Chapter 2 Homework Answers

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Chapter 2: Exercises on Units, Energy, and Power

Exercise 1

> A joule is an amount of energy, and a watt is a rate of using energy, defined as $1 \text{ W} = 1 \text{ J}/\text{s}$. How many joules of energy are required to run a 100 W light bulb for one day? Burning coal yields about 30×10^6 J of energy per kg of coal burned. Assuming that the coal power plant is 30% efficient, how much coal has to be burned to light that light bulb for one day?

A 100 W light bulb burns 100 Joules per second. There are 3600 seconds in an hour and 24 hours in a day, so the light bulb will consume

$$\begin{aligned}
100 \text{ Watt} \times 1 \text{ day} &= 100 \frac{\text{Joule}}{\text{second}} \times 1 \text{ day} \\
&= 100 \frac{\text{Joule}}{\text{second}} \times 1 \cancel{\text{day}} \times \frac{24 \text{ hours}}{\cancel{\text{day}}} \\
&= 100 \frac{\text{Joule}}{\text{second}} \times 24 \cancel{\text{hour}} \times \frac{3600 \text{ seconds}}{\cancel{\text{hour}}} \\
&= 100 \frac{\text{Joule}}{\cancel{\text{second}}} \times 86,400 \cancel{\text{seconds}} \\
&= 8.64 \times 10^6 \text{ Joules}
\end{aligned}$$

Now, figure out how much coal you have to burn to produce the energy.

$$\begin{aligned}
\text{coal burned} &= \frac{\text{Energy to power bulb}}{\text{Power plant efficiency} \times \text{Joules/kg coal}} \\
&= \frac{8.64 \times 10^6 \text{ Joules}}{0.3 \times 3.00 \times 10^7 \text{ Joules/kg coal}} \\
&= \frac{8.64 \times 10^6 \cancel{\text{Joules}}}{9.00 \times 10^6 \cancel{\text{Joules}}\text{/kg coal}} \\
&= 0.96 \text{ kg coal}
\end{aligned}$$

Exercise 2

This exercise asks you to calculate how many Joules of energy you can get for a dollar from different sources of energy.

Part 2(a)

(a) A gallon of gasoline carries with it about 1.3×10^8 J of energy. Given a price of \$3 per gallon, how many Joules can you get for a dollar?

Answer: 3 dollars buys you a gallon of gasoline, and a gallon of gasoline gives you 4.33×10^7 Joules, so you get

$$\frac{1 \text{ gallon}}{3 \text{ dollars}} \times 1.30 \times 10^8 \frac{\text{Joules}}{\text{gallon}} = 4.33 \times 10^7 \frac{\text{Joules}}{\text{dollar}}$$

from gasoline.

Part 2(b)

(b) Electricity goes for about \$0.05 per kilowatt hour. A kilowatt hour is just a weird way to write Joules because a watt is a Joule per second, and a kilowatt hour is the number of Joules one would get from running 1000 W for one hour (3,600 seconds). How many Joules of electricity can you get for a dollar?

A kilowatt hour is the energy from using 1000 Watts for 1 hour, or 3,600 seconds. A Watt is 1 Joule per second, so 1 kWh = 1000 Watts × 3600 seconds.

Answer: \$0.05 buys you a kilowatt hour of electricity, and a kilowatt hour of electricity has

$$
\begin{aligned}
1 \text{ kilowatt hour} &= 1 \cancel{\text{kilowatt}} \text{ hour} \times 1{,}000 \frac{\text{Watts}}{\cancel{\text{kilowatt}}} \\
&= 1{,}000 \text{ Watt hours} \\
&= 1{,}000 \text{ Watt } \cancel{\text{hours}} \times \frac{3{,}600 \text{ seconds}}{\cancel{\text{hour}}} \\
&= 3.60 \times 10^6 \text{ Watt seconds} \\
&= 3.60 \times 10^6 \cancel{\text{Watt}} \text{ seconds} \times 1 \frac{\text{Joule/second}}{\cancel{\text{Watt}}} \\
&= 3.60 \times 10^6 \cancel{\text{seconds}} \times 1 \frac{\text{Joule}}{\cancel{\text{second}}} \\
&= 3.60 \times 10^6 \text{ Joules}
\end{aligned}
$$

so you get

$$\frac{1 \text{ kWh}}{0.05 \text{ dollars}} \times 3.60 \times 10^6 \frac{\text{Joules}}{\text{kWh}} = 7.20 \times 10^7 \frac{\text{Joules}}{\text{dollar}}$$

from electricity. Written differently, that's 72,000,000 Joules per dollar.

Part 2(c)

(c) A standard cubic foot of natural gas carries with it about 1.1×10^6 Joules of energy. You can get about 5×10^5 British Thermal Units (BTUs) of gas for a dollar, and there are about 1,030 BTUs in a standard cubic foot. How many Joules of energy in the form of natural gas can you get for a dollar?

Answer:

You can get 500,000 BTU per dollar from natural gas, and there are 1,030 BTU per scf (standard cubic foot), so you can get

$$500{,}000 \cancel{\text{BTU}} \times \frac{1 \text{ scf}}{1{,}030 \cancel{\text{BTU}}} = 485 \text{ scf}$$

for a dollar.

One scf of natural gas has 1.10×10^6 Joules of energy, so you can get

$$485 \frac{\cancel{\text{scf}}}{\text{dollar}} \times 1.10 \times 10^6 \frac{\text{Joules}}{\cancel{\text{scf}}} = 5.34 \times 10^8 \frac{\text{Joules}}{\text{dollar}}$$

Part 2(d)

(d) A ton of coal holds about 3.2×10^{10} J of energy and costs about \$40. How many Joules of energy in the form of coal can you get for a dollar?

Answer: One ton of coal has 3.20×10^{10} Joules of energy, so you can get

$$\frac{1 \cancel{\text{ton coal}}}{40 \text{ dollar}} \times 3.20 \times 10^{10} \frac{\text{Joules}}{\cancel{\text{ton coal}}} = 8.00 \times 10^8 \frac{\text{Joules}}{\text{dollar}}$$

Part 2(e)

(e) Corn oil costs about \$0.10 per fluid ounce wholesale. A fluid ounce carries about 240 dietary Calories (which a scientist would call kilocalories). A dietary Calorie is about 4200 J. How many Joules of energy in the form of corn oil can you get for a dollar?

Answer: One ounce of oil has 240 Calories, and there are 4,200 Joules in a Calorie, so oil has

$$240 \frac{\cancel{\text{Calories}}}{\text{ounce}} \times 4,200 \frac{\text{Joules}}{\cancel{\text{Calorie}}} = 1.01 \times 10^6 \frac{\text{Joules}}{\text{ounce}}$$

One ounce of corn oil costs \$0.10, so you get

$$\frac{1\ \cancel{\text{ounce}}}{0.10\ \text{dollars}} \times 1.01 \times 10^6 \frac{\text{Joules}}{\cancel{\text{ounce}}} = 1.01 \times 10^7 \frac{\text{Joules}}{\text{dollar}}$$

Part 2(f)

(f) Now we compare the different energy sources. Rank these five energy sources from cheap to expensive. What is the range of prices per Joule?

Answer:

- Coal = $\$1.25\times10^{-9}$ per joule
- Natural gas = $\$1.87\times10^{-9}$ per joule
- Electricity = $\$1.39\times10^{-8}$ per joule
- Gasoline = $\$2.31\times10^{-8}$ per joule
- Corn oil = $\$9.92\times10^{-8}$ per joule

Exercise 4

In this exercise, we compare the energy it took to produce the concrete in the Hoover Dam (outside Las Vegas) to the energy the dam produces from hydroelectric generation.

Part 4(a)

The Hoover Dam produces 2×10^9 W of electricity. It is composed of 7×10^9 kg of concrete. It requires 1 MJ of energy (1 megajoule, 1,000,000 Joules) to produce each kilogram of concrete. How much energy did it take to produce the concrete for the dam?

Answer: It took 7.0×10^{15} Joules to produce the concrete for the Hoover dam.

Part 4(b)

How long is the payback time for the dam to generate as much energy in electricity as it took to produce the concrete?

Answer: The electric power the dam generates is measured in Watts, which are Joules per second. If we divide the energy to produce the concrete by the power the dam produces, the result will be the number of seconds for the dam's electric generation to pay back the energy it took to produce the concrete.

$$
\begin{aligned}
\text{Time to pay back energy} &= \frac{\text{Energy to make concrete}}{\text{Power from dam}} \\
&= \frac{7.00 \times 10^{15}\text{ Joules}}{2.00 \times 10^{9}\text{ Watts}} \\
&= \frac{7.00 \times 10^{15}\ \cancel{\text{Joules}}}{2.00 \times 10^{9}\ \cancel{\text{Joules}}/\text{second}} \\
&= 3.50 \times 10^{6}\text{ seconds} \\
&= 3.50 \times 10^{6}\ \cancel{\text{seconds}} \times \frac{1\ \cancel{\text{hour}}}{3,600\ \cancel{\text{seconds}}} \times \frac{1\text{ day}}{24\ \cancel{\text{hours}}} \\
&= 40\text{ days}
\end{aligned}
$$

3,500,000 seconds, or 40 days, for the electricity generated by the Hoover dam to repay the energy it took to produce the concrete in the dam.

Part 4(c)

> The area of Lake Mead, formed by Hoover Dam, is 247 mi^2. Assuming 250 W/m^2 of sunlight falls on Lake Mead, how much energy could you produce if instead of the lake you installed solar cells that were 12% efficient?

$$
\begin{aligned}
1\text{ mile} &= 1.6\text{ km} \\
1\text{ mile}^2 &= 2.6\text{ km}^2 \\
&= 2.6\ \cancel{\text{km}^2} \times \frac{10^6\text{m}^2}{\cancel{\text{km}^2}} \\
&= 2.56 \times 10^6\text{ m}^2
\end{aligned}
$$

Now apply this to calculating the power that could be generated from Lake Mead:

$$
\begin{aligned}
247\ \cancel{\text{mile}^2} \times \frac{2.6\text{ km}^2}{\cancel{\text{mile}^2}} &= 632\text{ km}^2 \\
&= 6.32 \times 10^8\text{ m}^2
\end{aligned}
$$

ri_sun' Watts/m^2 falling on this area, and converted to electricity with 12% efficiency would produce

$$6.32 \times 10^8\ \cancel{\text{m}^2} \times 250\ \frac{\text{Watt}}{\cancel{\text{m}^2}} \times 0.12 = 1.90 \times 10^{10}\text{ Watts}$$

This is about 10 times more than the dam produces.

Exercise 5

> It takes approximately 2.0×10^9 J of energy to manufacture 1 m^2 of crystalline-silicon photovoltaic cell. An average of 250 W/m^2 falls on the Earth. Assume that the solar cell is 12% efficient (that is, it converts 12% of the energy from sunlight into electricity). Calculate how long it would take for the solar cell to repay the energy it took to manufacture it.

Answer: A photovoltaic cell with an area of 1 square meter would receive an average of 250 W of sunlight, and at an efficiency of 12% it would produce $250 \times 0.12 = 30.$ Watts of electricity.

To pay back the 2.0×10^9 Joules it took to manufacture the photovoltaic cell would require

$$\begin{aligned}\frac{2.0\times10^9 \text{ Joules}}{30 \text{ Watts}} &= \frac{2.0\times10^9 \cancel{\text{Joules}}}{30 \cancel{\text{Joules}}/\text{second}} \\ &= 6.7\times10^7 \text{ seconds} \\ &= 770 \text{ days} \\ &= 2 \text{ years}\end{aligned}$$

It takes 6.7×10^7 seconds, or 770. days, or 2.1 years.

Exercise 7

Part 7(a)

Infrared light has a wavelength of about 10 microns. What is its wavenumber in cm^{-1}?

From page 11 in the textbook,

$$n\left[\frac{\text{cycles}}{\text{cm}}\right] = \frac{1}{\lambda\left[\frac{\text{cm}}{\text{cycle}}\right]}$$

To convert between cm and μm, 1 cm $= 10,000\mu$m.

$$\begin{aligned}n &= \frac{1}{10\ \mu\text{m}} \\ &= \frac{1}{10\ \cancel{\mu\text{m}}\times\frac{1\text{ cm}}{10{,}000\cancel{\mu\text{m}}}} \\ &= \frac{1}{\frac{1}{1000}\text{ cm}} \\ &= 1000\text{ cm}^{-1}\end{aligned}$$

Part 7(b)

Visible light has a wavelength of about 0.5 microns. Whas is its frequency in Hz (cycles per second)?

From page 10 of the textbook,

$$\lambda\left[\frac{\text{cm}}{\text{cycle}}\right] = \frac{c\left[\frac{\text{cm}}{\text{second}}\right]}{\nu\left[\frac{\text{cycles}}{\text{second}}\right]},$$

where $c = 3\times10^{10}$ cm/second. We can rearrange this equation to give ν as a function of λ:

$$\nu\left[\frac{\text{cycles}}{\text{second}}\right] = \frac{c\left[\frac{\text{cm}}{\text{second}}\right]}{\lambda\left[\frac{\text{cm}}{\text{cycle}}\right]}$$

Use this to solve this exercise:

$$\begin{aligned}
\nu\left[\frac{\text{cycles}}{\text{second}}\right] &= \frac{c\left[\frac{\text{cm}}{\text{second}}\right]}{\lambda\left[\frac{\text{cm}}{\text{cycle}}\right]} \\
\nu &= \frac{3\times10^{10}\ \text{cm/second}}{0.5\ \cancel{\mu m}\times\frac{1\ \text{cm}}{10{,}000\ \cancel{\mu m}}} \\
&= \frac{3\times10^{10}\ \cancel{\text{cm}}/\text{second}}{5\times10^{-5}\ \cancel{\text{cm}}} \\
&= 6.00\times10^{14}\ \left[\frac{\text{cycles}}{\text{second}}\right]
\end{aligned}$$

Part 7(c)

FM radio operates at a frequency of about 40 kHz. What is its wavelength?

Again, we use the equation from page 10, noting that kHz is 1,000 cycles per second:

$$\begin{aligned}
\lambda\left[\frac{\text{cm}}{\text{cycle}}\right] &= \frac{c\left[\frac{\text{cm}}{\text{second}}\right]}{\nu\left[\frac{\text{cycles}}{\text{second}}\right]} \\
&= \frac{3\times10^{10}\text{cm}/\cancel{\text{second}}}{4.0\times10^{4}\ \left[\frac{\text{cycles}}{\cancel{\text{second}}}\right]} \\
&= 750{,}000\ \text{cm} \\
&= 7{,}500\ \text{meters}
\end{aligned}$$