

# Chapter 3

## Fossil Fuel Resources and Use

**Problem 3.1** Write down the chemical formulae for the combustion of the alkanes in Table 3.2 with  $n = 2$  to  $n = 8$ . Determine the mass of  $\text{CO}_2$  produced per megajoule of energy.

**Solution** The oxidation process is shown below

$n$	name	formula	combustion reaction
2	ethane	$\text{C}_2\text{H}_6$	$2\text{C}_2\text{H}_6 + 7\text{O}_2 \rightarrow 4\text{CO}_2 + 6\text{H}_2\text{O}$
3	propane	$\text{C}_3\text{H}_8$	$\text{C}_3\text{H}_8 + 5\text{O}_2 \rightarrow 3\text{CO}_2 + 4\text{H}_2\text{O}$
4	butane	$\text{C}_4\text{H}_{10}$	$2\text{C}_4\text{H}_{10} + 13\text{O}_2 \rightarrow 8\text{CO}_2 + 10\text{H}_2\text{O}$
5	pentane	$\text{C}_5\text{H}_{12}$	$\text{C}_5\text{H}_{12} + 8\text{O}_2 \rightarrow 5\text{CO}_2 + 6\text{H}_2\text{O}$
6	hexane	$\text{C}_6\text{H}_{14}$	$2\text{C}_6\text{H}_{14} + 19\text{O}_2 \rightarrow 12\text{CO}_2 + 14\text{H}_2\text{O}$
7	heptane	$\text{C}_7\text{H}_{16}$	$\text{C}_7\text{H}_{16} + 11\text{O}_2 \rightarrow 7\text{CO}_2 + 8\text{H}_2\text{O}$
8	octane	$\text{C}_8\text{H}_{18}$	$2\text{C}_8\text{H}_{18} + 25\text{O}_2 \rightarrow 16\text{CO}_2 + 18\text{H}_2\text{O}$

The number of moles of  $\text{CO}_2$  produced per mole of alkane is clearly shown. The molecular mass of the alkane is shown below. The molecular mass ( $M$ ) of  $\text{CO}_2$  (44 g/mol) can be used to determine the relative mass of  $\text{CO}_2$  produced per unit mass of alkane. The heat of combustion is given in Table 3.2 and the amount of  $\text{CO}_2$  per MJ heat is found.

$n$	$R = (\text{moles } \text{CO}_2)/(\text{moles alkane})$	$M$ (alkane)	$R \times 44/M = (\text{kg } \text{CO}_2)/(\text{kg alkane})$	heat of combustion MJ/kg	kg( $\text{CO}_2$ )/MJ
2	2	30	2.93	51.9	0.0565
3	3	44	3.00	50.3	0.0596
4	4	58	3.03	49.5	0.0612
5	5	72	3.06	48.7	0.0628
6	6	86	3.07	48.1	0.0638
7	7	100	3.08	48.1	0.0640
8	8	114	3.09	46.8	0.0660

**Problem 3.2** Locate the current world price of oil (US\$/bbl) and the current retail price of regular gasoline in your area (per liter or per gallon, as appropriate). What is the markup in the price per unit energy between crude oil and retail gasoline?

**Solution** World price per bbl of crude oil is \$88.94 US\$ @ 14 Sept 2011 (source: [www.oil-price.net](http://www.oil-price.net)). Current price of regular gasoline in Halifax, Nova Scotia, at the same date is \$1.318 CDN/L at the exchange rate of \$1.00 CDN=1.00899 US\$. The price of gasoline is 1.33 US\$/L. The content of one bbl oil is (see Appendix III) ~159 L/bbl, so the price per L of crude oil is 0.56 US\$/L. Thus the markup in % is

$$100 \times \left( \frac{\text{gas}(\$/\text{L})}{\text{oil}(\$/\text{L})} - 1 \right) = 137\% \text{ mark up}$$

The answer will, of course depend on when and where prices are obtained, but this mark up is substantial and includes many factors including refining costs, oil company profits and taxes.

**Problem 3.3** Locate the current world price of oil (US\$/bbl), coal (bituminous coal, per tonne), and natural gas (per 1000 m<sup>3</sup>). For each fossil fuel, calculate the cost of energy per gigajoule assuming that the fuel can be converted to usable energy with an efficiency of 100%.

**Solution** From the web (at 14 September 2011) [[www.oil-price.net](http://www.oil-price.net)] oil = 88.94 US\$/bbl. The price of coal is less well defined but one source gives a recent price in the US as of \$152 per tonne [[http://www.alibaba.com/product-free/110812567/Met\\_Coal.html](http://www.alibaba.com/product-free/110812567/Met_Coal.html)]. Natural gas prices are somewhat more standardized than coal prices and a recent price (Aug 2011) is \$146.13 per 10<sup>3</sup> m<sup>3</sup> [<http://www.indexmundi.com/commodities/?commodity=natural-gas>].

From Appendix IV the energy content of these fuels is

oil	–	6.12×10 <sup>9</sup> J/bbl=6.12 GJ/bbl
coal (bituminous)	–	3.10×10 <sup>10</sup> J/tonne=31.0 GJ/tonne
natural gas	–	3.85×10 <sup>10</sup> J/1000 m <sup>3</sup> =38.5 GJ/1000 m <sup>3</sup>

From the prices given above the cost per GJ is

oil	–	\$14.53/GJ
coal	–	\$ 4.90/GJ
natural gas	–	\$ 3.79/GJ

**Problem 3.4** Assume that all of the United States' annual electricity requirement of 3×10<sup>12</sup> kWh is produced by coal-fired generating stations operating at a net overall efficiency of 40%.

- How many tonnes of coal are burned per second? (Assume the coal is all bituminous)
- Assuming that coal is 100% carbon, how many tonnes of CO<sub>2</sub> will be produced each year?

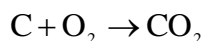
**Solution** The total coal energy needed is  $3 \times 10^{12} / 0.4 = 7.5 \times 10^{12}$  kWh. Averaged over the year, this is a power output of

$$\frac{7.5 \times 10^{12} \text{ kWh}}{365 \text{ d} \times 24 \text{ h/d} \times 10^3 \text{ kW/MW}} = 8.56 \times 10^5 \text{ MW}$$

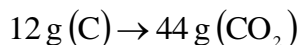
This is  $8.56 \times 10^5$  MJ per second. As the energy content of bituminous coal is  $3.1 \times 10^4$  MJ/t from the Appendix IV, the number of tonnes per second is

$$(8.56 \times 10^5 \text{ MJ/s}) / (3.1 \times 10^4 \text{ MJ/t}) = 27.6 \text{ t/s}$$

for the combustion process



then 1 mole of C produces 1 mole  $\text{CO}_2$  or



so 1 t of C produces 3.67 t  $\text{CO}_2$ . Thus  $(27.6 \text{ t/s}) \times (3.67 \text{ t/t}) = 101 \text{ t}$  of  $\text{CO}_2$  per second are released.

**Problem 3.5** On land, coal is transported primarily by train. A typical large coal train may be about 1.5 km long and may consist of 120 cars, each holding 110 tonnes of coal. As each tonne of coal has an equivalent energy content (in terms of the stored chemical energy it contains), a moving coal train represents a flow of (chemical) energy or a power. For a coal train traveling at 100 km/h, calculate the equivalent power in watts.

**Solution** One tonne of coal has energy content of  $3.1 \times 10^{10}$  J. The total amount of coal on the train is  $120 \times 110$  tonnes = 13,200 tonnes. This has an energy content of

$$(13,200 \text{ tons}) \times (3.1 \times 10^{10} \text{ J/ton}) = 4.09 \times 10^{14} \text{ J.}$$

100 km/h corresponds to

$$(100 \text{ km/h}) \times (1000 \text{ m/km}) / (3600 \text{ s/h}) = 27.8 \text{ m/s}$$

A 1.5-km long train will pass a reference point in

$$(1500 \text{ m}) / (27.8 \text{ m/s}) = 54 \text{ s}$$

Thus the rate of flow of energy is

$$\frac{4.09 \times 10^{14} \text{ J}}{54 \text{ s}} = 7.57 \times 10^{12} \text{ W} = 7.57 \times 10^6 \text{ MW}$$

**Problem 3.6** How many tonnes of oil shale which produces 120 L/t would be needed to produce the same energy as 1 tonne of bituminous coal?

**Solution** The shale oil energy content per tonne is

$$(120 \text{ L/t}) \times (3.85 \times 10^7 \text{ J/L}) = 4.62 \times 10^9 \text{ J/t}$$

The energy content of one tonne of bituminous coal will be

$$(1000 \text{ kg}) \times (31 \times 10^6 \text{ J/kg}) = 3.1 \times 10^{10} \text{ J}$$

Thus it will require

$$\frac{3.1 \times 10^{10} \text{ J}}{4.62 \times 10^9 \text{ J}} = 6.7 \text{ t}$$

of oil shale to yield the same energy as one tonne of bituminous coal.

**Problem 3.7** Assume that the total energy needs of a person in the United States (Chapter 2) is satisfied by burning coal. If each person is responsible for the mining, transportation, processing, and burning of their own coal, how much coal must each person process, on average, per day?

**Solution** Each person uses an average of 11,730 W. This is

$$(11730 \text{ W} \times 24 \text{ h/d}) / 10^3 \text{ W/kW} = 282 \text{ kWh per day}$$

Converting this to MJ gives

$$\frac{282 \text{ kWh/d} \times 3.6 \times 10^6 \text{ J/kWh}}{10^6 \text{ J/MJ}} = 1015 \text{ MJ}$$

For coal with an energy content of 31 MJ/kg then so  $(1015 \text{ MJ}) / (31 \text{ MJ/kg}) = 32.6 \text{ kg per day}$  must be processed.

**Problem 3.8** If shale oil replaced coal in the United States, how many years would the U.S. resources last at the current rate of use?

**Solution** From Example 3.3, the annual coal use in the U.S. is  $1.01 \times 10^9$  t/y. From Appendix IV the primary energy content of this coal is

$$(1.01 \times 10^9 \text{ t/y}) \times (3.1 \times 10^4 \text{ MJ/t}) = 3.13 \times 10^{13} \text{ MJ/y}$$

From Table 3.12 the US resources of shale oil are equivalent to  $2.59 \times 10^{12}$  bbl of oil. This has an energy content at  $6.12 \times 10^3$  MJ/bbl of

$$(2.59 \times 10^{12} \text{ bbl}) \times (6.12 \times 10^3 \text{ MJ/bbl}) = 1.59 \times 10^{16} \text{ MJ.}$$

At the energy use of coal per year as above, the shale oil will last for

$$(1.59 \times 10^{16} \text{ MJ}) / (3.13 \times 10^{13} \text{ MJ/y}) = 508 \text{ years.}$$

