Answers to Coursebook questions – Chapter 7.1

1 The thermal energy discarded must be returned to a reservoir that has a lower temperature from where the energy was extracted. In this case the temperatures are the same and so this will not work.

2 Energy degradation refers to energy that can no longer be used to perform useful work. A typical example is the thermal energy that is discarded from the exhaust pipe of an automobile engine. This is thermal energy that is wasted.

3 **a** Energy density is the amount of energy per unit mass that can be extracted from a fuel.

b The potential energy of the water is *mgh* and so the energy density is $\frac{mgh}{m} = gh \approx 10 \times 75 = 700\ \text{J kg}^{-1}$.

4 **a** In 1 s the energy is 500 MJ or

i $5.0 \times 10^{8}\ \text{J}$,

ii $5.0 \times 10^{5}\ \text{kW} \times \frac{1}{3600}\ \text{h} \approx 140\ \text{kW h}$ or

iii $0.140\ \text{MW h}$.

b In one year the energy is $5.0 \times 10^{8} \times 365 \times 24 \times 60 \times 60 = 1.6 \times 10^{16}\ \text{J}$.

5 The overall efficiency is $0.80 \times 0.40 \times 0.12 \times 0.65 = 0.025$.

6 **a** The energy produced by burning the fuel is $10^{7} \times 30 \times 10^{6} = 3.0 \times 10^{14}\ \text{J}$.
Of this, 70% is converted to useful energy and so the power output is
$P = \frac{0.30 \times 3.0 \times 10^{14}}{24 \times 60 \times 60} = 1.04 \times 10^{9}\ \text{W}$.

b The rate at which energy is discarded is $P_{\text{discard}} = \frac{0.70 \times 3.0 \times 10^{14}}{24 \times 60 \times 60} = 2.43 \times 10^{9}\ \text{W}$.

c Use $\frac{\Delta m}{\Delta t} c\Delta\theta = P_{\text{discard}}$ to get $\frac{\Delta m}{\Delta t} = \frac{P_{\text{discard}}}{c\Delta\theta} = \frac{2.43 \times 10^{9}}{4200 \times 5} = 1.2 \times 10^{5}\ \text{kg s}^{-1}$.

7 In time *t* the energy used by the engine is $20 \times 10^{3} \times t$.
The energy available is $0.40 \times 35 \times 10^{6}\ \text{J}$
and so $20 \times 10^{3} \times t = 0.40 \times 35 \times 10^{6} \Rightarrow t = 700\ \text{s}$.
The distance travelled is then $x = vt = 9.0 \times 700 = 6.3\ \text{km}$.

8 The useful energy produced each day is
$E = Pt = 1.0\times10^{9}\times24\times60\times60 = 8.64\times10^{13}$ J.
The energy produced by burning the coal is therefore
$$0.40 = \frac{8.64\times10^{13}}{E_c} \Rightarrow E_c = 2.16\times10^{14}\ \text{J}.$$
So the mass of coal to be burned is $m = \dfrac{2.16\times10^{14}}{30\times10^{6}} = 7.2\times10^{6}$ kg per day.

9 **a** The fissionable isotope of uranium is U-235. This is found in very small concentrations in uranium ore, which is mostly U-238. Enrichment means increasing the concentration of U-235 in a sample of uranium.

b The moderator is the part of the nuclear reactor where neutrons released from the fission reactions slow down as a result of collisions with the atoms of the moderator. The temperature of the moderator can be kept constant with a cooling system that removes the excess thermal energy generated in the moderator.

c Critical mass refers to the least mass of uranium that must be present for nuclear fission reactions to be sustained. If the mass of uranium is too small (i.e. below the critical mass) the neutrons may escape without causing fission reactions.

10 **a** The reaction is ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \to {}^{140}_{54}\text{Xe} + {}^{94}_{38}\text{Sr} + 2\,{}^{1}_{0}\text{n}$. The mass difference is

$$\begin{aligned}\delta &= (235.043992 - 92\times0.000549) + 1.008665 - \\ &\quad \big((139.921636 - 54\times0.000549) + (93.915360 - 38\times0.000549) + 2\times1.008665)\big) \\ &= 0.198331\ \text{u}\end{aligned}$$

And so the energy released is $E = 0.198331\times931.5\text{c}^2\ \ \text{MeV c}^{-2} = 185\ \ \text{MeV}$.

b With N reactions per second the power output is $N\times185\ \text{MeV s}^{-1}$.
In other words, $N\times185\times10^{6}\times1.6\times10^{-19} = 200\times10^{6} \Rightarrow N = 6.8\times10^{18}\ \text{s}^{-1}$.

11 **a** One kilogram of uranium corresponds to $\dfrac{1000}{235} = 4.26$ moles and so
$4.26\times6.02\times10^{23} = 2.57\times10^{24}$ nuclei.
Each nucleus produces 200 MeV and so the energy produced by 1 kg (the energy density) is $2.57\times10^{24}\times200\times10^{6}\times1.6\times10^{-19} \approx 8\times10^{13}\ \text{J kg}^{-1}$.

b $\dfrac{8\times10^{13}}{30\times10^{6}} = 2.7\times10^{6}$ kg.

12 **a** The energy that must be produced in 1 s is $E = \frac{500\times10^{6}}{0.40} = 1.25\times10^{9}$ J.
Hence the number of fission reactions per second is
$\frac{1.25\times10^{9}}{200\times10^{6}\times1.6\times10^{-19}} = 3.9\times10^{19}$.

b The number of nuclei required to fission per second is 3.9×10^{19} ,
which corresponds to $\frac{3.9\times10^{19}}{6.02\times10^{23}} = 6.5\times10^{-5}$ mol,
i.e. a mass of $6.5\times10^{-5}\times235\times10^{-3} = 1.5\times10^{-5}$ kg s^{-1}.

13 **a** For a diagram see page 421 in *Physics for the IB Diploma*.

i Fuel rods are pipes in which the fuel (i.e. uranium-235) is kept.

ii Control rods are rods that can absorb neutrons. These are lowered in or raised out of the moderator so that the rate of reactions is controlled. The rods are lowered in if the rate is too high – the rods absorb neutrons so that these neutrons do not cause additional reactions. They are raised out if the rate is too small leaving the neutrons to cause further reactions.

iii The moderator is the part of the nuclear reactor where neutrons released from the fission reactions slow down as a result of collisions with the atoms of the moderator. The temperature of the moderator can be kept constant with a cooling system that removes the excess thermal energy generated in the moderator.

b It is kinetic energy of the neutrons produced which is converted into thermal energy in the moderator as the neutrons collide with the moderator atoms.

14 Up to you.

15 A solar panel receives solar radiation incident on it and uses it to heat up water, i.e. it converts solar energy into thermal energy.
The photovoltaic cell converts the solar incident on it to electrical energy.

16 In order for the electrons to make the transition to the conduction band, an energy equal to the difference between the valence and the conduction band must be supplied.
If the photons' energy is only 2 eV and the gap energy greater than 2 eV, this will not be possible.

17 The power that must be supplied is 3.0 kW, and this equals $700\times A\times0.70\times0.50$. Hence
$700\times A\times0.70\times0.50 = 3.0\times10^{3} \Rightarrow A = 12\text{ m}^{2}$.

18 The power that is provided is $0.65\times240\times A$
and this must equal $\frac{mc\Delta\theta}{\Delta t} = \frac{300\times4200\times35}{12\times60\times60}$.
Hence $0.65\times700\times A = \frac{300\times4200\times35}{12\times60\times60} \Rightarrow A = 6.5\text{ m}^{2}$.

19

For solar radiation of 600 W m^{-2} the power incident on the panel is $600 \times 4.0 \times 0.60 = 1440$ W .

The energy needed to warm the water is $mc\Delta\theta = 150 \times 4200 \times 30 = 1.89 \times 10^7$ J

and so $1440 \times t = 1.89 \times 10^7 \Rightarrow t = \dfrac{1.89 \times 10^7}{1440} = 1.31 \times 10^4 \text{ s} = 3.6 \text{ h}$.

20 **a** From the graph this is about $T = 338$ K

b $P = IA = 400 \times 2 = 800$ W .

c The useful power is the 320 W that is extracted.

The efficiency is thus $\dfrac{320}{800} = 0.40$.

21 The power supplied at the given speed is (reading from the graph) 100 kW.
Hence the energy supplied in 100 h is $100 \times 10^3 \times 1000 \times 60 \times 60 = 3.6 \times 10^{11}$ J .

22 We look at the power formula for windmills, $P = \dfrac{1}{2}\rho A v^3$ to deduce that:

a the area will increase by a factor of 4 if the length is doubled and so the power increases by a factor of 4,

b the power will increase by a factor of $2^3 = 8$ and

c the combined effect is $4 \times 8 = 32$.

d Not all the kinetic energy of the wind can be extracted because not all the wind is stopped by the windmill (as the formula has assumed). In addition, there will be frictional losses as the turbines turn as well as losses due to turbulence.

23 **a** The proof of this formula is on page 427 in *Physics for the IB Diploma*.

b Assumptions include:

i no losses of energy due to frictional forces as the turbines turn,

ii no turbulence in the air and

iii all the air stops at the turbines so that the speed of the air behind the turbines is zero (which is impossible).

24 The power in the wind before hitting the turbine is $\frac{1}{2}\rho_1 A v_1^3$

and right after passing through the turbine is $\frac{1}{2}\rho_2 A v_2^3$

so the extracted power is

$\frac{1}{2}\rho_1 A v_1^3 - \frac{1}{2}\rho_2 A v_2^3 = \frac{1}{2}\times\pi\times 1.5^2(1.2\times 8.0^3 - 1.8\times 3.0^3)\approx 2.0\ \mathrm{kW}$.

25 From $P=\frac{1}{2}\rho A v^3$ we get $25\times 10^3 = \frac{1}{2}\times 1.2\times A\times 9.0^3 \Rightarrow A = 57.16\ \mathrm{m}^2$

and so $\pi R^2 = 57.16 \Rightarrow R = 4.3\ \mathrm{m}$.

The assumptions made are the usual ones (see **Q23**):

i no losses of energy due to frictional forces as the turbines turn

ii no turbulence in the air and

iii all the air stops at the turbines so that the speed of the air behind the turbines is zero (which is impossible).

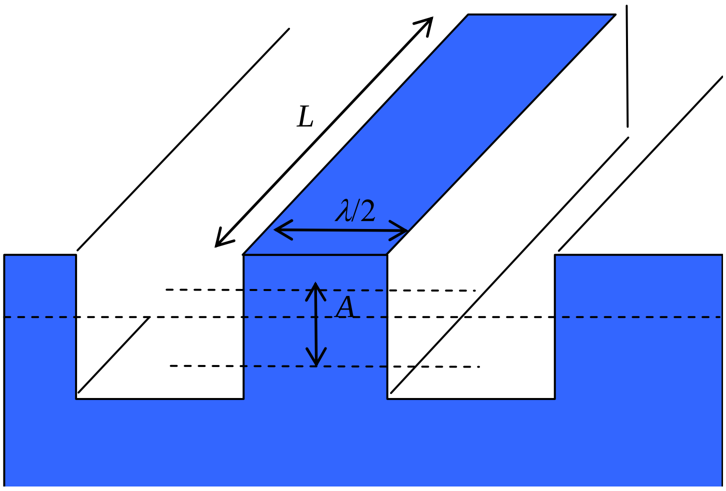
26 The potential energy of a mass Δm of water is $\Delta m\, gh$ and so the power developed is the rate of change of this energy,

i.e. $\frac{\Delta m}{\Delta t} gh = 500\times 9.8\times 40 = 1.96\times 10^5 \approx 2.0\times 10^5\ \mathrm{W}$.

27 The potential energy of a mass Δm of water is $\Delta m\, gh$ and so the power developed is the rate of change of this energy, i.e. $\frac{\Delta m}{\Delta t} gh = \rho\frac{\Delta V}{\Delta t} gh = \rho Q g h$.

28 The amount of electrical energy generated will always be less than the energy required to raise the water back to its original height. This is because the electrical energy generated is less than what theoretically could be provided by the water (because of various losses). So this claim cannot be correct.

29 **a**



A mass of volume $\frac{\lambda}{2}LA$ in the trough is raised so it now occupies a crest.

The centre of mass has been raised by A and so the potential energy is $\rho\frac{\lambda}{2}LAgA = \frac{1}{2}\rho g A^2 \lambda L$.

The frequency of the wave is f and so the potential energy per second per unit wavefront length L is $\frac{P}{L} = \frac{1}{2}\rho g A^2 \lambda f = \frac{1}{2}\rho g A^2 v$.

b From $\frac{P}{L} = \frac{1}{2}\rho g A^2 v$ we find $\frac{P}{L} = \frac{1}{2}\times 10^3 \times 9.8 \times 5.0^2 \times 4.8 = 5.9\times 10^5$ W m^{-1}.

c $5.9\times 10^5 \times L = 1.0\times 10^6 \Rightarrow L = 1.7$ m.

30 The OWC works by sending air that is compressed as a wave approaches the shore through a turbine that turns in a magnetic field producing electricity. As the wave recedes, air flows through the turbine in reverse, again turning it. The big advantage of the OWC device is that, by adjusting the valves through which the air flows, the air speed can be increased to values suitable for producing AC electricity at frequencies much higher than the (low) water wave frequency.

31 **a** Coal power plant: chemical energy of coal $\rightarrow$ thermal energy $\rightarrow$ kinetic energy of steam $\rightarrow$ kinetic energy of turbine $\rightarrow$ electrical energy.

b Hydroelectric power plant: potential energy of water $\rightarrow$ kinetic energy of water $\rightarrow$ kinetic energy of turbine $\rightarrow$ electrical energy.

c Wind turbine: kinetic energy of wind $\rightarrow$ kinetic energy of turbine $\rightarrow$ electrical energy.

d Nuclear power plant: nuclear energy of fuel $\rightarrow$ kinetic energy of neutrons $\rightarrow$ thermal energy in moderator $\rightarrow$ kinetic energy of steam $\rightarrow$ kinetic energy of turbine $\rightarrow$ electrical energy.

32 **a** The surface area of the tank is $2\times1.0\times1.0+4\times1.0\times0.10=2.4\ \text{m}^2$
and so its volume is $2.4\times5.0\times10^{-3}=1.2\times10^{-2}\ \text{m}^3$
and hence its mass is $1.2\times10^{-2}\times1200=14.4\ \text{kg}$.

b The tank receives energy at a rate of 800 W.
Thus from $\frac{\Delta Q}{\Delta t}=kA\frac{T_1-T_2}{x}$
we get $0.80\times800=0.30\times1.0\times\frac{T_1-20}{5.0\times10^{-3}}\Rightarrow T_1=31\ ^\circ\text{C}$.

c $C=14.4\times450+100\times4200=4.3\times10^5\ \text{J K}^{-1}$.

d The thermal energy supplied to the water equals the energy it receives from the sun minus what it loses to the surroundings.
The rate at which energy is received from the sun is AI_{in} and it loses energy at a rate $kA\frac{T-20}{x}$.
The thermal energy needed to raise the water-tank system temperature is $\Delta Q=C\Delta T$ and so the rate at which the energy is used is $\frac{\Delta Q}{\Delta t}=C\frac{\Delta T}{\Delta t}$.
Hence, $C\frac{\Delta T}{\Delta t}=AI_{\text{in}}-kA\frac{T-20}{x}$.

e The average is $\frac{31+20}{2}=25.5\ ^\circ\text{C}$.
Hence $4.3\times10^5\times\frac{\Delta T}{\Delta t}=1.0\times800\times0.80-0.30\times1.0\times\frac{25.5-20}{5.0\times10^{-3}}$
giving $\frac{\Delta T}{\Delta t}=7.2\times10^{-4}\ \text{K s}^{-1}$.

f At this rate the final temperature is reached after a time given by
$\frac{11}{\Delta t}=7.2\times10^{-4}\Rightarrow\Delta t=1.5\times10^4\ \text{s}=4.2\ \text{h}$.