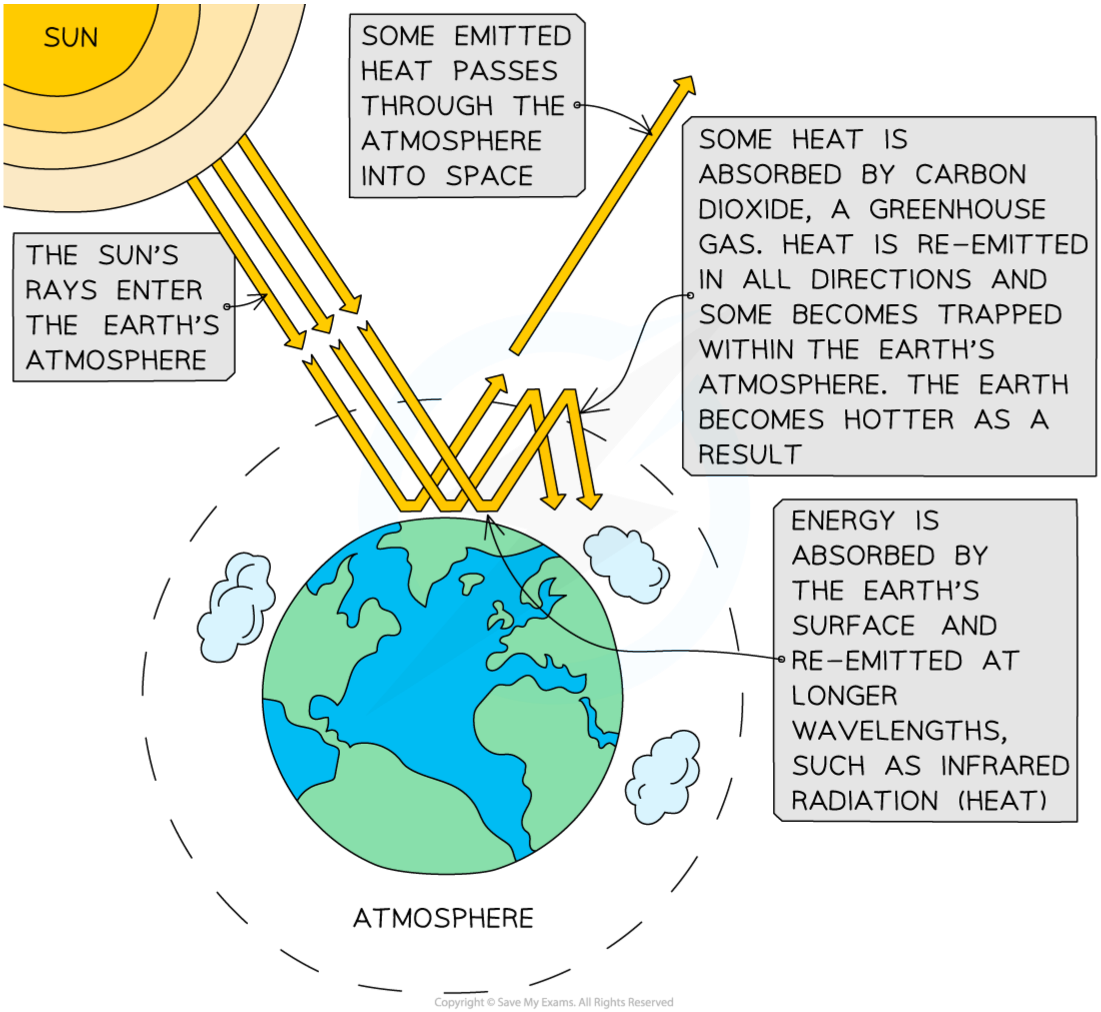


Greenhouse gases absorb the long-wave radiation emitted by Earth, warming the atmosphere

- There are many mechanisms that may increase the rate of global warming
- As the temperature of the Earth increases:
  - Ice and snow will melt – this will lead to a **decrease** in **albedo** and hence, an increased rate of **heat absorption**
  - The **solubility** of carbon dioxide in the sea will **decrease** – this will lead to an increase in atmospheric **carbon dioxide** concentration
  - Surface water will **evaporate** – this will lead to an increase in atmospheric **water vapour** concentration
- As a result, small increases in global temperature can lead to large runaway chain reactions which lead to catastrophic climate changes, such as
  - Significant rises in sea level due to the melting of ice
  - Extreme weather such as heatwaves and heavy floods

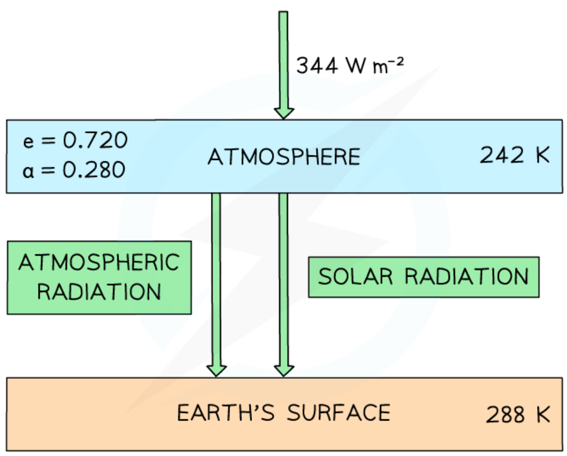
YOUR NOTES

Earth's Surface-Atmosphere System

- It is useful to consider Earth's energy balance in terms of how much incoming energy from the Sun is used and how much is returned to space
- If incoming and outgoing energy are in balance, the Earth's temperature will remain constant
- This can be used to create models which can help climate scientists predict temperature fluctuations based on current and increased concentrations of greenhouse gases
  - At it's simplest, the model involves a one-layer atmosphere above the Earth's surface

Worked Example

The diagram below shows a simple energy balance climate model in which the atmosphere and the Earth's surface are treated as two bodies.



The Earth's surface receives both solar radiation and radiation emitted from the atmosphere.

At current atmospheric greenhouse gas concentrations, the temperature of Earth's atmosphere is set to increase by 6 K.

Data for this model:

- Current mean temperature of the Earth's atmosphere = 242 K
- Current mean temperature of the Earth's surface = 288 K
- Solar power per unit area at top of the atmosphere = 344 W m^{-2}
- Emissivity of the atmosphere, e = 0.720
- Albedo of the atmosphere, *a* = 0.280

Use this data to estimate the increase in temperature of the Earth's surface.

Step 1: List the known quantities

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- Solar power above atmosphere, $P_a = 344\ \text{W m}^{-2}$
- Emissivity of the atmosphere, e = 0.720
- Emissivity of the surface, e = 1
- New temperature of Earth's atmosphere, $T_a = 242 + 6 = 248$ K
- Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}\ \text{W m}^{-2}\ \text{K}^{-4}$
- Power absorbed at the Earth's surface = P_s
- New temperature of Earth's surface = T_s

Step 2: Calculate the solar power absorbed at the Earth's surface

- This can be calculated using the emissivity and the solar power above the atmosphere

$$P_s = e \times P_a$$

$$P_s = 0.720 \times 344 = 247.68 = 248\ \text{W m}^{-2}$$

Step 3: Write the equation for the power emitted by a body

$$P = e\sigma T^4$$

Step 4: Calculate the new power radiated by the atmosphere

$$P = 0.720 \times (5.67 \times 10^{-8}) \times 248^4 = 154.43 = 154\ \text{W m}^{-2}$$

Step 5: Calculate the new power absorbed by the Earth's surface

- The power absorbed by the Earth's surface is a sum of the solar radiation that reaches the surface plus the power radiated by the atmosphere

$$\text{New power, } P_s = 248 + 154 = 402\ \text{W m}^{-2}$$

Step 6: Calculate the new temperature of the Earth's surface

- The Earth's surface can be assumed to be a black body, hence e = 1

$$P_s = \sigma T_s^4$$

$$400 = (5.67 \times 10^{-8}) \times T_s^4$$

$$T_s = \sqrt[4]{\frac{400}{5.67 \times 10^{-8}}} = 290\ \text{K}$$

Step 7: Determine the increase in temperature

$$\Delta T = 290 - 288 = 2\ \text{K}$$

Exam Tip

In simplified climate models, you can generally assume the Earth's surface and the atmosphere:

- Act as black bodies - this means the emissivity of the surface will be equal to 1!
- Remain at a constant temperature