Test yourself

1 a Distinguish between specific energy and energy density of a fuel.

b Estimate the energy density of water that falls from a waterfall of height 75 m and is used to drive a turbine.

2 A power plant produces 500 MW of power.

a Determine the energy produced in one second. Express your answer in joules.

b Determine the energy (in joules) produced in one year.

3 A power plant operates in four stages. The efficiency in each stage is 80%, 40%, 12% and 65%.

a Find the overall efficiency of the plant.

b Sketch a Sankey diagram for the energy flow in this plant.

4 A coal power plant with 30% efficiency burns 10 million kilograms of coal a day. (Take the specific energy of coal to be 30 MJ kg^{-1}.)

a Calculate the power output of the plant.

b Estimate the rate at which thermal energy is being discarded by this plant.

c The discarded thermal energy is carried away by water whose temperature is not allowed to increase by more than 5 °C. Calculate the rate at which water must flow away from the plant.

5 One litre of gasoline releases 34 MJ of energy when burned. The efficiency of a car operating on this gasoline is 40%. The speed of the car is 9.0 m s^{-1} when the power developed by the engine is 20 kW. Calculate how many kilometres the car can go with one litre of gasoline when driven at this speed.

6 A coal-burning power plant produces 1.0 GW of electricity. The overall efficiency of the power plant is 40%. Taking the specific energy of coal to be 30 MJ kg^{-1}, calculate the amount of coal that must be burned in one day.

7 In the context of nuclear fission reactors, state what is meant by:

a uranium enrichment

b moderator

c critical mass.

8 a Calculate the energy released in the fission reaction:

$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2{}^{1}_{0}n$$

(Mass data: uranium-235, ${}^{235}_{92}U = 235.043\,923$ u; xenon-140, ${}^{140}_{54}Xe = 139.921\,636$ u; strontium-94, ${}^{94}_{38}Sr = 93.915\,360$ u; neutron, ${}^{1}_{0}n = 1.008\,665$ u.)

b The power output is 200 MW. Estimate the number of fission reactions per second.

9 The energy released in a typical fission reaction involving uranium-235 is 200 MeV.

a Calculate the specific energy of uranium-235.

b Estimate how much coal (specific energy 30 MJ kg^{-1}) must be burned in order to give the same energy as that released in nuclear fission with 1 kg of uranium-235.

10 a A 500 MW nuclear power plant converts the energy released in nuclear reactions into electrical energy with an efficiency of 40%. Calculate how many fissions of uranium-235 are required per second. Take the energy released per reaction to be 200 MeV.

b What mass of uranium-235 is required to fission per second?

11 a Draw a diagram of a fission reactor, explaining the role of **i** fuel rods, **ii** control rods and **iii** moderator.

b In what form is the energy released in a fission reactor?

12 Distinguish between a solar panel and a photovoltaic cell.

13 Sunlight of intensity 700 W m^{-2} is captured with 70% efficiency by a solar panel, which then sends the captured energy into a house with 50% efficiency.

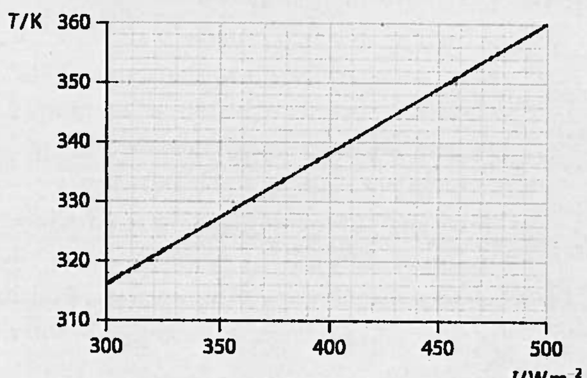
a The house loses thermal energy through bad insulation at a rate of 3.0 kW. Find the area of the solar panel needed in order to keep the temperature of the house constant.

b Draw a Sankey diagram for the energy flow from the panel to the house.

14 A solar heater is to heat 300 kg of water initially at 15 °C to a temperature of 50 °C in a time of 12 hours. The amount of solar radiation falling on the collecting surface of the solar panel is 240 W m^{-2} and is collected at an efficiency of 65%. Calculate the area of the collecting panel that is required.

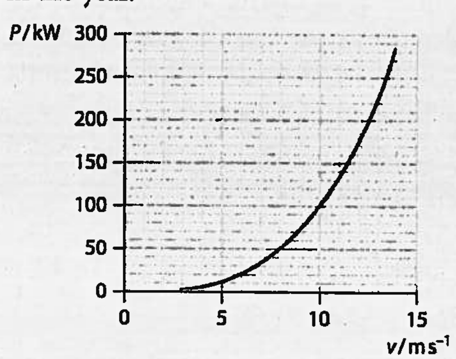
15 A solar heater is to warm 150 kg of water by 30 K. The intensity of solar radiation is 600 W m^{-2} and the area of the panels is 4.0 m^{-2}. The specific heat capacity of water is 4.2×10^3 J kg^{-1} K^{-1}. Estimate the time this will take, assuming a solar panel efficiency of 60%.

16 The graph shows the variation with incident solar intensity I of the temperature of a solar panel used to heat water. Thermal energy is extracted from the water at a rate of 320 W. The area of the panel is 2.0 m^2. Calculate, for a solar intensity of 400 W m^{-2}:



a the temperature of the water
b the power incident on the panel
c the efficiency of the panel.

17 The graph shows the power curve of a wind turbine as a function of the wind speed. For a wind speed of 10 m s^{-1}, calculate the energy produced in the course of one year, assuming that the wind blows at this speed for 1000 hours in the year.



18 a State the expected increase in the power extracted from a wind turbine when:
i the length of the blades is doubled
ii the wind speed is doubled
iii both the length of the blades and the wind speed are doubled.
b Outline reasons why the actual increase in the extracted power will be less than your answers.

19 Wind of speed v is incident on the blades of a wind turbine. The blades present the wind with an area A. The maximum theoretical power that can be extracted is given by:

$$P = \frac{1}{2}\rho A v^3$$

State the assumptions made in deriving this equation.

20 Air of density 1.2 kg m^{-3} and speed 8.0 m s^{-1} is incident on the blades of a wind turbine. The radius of the blades is 1.5 m. Immediately after passing through the blades, the wind speed is reduced to 3.0 m s^{-1} and the density of air is 1.8 kg m^{-3}. Estimate the power extracted from the wind.

21 Calculate the blade radius of a wind turbine that must extract 25 kW of power out of wind of speed 9.0 s^{-1}. The density of air is 1.2 kg m^{-3}. State any assumptions made in this calculation.

22 Find the power developed when water in a waterfall with a flow rate of 500 kg s^{-1} falls from a height of 40 m.

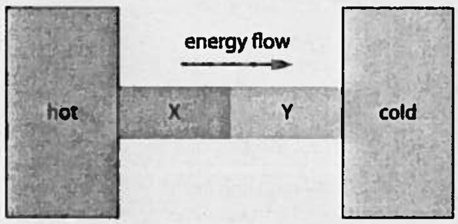
23 Water falls from a vertical height h at a flow rate (volume per second) Q. Deduce that the maximum theoretical power that can be extracted is given by $P = \rho Q g h$.

24 A student explaining pumped storage systems says that the water that is stored at a high elevation is allowed to move lower, thus producing electricity. Some of this electricity is used to raise the water back to its original height, and the process is then repeated. What is wrong with this statement?

25 Make an annotated energy flow diagram showing the energy changes that are taking place in each of the following:
a a conventional electricity-producing power station using coal
b a hydroelectric power plant
c an electricity-producing wind turbine
d an electricity-producing nuclear power station.

? Test yourself

26 A cylindrical solid tube is made out of two smaller tubes, X and Y, of different material. X and Y have the same length and cross-sectional area. The tube is used to conduct energy from a hot to a cold reservoir.



State and explain whether the following are equal or not:

a the rates of flow of energy through X and Y

b the temperature differences across X and Y.

27 Suggest whether there is any point in using a ceiling fan in winter.

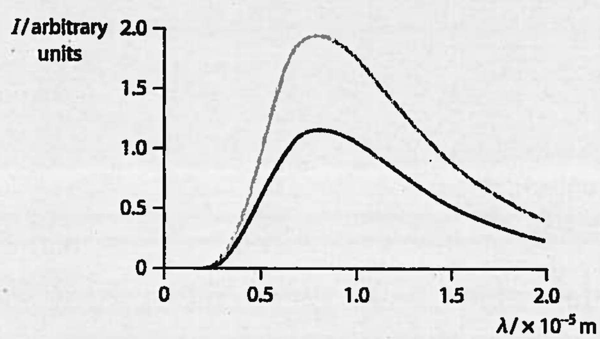
28 Calculate the ratio of the power radiated per unit area from two black bodies at temperature 900 K and 300 K.

29 a State what you understand by the term **black body**.

b Give an example of a body that is a good approximation to a black body.

c By what factor does the rate of radiation from a body increase when the temperature is increased from 50 °C to 100 °C?

30 The graph shows the variation with wavelength of the intensity of radiation emitted by two bodies of identical shape.



a Explain why the temperature of the two bodies is the same.

b The upper line corresponds to a black body. Calculate the emissivity of the other body.

31 The total power radiated by a body of area 5.00 km^2 and emissivity 0.800 is 1.35×10^9 W. Assume that the body radiates into a vacuum at temperature 0 K. Calculate the temperature of the body.

32 Assume that the distance d between the Sun and the Earth decreases. Then the Earth's average temperature T will go up. The fraction of the power radiated by the Sun that is received on Earth is proportional to $\frac{1}{d^2}$; the power radiated by the Earth is proportional to T^4.

a Deduce the dependence of the temperature T of the Earth on the distance d.

b Hence estimate the expected rise in temperature if the distance decreases by 1.0%. Take the average temperature of the Earth to be 288 K.

33 **a** Define the term **intensity** in the context of radiation.

b **Estimate** the intensity of radiation emitted by a naked human body of surface area 1.60 m^2, temperature 37 °C and emissivity 0.90, a distance of 5.0 m from the body.

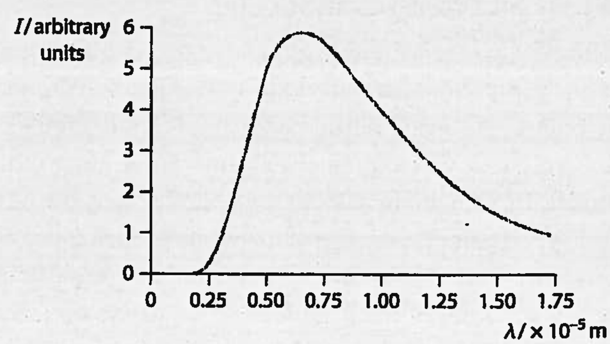
34 A body radiates energy at a rate (power) P.

a Deduce that the intensity of this radiation at distance d from the body is given by:

$$I = \frac{P}{4\pi d^2}$$

b State **one** assumption made in deriving this result.

35 The graph shows the variation with wavelength of the intensity of the radiation emitted by a black body.



a Determine the temperature of the black body.

b Copy the diagram and, on the same axes, draw a graph to show the variation with wavelength of the intensity of radiation emitted by a black body of temperature 600 K.

36 a Define the term **albedo**.

b State **three** factors that the albedo of a surface depends on.

37 a State what is meant by the **greenhouse effect.**

b State the main greenhouse gases in the Earth's atmosphere, and for each give **three** natural and **three** man-made sources.

38 A researcher uses the following data for a simple climatic model of an Earth without an atmosphere (see Worked example **8.10**): incident solar radiation = 350 W m^{-2}, absorbed solar radiation = 250 W m^{-2}.

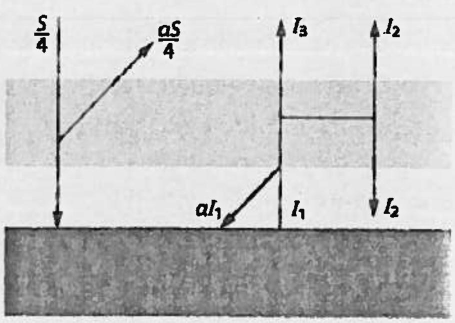
a Make an energy flow diagram for these data.

b Determine the average albedo for the Earth that is to be used in the modelling.

c Determine the intensity of the outgoing long-wave radiation.

d Estimate the temperature of the Earth according to this model, assuming a constant Earth temperature.

39 The diagram shows a more involved model of the greenhouse effect.



Exam tip

You will not get anything as complicated as this in the exam, but this is excellent practice in understanding energy balance equations.

The average incoming radiation intensity is $\frac{S}{4} = 350\ \text{W m}^{-2}$. The albedo of the atmosphere is 0.300. Assume that only a fraction t of the energy radiated by the Earth actually escapes the Earth and that the surface behaves as a black body. The model assumes that part of the radiation from the Earth is reflected back down from the atmosphere.

a The intensity radiated by the Earth is I_1, the intensity radiated by the atmosphere is I_2 and the fraction of the intensity escaping the Earth is I_3. By examining the energy balance of the atmosphere and the surface separately, show that:

$$I_1 = \frac{2}{1-\alpha+t} \times \frac{(1-\alpha)S}{4},$$

$$I_2 = \frac{1-\alpha-t}{1-\alpha+t} \times \frac{(1-\alpha)S}{4} \quad \text{and}$$

$$I_3 = \frac{2t}{1-\alpha+t} \times \frac{(1-\alpha)S}{4}$$

b Show that as much energy enters the Earth–atmosphere system as leaves it.

c Show that a surface temperature of $T \approx 288$ K implies that $t = 0.556$.

d i Explain why the emissivity of the atmosphere is $1 - t - \alpha$.

ii Calculate the temperature of the atmosphere.

40 Outline the main ways in which the surface of the Earth loses thermal energy to the atmosphere and to space.

41 a Compare the albedo of a subtropical, warm, dry land with that of a tropical ocean.

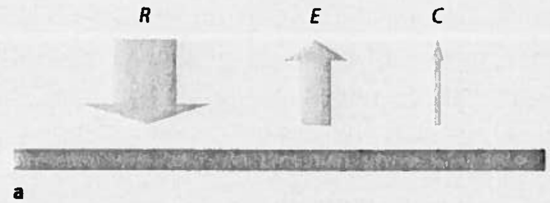
b Suggest mechanisms through which the subtropical land and the tropical ocean lose thermal energy to the atmosphere.

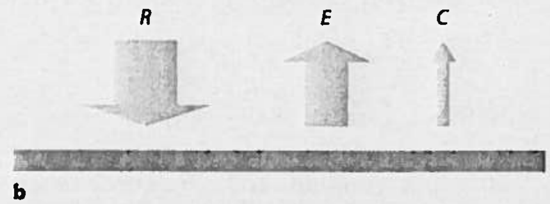
c If the sea level were to increase, sea water would cover dry land. Suggest **one** change in the regional climate that might come about as a result.

42 Evaporation is a method of thermal energy loss. Explain whether you would expect this method to be more significant for a tropical ocean or an arctic ocean.

43 The diagram shows two energy flow diagrams for thermal energy transfer to and from specific areas of the surface of the Earth. *R* represents the net energy incident on the surface in the form of radiation, *E* is the thermal energy lost from the Earth due to evaporation, and *C* is the thermal energy conducted to the atmosphere because of the temperature difference between the surface and the atmosphere.

Suggest whether the Earth area in each diagram is most likely to be dry and cool or moist and warm.





44 It is estimated that a change of albedo by 0.01 will result in a 1 °C temperature change. A large area of the Earth consists of 60% water and 40% land. Calculate the expected change in temperature if melting ice causes a change in the proportion of the area covered by water from 60% to 70%. Take the albedo of dry land to be 0.30 and that of water to be 0.10.

Exam-style questions

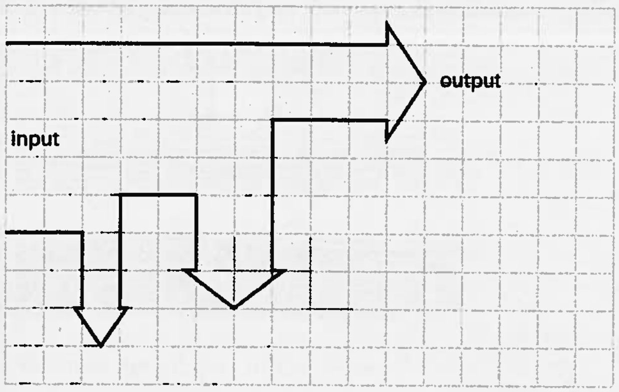
1 A power plant produces 500 MW of electrical power with an overall efficiency of 20%. What is the input power to the plant?

A 100 MW **B** 400 MW **C** 625 MW **D** 2500 MW

2 The specific energy of a fuel is the:

A energy that can be extracted from a unit volume of the fuel
B energy that can be extracted from a unit mass of the fuel
C energy contained in a unit volume of the fuel
D energy contained in a unit mass of the fuel.

3 What is the efficiency of a system whose Sankey diagram is shown below?



A 10% B 20% C 30% D 40%

4 Which of the following lists contains one renewable and one non-renewable source of power?

A uranium, coal
B natural gas, biomass
C wind power, wave power
D hydropower, solar power

5 A plastic ruler and a metallic ruler are in the same room. The metallic ruler 'feels' colder when touched. What is the reason for this?

A Plastic has a lower specific heat capacity than metal.
B Plastic has a higher specific heat capacity than metal.
C Plastic is a better conductor of heat than metal
D Plastic is a worse conductor of heat than metal.

6 A fireplace warms a room by:

A conduction
B convection
C radiation
D conduction, convection and radiation

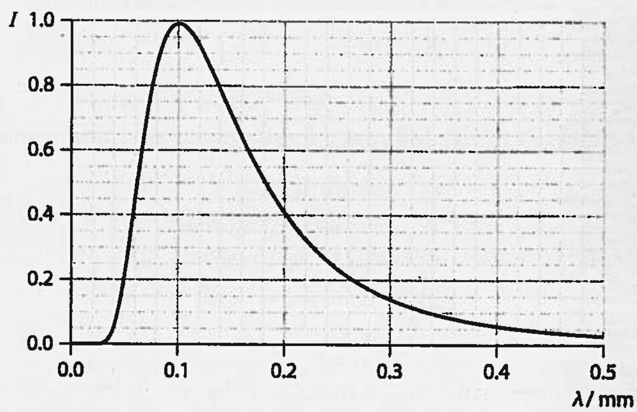
7 A star explodes in the vacuum of space. The thermal energy transferred by the star takes place through:

A radiation B conduction C convection D evaporation

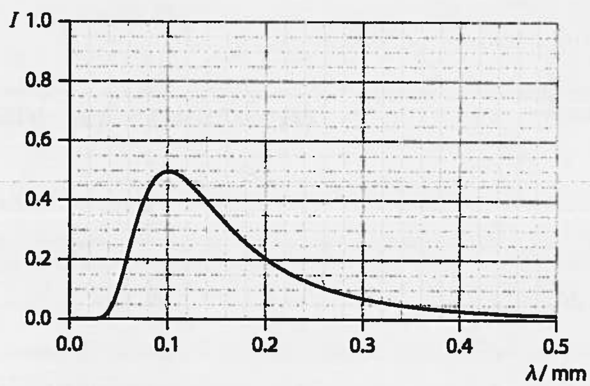
8 Four different rooms are losing energy to the outside through a wall. The temperature difference between the inside and the outside of the rooms is the same. Which combination of wall area and wall thickness results in the smallest rate of heat loss?

	Area	**Thickness**
A	S	d
B	$2S$	$\frac{d}{2}$
C	S	$2d$
D	$2S$	$2d$

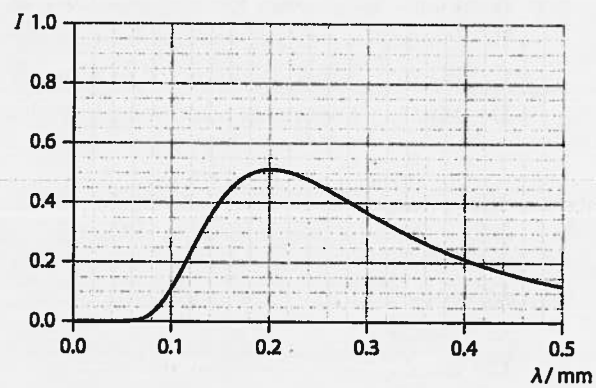
9 The graph shows the variation with wavelength of the intensity from a unit area of a black body. The scale on the vertical axis on all graphs in this question is the same.



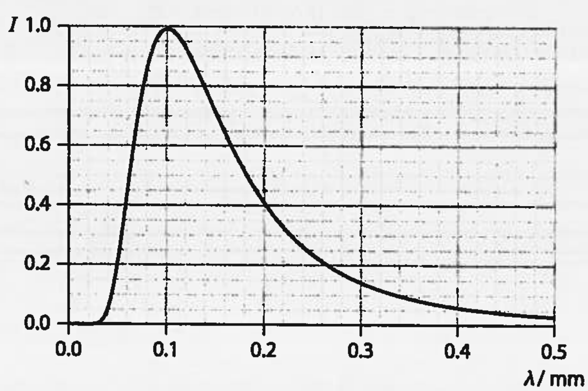
The area and the temperature of the black body are both halved. Which graph now shows the correct variation with wavelength of the intensity from a unit area of the body?



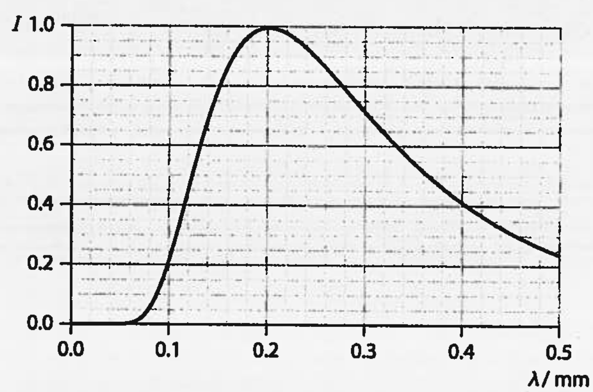
A



B

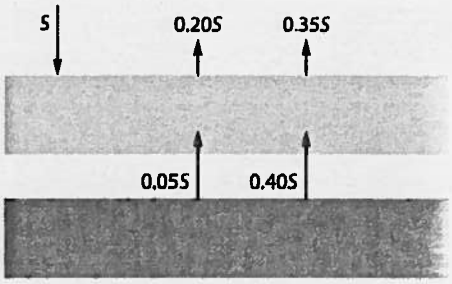


C



D

10 The intensity of solar radiation incident on a planet is S. The diagram represents the energy balance of the planet. The atmosphere reflects an intensity 0.20S and radiates 0.35S. The surface reflects 0.05S and radiates 0.40S.



What is the albedo of the planet?

A 0.05 **B** 0.20 **C** 0.25 **D** 0.60

11 A nuclear power plant produces 800 MW of electricity with an overall efficiency of 0.32. The fission reaction taking place in the core of the reactor is:

$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2{}^{1}_{0}n$$

a **i** Using the masses provided below show that the energy released in one fission reaction is about 180 MeV. **[2]**

$${}^{1}_{0}n = 1.009\,u,\ {}^{235}_{92}U = 235.044\,u,\ {}^{140}_{54}Xe = 139.922\,u,\ {}^{94}_{38}Sr = 93.915\,u.$$

ii Estimate the specific energy of uranium-235. **[2]**

iii Show that the mass of uranium-235 undergoing fission in one year is about 1500 kg. **[3]**

b In a nuclear fission reactor, describe the role of:

i the moderator **[2]**

ii the control rods **[2]**

iii the heat exchanger. **[2]**

c Suggest what might happen to a nuclear fission reactor that does not have a moderator. **[2]**

d State **one** advantage and **one** disadvantage of nuclear power. **[2]**

12 In a pumped storage system, the high reservoir of water has area $4.8 \times 10^4\,m^2$ and an average depth of 38 m. When water from this reservoir falls to the lower reservoir the centre of mass of the water is lowered by a vertical distance of 225 m. The water flows through a turbine connected to a generator at a rate of $350\,m^3\,s^{-1}$.

a Calculate the mass of the water in the upper reservoir. **[1]**

b Determine the loss of gravitational potential energy when the upper reservoir has been completely emptied. **[2]**

c Estimate the power supplied by the falling water. **[2]**

The efficiency of the plant in converting this energy into electricity is 0.60. The price of electricity sold by this power station at peak times is \$0.12 per kW h. The plant can buy off-peak electrical power at \$0.07 per kW h. The efficiency at which water can be pumped back up to the high reservoir is 0.64.

d Estimate the profit made by the power plant for a single emptying and refilling of the high reservoir. **[3]**

13 **a** Outline, in the context of a wind turbine, the meaning of **primary** and **secondary** energy. **[2]**

b The power that can be theoretically extracted by a wind turbine of blade radius R in wind of speed v is $P_{max} = \frac{1}{2}\pi\rho R^2 v^3$

i State **one** assumption that has been made in deriving this expression. **[1]**

ii Explain **one** other reason why the actual power derived from the wind turbine will be less than P_{max}. **[2]**

c A wind turbine has an overall efficiency of 0.30. The following data are available:

Density of air entering turbine = $1.2\,kg\,m^{-3}$

Density of air leaving turbine = $1.9\,kg\,m^{-3}$

Speed of air entering turbine = $8.2\,m\,s^{-1}$

Speed of air leaving turbine = $5.3\,m\,s^{-1}$

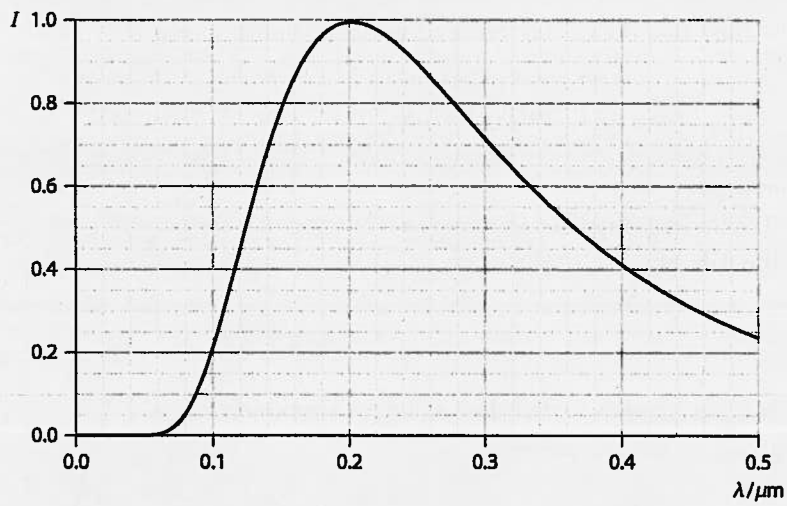
Blade radius = 12 m

Estimate the power extracted by this wind turbine. **[3]**

14 **a** On a hot summer day there is usually a breeze from the sea to the shore. Explain this observation. **[3]**

b Explain why walking on a day when the temperature is 22 °C would be described as very comfortable but swimming in water of the same temperature would be described as cool. **[2]**

A black body has temperature T. The graph shows the variation with wavelength of the intensity of radiation emitted by a unit area of the body. The units on the vertical axis are arbitrary.



c **i** Describe what is meant by a **black body**. **[2]**

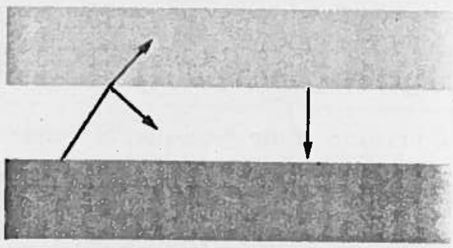
ii Estimate T. **[2]**

d On a copy of the axes above sketch a graph to show the variation with wavelength of the intensity of radiation emitted by a unit area of:

i a grey body of emissivity 0.5 and temperature T (label this graph G) **[2]**

ii a black body of temperature $\frac{2T}{3}$ (label this graph B). **[2]**

15 The diagram shows a black body of temperature T_1 emitting radiation towards a grey body of lower temperature T_2 and emissivity e. No radiation is transmitted through the grey body.



a Using all or some of the symbols T_1, T_2, e and σ, state expressions for the intensity:
  i radiated by the black body [1]
  ii radiated by the grey body [1]
  iii absorbed by the grey body [1]
  iv reflected by the grey body. [1]

b The black and the grey bodies in **a** gain as much energy as they lose. Deduce that their temperatures must be the same. [2]

16 The power radiated by the Sun is P and the Earth–Sun distance is d. The albedo of the Earth is α.

a i Deduce that the solar constant (i.e. the intensity of the solar radiation) at the position of the Earth is $S = \frac{P}{4\pi d^2}$ [2]
  ii State what is meant by **albedo**. [1]

b i Explain why the average intensity absorbed by the Earth surface is $\frac{S(1-\alpha)}{4}$ [3]
  ii $P = 3.9 \times 10^{26}\,\text{W}$, $d = 1.5 \times 10^{11}\,\text{m}$ and $\alpha = 0.30$. Assuming the Earth surface behaves as a black body, estimate the average equilibrium temperature of the Earth. [2]

c The average Earth temperature is much higher than the answer to **b ii**. Suggest why this is so. [3]