

Chapter 6

FOSSIL FUELS: OVERVIEW

We saw in Chapter 5 that there is no *energy* crisis and that there never has been one. There is, however, a definite disproportion in the quantities of fossil fuels remaining on earth. There is also the fact that, in contrast to solar energy, fossil fuels are very unevenly distributed over our planet. In the present chapter we take a closer look at fossil fuels in general. In Chapters 7-9 we analyze in detail the principal fossil fuels: coal, petroleum and natural gas.

We begin by analyzing the carbon cycle. This is the most important of the three energy-related cycles. The other two are the nuclear fuel cycle (Chapter 13) and the hydrologic cycle (Chapter 16). Clearly, there is something profound in the cyclical nature of our world. In Richard Wagner's "The Ring of the Nibelung," that "vastest piece of music ever conceived by the mind of man" ("Wagner's Ring," by M. Owen Lee, Limelight Eds., NY, 1994), the cycle begins with the world beginning and ends with the world ending. The carbon cycle is not as all-encompassing as this, but it comes close. It is responsible for life on earth. It provides the basis for understanding the formation of all fossil fuels. It also helps us to understand some of the environmental problems associated with the utilization of fossil fuels. We introduce here the rudimentary chemistry that is necessary and sufficient to understand how fossil fuels are used in the various energy conversion devices that were discussed in Chapters 3 and 4. We then analyze the past, present and future of the supply of fossil fuels.

The Carbon Cycle

The fossil fuels used as energy sources today are coal, petroleum and natural gas. Enormous resources of other fossil fuels exist, but they are not yet in large-scale commercial use. Examples of fossil fuels not used currently, but potentially useful in the future, are oil shale and tar sands (see Chapter 10).

That fossil fuels are essential for the well-being of today's society is clear enough: their consumption accounts for about 85% of all the energy used in the United States (see Figure 5-14). Indeed, the entire world relies very heavily on fossil fuels. This is shown in Figure 5-13. Also, more than two thirds of all the electric energy used in the United States is generated by burning fossil fuels. Collectively, fossil fuels represent the most important source of energy we have, not only for electricity generation but also for other uses such as transportation, manufacturing and residential heating.

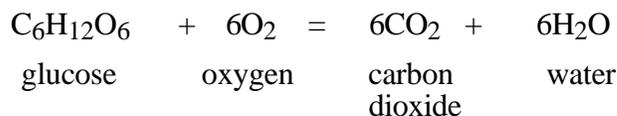
Where do fossil fuels come from? We can begin to answer this question by unraveling the meaning of the term. *Fuels* are substances that are burned to generate heat or power. *Fossils* are remains or traces of animals or plants from past ages. Thus, *fossil fuels* are substances that are derived from the remains of organisms that lived millions of years ago. They have been preserved as deposits in reasonable proximity to the earth's surface (typically less than 10 kilometers deep). We can thus extract them and use them as a source of energy.

Despite their apparently diverse nature – coal is a brown or black solid, petroleum is a yellowish to black liquid, and natural gas is a colorless gas – fossil fuels have several things in common. Most notably, they are all derived from the remains of animals and plants and, in terms of chemical composition, their principal constituents are carbon (C) and hydrogen (H). The other important constituents are nitrogen (N), oxygen (O) and sulfur (S). These elements combine to form the organic compounds in fossil fuels, in contrast to most other earth's constituents which are inorganic (such as sand and other rocks and minerals).

Because carbon is the most abundant element in all fossil fuels (see Chapters 7-9), we can begin to think about their origin by following the fate of carbon in natural geological and biological processes. The behavior of carbon in the natural world is summarized in the global carbon cycle, shown in Figure 6-1.

FIGURE 6-1. Schematic representation of the global carbon cycle.

The interaction between carbon dioxide (CO₂) in the atmosphere and carbon dioxide dissolved in the oceans, or carbon dioxide incorporated in the earth as carbonate rocks, is generally very slow and we need not analyze it further. The major processes of interest are those involving living organisms. They are shown in the lower portion of Figure 6-1. Plants absorb CO₂ by virtue of a process known as photosynthesis (see p. 13). The carbon from CO₂ thus becomes part of the living plants. It also finds its way into the cells of animals that eat the plants. Eventually, this food chain in living organisms comes to a halt: the remains of dead plants or dead animals decompose and produce gaseous CO₂ which is returned to the atmosphere. This normal 'aerobic' decay process, which occurs in the presence of abundant oxygen from the air, completes the carbon cycle by returning gaseous CO₂ to the atmosphere. This can be illustrated by the following representative chemical reaction (see p. 14):



Fossil fuels arise when this normal decay process is interrupted. This is illustrated in Figure 6-2. The existence of an environment that favors abundant growth of living organisms, while preventing their rapid decay to CO₂ and H₂O, makes possible this 'detour' in the carbon cycle. Three conditions must exist for the development of such an environment: abundant light (required to promote *photosynthesis*), warmth (since not many

FIGURE 6-2. Origin of fossil fuels: a 'detour' in the carbon cycle.

organisms flourish in the arctic or antarctic regions), and moisture (since not many organisms flourish in deserts). The kinds of environments that provide these conditions are subtropical or tropical swamps, river deltas, lakes, lagoons or shallow seas. Precisely such conditions prevailed in many regions of the world in the late Paleozoic and the Mesozoic period of earth's history. Since then the formation of coal, petroleum or natural gas involved a series of complex biological and geological processes. These are briefly summarized next.

The organisms that contributed to fossil fuel formation are both single-cell planktonic plants and animals and the more complex higher plants (like trees and shrubs). These organisms are composed of a variety of chemical compounds, such as carbohydrates (like sugars, starches and cellulose), fats, oils, waxes, proteins and lignin. They are typically constituted by complex molecular skeletons of carbon atoms 'decorated' by chains of different size containing oxygen, nitrogen and hydrogen, as well as carbon atoms. Only three examples are given here as a prelude to the brief discussion of fossil fuel structure in Chapters 7-9. The one on the left is the common sugar glucose (the terminal C atoms are actually connected into a cyclic structure), the one in the middle is a representative fatty molecule, while the one on the right represents a segment of a protein molecule.

The final product of the biochemical decay of such organic matter, largely in the presence of bacteria and under anaerobic conditions, is an insoluble solid material known under the generic name of *kerogen*. Over the course of geological time (typically, millions of years), the accumulated kerogen was buried more and more deeply in the earth's crust. The more deeply it was buried, the higher the temperature and pressure to which it was exposed. In some cases, sulfur-containing compounds from salty waters were incorporated into these fossil fuel reservoirs. At moderate temperatures inside the earth, the long chains of carbon atoms, characteristic of kerogen derived primarily from planktonic organisms, broke apart into shorter ones. The details of this geochemical process need not concern us here. The important consequence is that a complex mixture of liquid compounds was the final product. Most of the compounds in the newly formed chains contained between five and

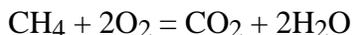
twenty carbon atoms. This liquid is known as *petroleum* or *crude oil*. At still higher temperatures inside the earth, the breaking of carbon-to-carbon bonds continued, eventually resulting in the formation of compounds containing only one to four carbon atoms. These molecules are so small that they are gases at ordinary atmospheric conditions. This gaseous mixture is known as *natural gas*.

The type of kerogen produced from the higher plants contained abundant quantities of lignin. Lignin is the substance responsible for mechanical rigidity of plants. Its molecular structure is also quite complex; in contrast to the long chains of carbon atoms typical of petroleum-producing kerogen, here most carbon atoms are incorporated into ring structures such as that shown above for the protein. Furthermore, these carbon skeletons are interconnected, much like chickenwire, to produce a strong, rigid structure. As this kerogen was transformed inside the earth's crust, the original lignin-like structure gradually 'condensed' further so that the carbon rings fused together into larger systems of rings and the molecular structure became more and more like that of graphite, the material used in pencils. Rather than decomposing into a myriad of liquid or gaseous products, the kerogen derived from higher plants was thus transformed into a solid material with a complex and somewhat ill-defined molecular structure. This material is known as *coal*.

An Elementary Chemical Prelude

In the previous section we mentioned a number of complex chemical substances and chemical reactions that are responsible for the formation of fossil fuels. The reader may be relieved to learn, however, that there is only one chemical reaction that we must become familiar with in order to understand the key benefits and problems of fossil fuel utilization. This reaction is the combination of molecules of fossil fuels with oxygen, called *combustion* (or burning).

As we know, all matter – including fuels – consists of atoms and molecules. A *chemical reaction* is simply a rearrangement of atoms between the molecules of the initial substances, called reactants, and the final products. (In this process, the atoms maintain their integrity; when they lose it, a nuclear reaction occurs, as we shall discuss in Chapter 12.) It turns out that many substances have a special affinity toward oxygen (O_2), which is the second principal constituent of air (beside nitrogen, N_2). As mentioned in the previous section, these substances, called *fuels*, are composed primarily of C and H atoms and when they combine with oxygen, the main products are CO_2 and H_2O . The simplest combustion reaction is the interaction between methane and oxygen molecules:



This chemical equation illustrates the fact that mass is conserved in a chemical reaction. In other words, reactants combine in definite proportions. We shall see in Chapter 12 that this

law of mass conservation is not valid in a nuclear reaction, and that the utilization of nuclear energy relies precisely on this fact.) When methane and oxygen combine, for every two oxygen molecules consumed, two water molecules are produced. Also, for every molecule of methane consumed, or for every carbon atom in this molecule, one molecule of carbon dioxide is produced.

When we discuss chemical reactions, it is not practical to speak of masses of atoms and molecules because the number of these elementary particles is very large. For example, in accordance with yet another law of nature, in 16 grams of atomic oxygen (O), there are 6×10^{23} atoms of oxygen. Also, in 32 grams of molecular oxygen (O₂), there are 6×10^{23} molecules of oxygen. Therefore, for convenience we speak of *moles*, rather than of atoms or molecules, and of *molar mass*, rather than of atomic or molecular mass. (In our discussion of nuclear reactions in Chapter 12, we shall not be able to avoid using atomic masses.) A mole is the mass of 6×10^{23} atoms or molecules of a substance. This value is called the Avogadro number in honor of Amedeo Avogadro (1776-1856), the Italian scientist who first realized that equal volumes of all gases contain equal number of atoms or molecules (at the same temperature and pressure). The molar mass of a substance in the atomic state (for example, atomic oxygen or uranium) is the mass (in grams) of 6×10^{23} atoms. Likewise, the molar mass of a substance in the molecular state (for example, molecular oxygen or uranium oxide) is the mass (in grams) of 6×10^{23} molecules. Table 6-1 summarizes all the molar masses of atomic substances (elements) that are of interest to us. The molar masses of molecular substances (compounds) can be easily calculated, as shown in Illustration 6-1.

TABLE 6-1
Molar masses of selected atomic substances (elements)

Element	Molar mass, grams
Hydrogen, H	1
Carbon, C	12
Nitrogen, N	14
Oxygen, O	16
Sulfur, S	32
Uranium, U	238

Returning to our simplest combustion reaction, we can now confirm that the law of conservation of mass is obeyed. This is shown in Illustration 6-2.

The most important feature of a combustion reaction is that it is an *exothermic reaction*. In other words, it is accompanied by a release of energy; *exo* in Greek means 'outside'. Most of the chemical energy of the fuel is converted to thermal energy. Some of it is

converted to visible radiation and a flame can be seen. The quantity of thermal energy released is called the *heat of combustion* of the fuel. It is also often referred to as the heating (or calorific) value.

Illustration 6-1. Determine the molar mass of octane, which is one of the principal constituents of gasoline, and whose chemical formula is C_8H_{18} .

Solution.

Molar mass of C_8H_{18} = (8) [molar mass of C] + (18) [molar mass of H] =

$$= (8)(12 \text{ grams}) + (18)(1 \text{ gram}) = 114 \text{ grams}$$

To compare coal, petroleum and natural gas as fuels, we need to consider the amount of energy that can be released from each one of them when they are burned. In other words, we need to compare their heating values. Since the total amount of heat released depends on how much fuel we burn, to have any meaning we must express the heating value in terms of the same quantity of fuel. Petroleum is normally sold in *barrels*. A barrel of petroleum contains 42 gallons. Although the heating value of petroleum varies somewhat, depending on its source (see Chapter 8), typically crude oils will contain 5.8×10^6 BTU/barrel, or about 1.4×10^5 BTU/gallon. The calorific value of coal varies greatly, depending on the 'rank' of the coal (see Chapter 7), but it is generally in the range of 6000 to 15,000 BTU/lb. Coals representative of those burned in many electric power plants will contain some 13,000 BTU/lb. Natural gas, which is mainly methane (see Chapter 9), has a calorific value of about 1000 BTU/ft³.

Although this information allows us to assess the energy content of one particular fossil fuel, in the form given in the previous paragraph it is not of much help for comparing one fuel to another. We can compare fuels on the basis of the amount of energy liberated from burning equal quantities of each, or on the basis of the amount of money we must spend for each fuel to purchase a given quantity of energy. The *energy-equivalent* amounts are the amounts of each fuel that must be burned to liberate the same quantity of thermal energy. Very rough but convenient and useful comparisons are the following:

$$1 \text{ gallon of petroleum} = 10 \text{ pounds of coal} = 150 \text{ cubic feet of natural gas.}$$

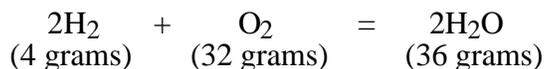
Burning these quantities of fuel liberates in each case about 140,000 BTU of thermal energy.

The energy content per unit *mass* indicates the amount of thermal energy that would be released upon burning a comparable mass of each fuel. It is usually convenient to make a comparison on the basis of one pound of each fuel. Since both natural gas and petroleum

Illustration 6-2. Calculate how many pounds of water are produced for every pound of hydrogen fuel consumed.

Solution.

From Table 6-1 and the calculations of molar masses according to Illustration 6-1, we have



Therefore,

$$\begin{aligned} \frac{\text{Water produced}}{\text{Hydrogen consumed}} &= \\ &= \left(\frac{36 \text{ grams of water}}{4 \text{ grams of hydrogen}} \right) \left(\frac{1 \text{ pound of water}}{454 \text{ grams of water}} \right) \left(\frac{454 \text{ grams of hydrogen}}{1 \text{ pound of hydrogen}} \right) = \\ &= \frac{36 \text{ pounds of water}}{4 \text{ pounds of hydrogen}} = \frac{9 \text{ pounds of water}}{1 \text{ pound of hydrogen}} \end{aligned}$$

Thus, nine pounds of water are produced for every pound of hydrogen consumed. (Pounds per pound are of course equal to grams per gram.)

Note: This simple calculation is a very important one, because it alone will allow us to assess the potential pollution and the greenhouse effect associated with the use of different fossil fuels (see Chapter 11).

are fluids, and are customarily measured in volume units (cubic feet or gallons), finding the energy content per unit mass requires knowing the density of these fuels. This is shown in Illustration 6-3. Thus on an equivalent mass basis, we find that natural gas has the highest heating value, followed by petroleum, and coal is last. No wonder airplanes do not carry coal as their fuel.

Comparison of Reserves of Fossil Fuels

Figure 6-3 shows the consumption history of fossil fuels over the last 150 years. At the turn of our century, coal replaced wood as the principal energy source. In the period since the Second World War, petroleum and natural gas displaced coal and are responsible today for about 60% of the energy consumption in the United States. In the last two decades,

however, their supply has been decreasing or stagnating, as shown in Figure 6-3 and in more detail in Figure 6-4. Whether or not this trend will continue depends on many factors. The most important one is the availability of fossil fuels in the U.S. and in the world. Much has been written about this issue and the numbers quoted in different publications may vary substantially. Some of the discrepancies are due to revisions in the geologic estimates or economic profitability of fossil fuel recovery, but others are due to inadequate comparisons. For example, a comparison of proven reserves of petroleum with identified resources of natural gas (see Chapter 5) is as misleading as comparing apples and oranges.

Illustration 6-3. Compare the calorific values of fossil fuels per unit mass of fuel. (This comparison is particularly important for aircraft fuels where we want to maximize the energy content of a kilogram of fuel.)

Solution.

In order to make the conversion we must multiply the energy content expressed on a volumetric basis by the volume occupied by one mass unit of the fuel. This volume of a mass unit is the reciprocal of the density of the fuel. Thus

$$\text{Energy content, } \frac{\text{BTU}}{\text{lb}} = (\text{Energy content, } \frac{\text{BTU}}{\text{volume}}) \left(\frac{\text{volume}}{\text{lb}} \right),$$

or

$$\text{Energy content, } \frac{\text{BTU}}{\text{lb}} = (\text{Energy content, } \frac{\text{BTU}}{\text{volume}}) \left(\frac{1}{\text{density}} \right).$$

For natural gas, the energy content is usually 1000 BTU/ft³. The density of natural gas is about 0.04 lb/ft³. Thus we have

$$\text{Energy content, } \frac{\text{BTU}}{\text{lb}} = (1000 \frac{\text{BTU}}{\text{ft}^3}) \left(\frac{1 \text{ ft}^3}{0.04 \text{ lb}} \right) = 25,000 \text{ BTU/lb.}$$

Similarly, for petroleum the energy content is about 140,000 BTU/gallon. An approximate value of its density is 7.4 lb/gallon. Then

$$\text{Energy content, } \frac{\text{BTU}}{\text{lb}} = (140,000 \frac{\text{BTU}}{\text{gallon}}) \left(\frac{1 \text{ gallon}}{7.4 \text{ lb}} \right) = 19,000 \text{ BTU/lb (approx.)}$$

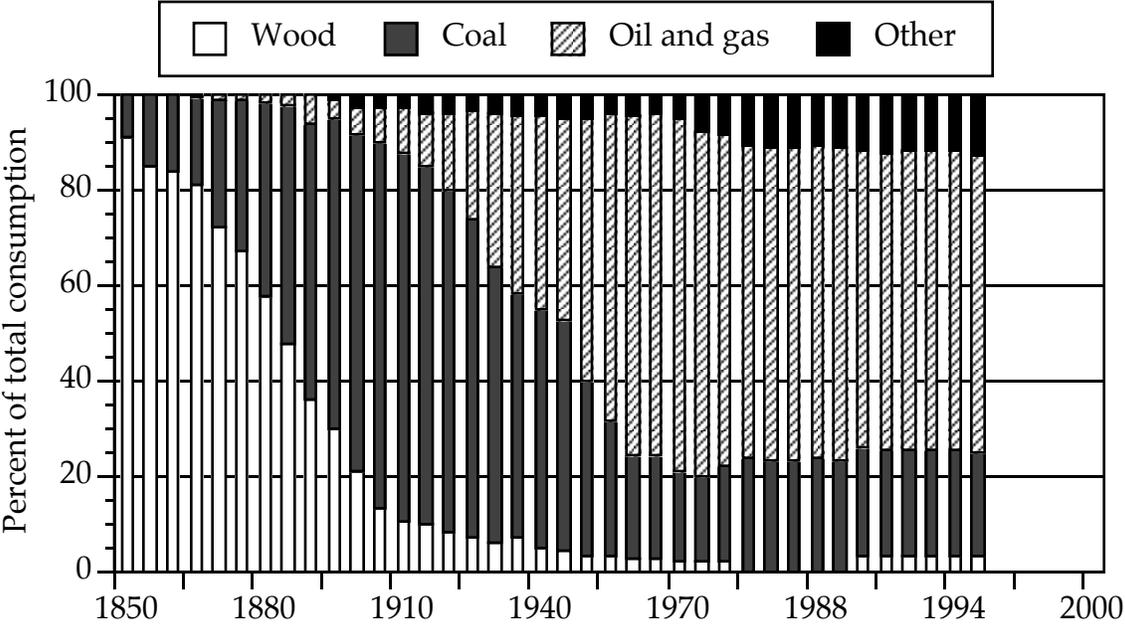


FIGURE 6-3. Fuel replacement cycles in the U.S.
[Sources: Fowler, op. cit. and Energy Information Administration.]

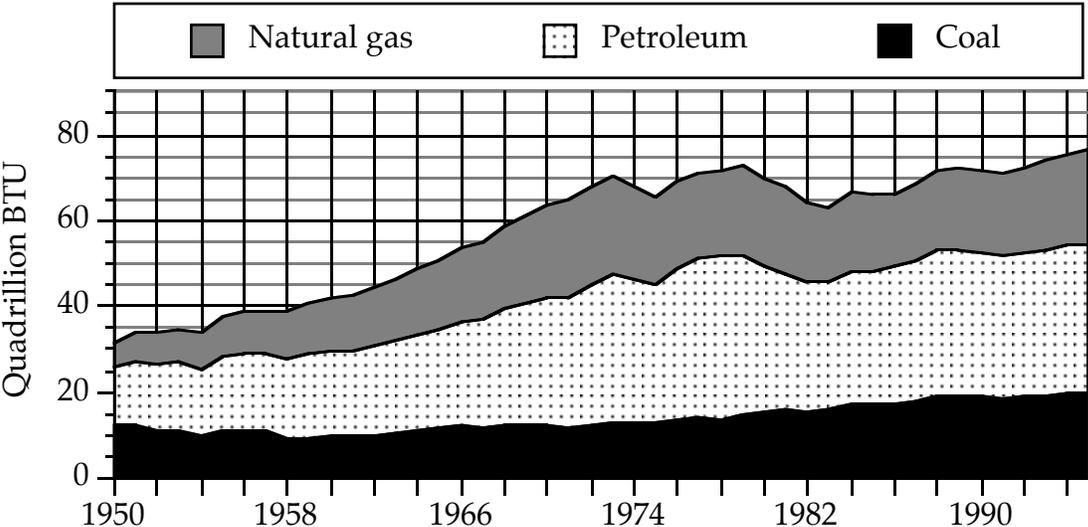


FIGURE 6-4. Fossil fuel consumption in the United States in the past forty five years.
[Source: Energy Information Administration.]

The best method for assessing the availability of fossil fuels (and other natural resources) is the use of a *logistic curve*. This method takes into account the fact that the exponential growth of a *finite* quantity (e.g., amount of petroleum on earth) must result in the sigmoidal consumption pattern illustrated in Figure 6-5.

FIGURE 6-5. Comparison of the exponential and logistic growth curves.

This sigmoidal (S-shaped) curve describing the cumulative discovery of a fossil fuel has three major segments. These are illustrated in Figure 6-6. Initially, when there are many undiscovered regions of the plentiful resource and its exploitation is just beginning, there is an exponential increase in the amount discovered and produced each year (region a-b). Were it not for its finite nature, exponential growth would continue as long as there is demand for it. The middle portion of the curve is the early indication that the resource is finite. The observation of a peak in the rate of production – point b in Figure 6-6b obtained as the slope of the cumulative production curve – suggests that the resource will become increasingly scarce. Indeed, in the last portion of the logistic curve the cumulative production reaches the limit of its ultimate recoverability and the rate of production decreases eventually to zero (region b-c in Figure 6-6b).

INTERNET INFO	The most recent information on the reserves of U.S. fossil fuels can be found at http://www.eia.doe.gov/neic/reserves.html .
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The statistical information on proven reserves of fossil fuels is quite complex (see Chapter 10). There is one very clear trend, however, and this is sufficient for the purposes of our discussion. Had it not been for the Prudhoe Bay discovery in Alaska, petroleum reserves would have been past point b, in region b-c, for the last 20 years. Today the rate of

domestic oil production exceeds the rate of discovery of new oil fields. The situation for natural gas is similar. Indeed, the Mobils and Exxons of this world are drilling for oil and gas in increasingly remote areas of the globe (see the Investigations in Chapter 8). In contrast, domestic coal reserve estimates are still in region a-b; the logistic curve is expected to reach point b some time around the year 2200.

(a)

(b)

FIGURE 6-6. Logistic curves. (a) Cumulative production versus time; (b) Production rate versus time. [Source: Cassedy and Grossman, *op. cit.*]

We can conclude this brief discussion of fossil fuel reserves with the following unquestionable statement: if the current consumption patterns continue, the world and the U.S. in particular shall use up the resources of petroleum and natural gas much earlier than those of coal.

In Chapters 7-11 we shall take a closer look at the advantages and disadvantages of the various fossil fuels. We will then analyze nuclear energy and renewable energy sources. It

will become apparent that for decades to come, the world will probably continue to rely on fossil fuels for satisfying its ever-growing energy appetite. Once we place into proper perspective this evident imbalance between the supply and the demand of petroleum (and natural gas, to a lesser extent), we shall be in a position to ask the “sixty-four thousand-dollar question:” How can we develop ‘wiser’ energy consumption patterns? An attempt to answer this question will take us to the shaky ground of energy economics and energy policy, issues that are very debatable – and very much debated – and which we address in the last chapter of the book. Let us just anticipate here that the most meaningful *technical comparison* of fossil fuels is based on the concept of efficiency of the conversion of their chemical energy into a particular desired energy form (e.g., heat, electricity, etc.), as discussed in Chapter 4. The most meaningful *economic comparison* of fossil fuels is in terms of cost per unit of useful energy. It is important to make sure that the energy units used are of the same form, for example, chemical or thermal energy. The most often used energy unit is one million BTU of chemical energy. An example is given below.

Illustration 6-4. To calculate the cost of energy per million BTU, the cost per sales unit (that is, per barrel, ton, cubic foot, etc.) and the energy content per sales unit must be known. This information allows us to calculate the cost of one BTU. (Multiplying by 1,000,000 allows us then to determine the cost per 10^6 BTU.)

For crude oil, let us assume a price of \$25/barrel. A barrel of crude oil contains about 5,800,000 BTU of chemical energy. Thus,

$$\left(\frac{\$25}{\text{barrel}}\right) \left(\frac{1 \text{ barrel}}{5.8 \times 10^6 \text{ BTU}}\right) \left(\frac{10^6 \text{ BTU}}{10^6 \text{ BTU}}\right) = \$4.31/10^6 \text{ BTU}$$

Similarly, commonly used coal might cost \$50/ton and have an energy content of 13,000 BTU/lb. (Note that in this case we must convert the cost per ton to the cost per pound.) Thus,

$$\left(\frac{\$50}{\text{ton}}\right) \left(\frac{1 \text{ ton}}{2000 \text{ lb}}\right) \left(\frac{1 \text{ lb}}{1.3 \times 10^4 \text{ BTU}}\right) \left(\frac{10^6 \text{ BTU}}{10^6 \text{ BTU}}\right) = \$1.92/10^6 \text{ BTU}$$

The cost of natural gas is usually given per 1000 cubic feet. Since 1 cubic foot of natural gas has an energy content of about 1000 BTU, the cost per 1000 cubic feet happens to be numerically equal to the cost per 10^6 BTU. Suppose gas costs \$3 per 1000 cubic feet.

$$\left(\frac{\$3}{1000 \text{ ft}^3}\right) \left(\frac{1 \text{ ft}^3}{1000 \text{ BTU}}\right) = \$3.00/10^6 \text{ BTU}$$

Note: In this and other approximate calculations, it does not matter whether we are using metric tons (1 metric ton = 2200 pounds) or short tons (1 short ton = 2000 pounds). For more precise calculations, this must be specified.

We can see by comparing the results of our calculations of energy content per unit of mass (Illustration 6-3) and energy cost per million BTU (Illustration 6-4) that, while coal has the lowest calorific value per pound, on an energy cost basis it is usually the least expensive of all fossil fuels.

Many more examples of such simple calculations are given in the following chapters. They will be shown to be powerful tools for making energy-related decisions at both the microeconomic level (for example, residential comfort) and the macroeconomic level. In making these economic comparisons of fuels, it is important to emphasize that the cost of a fuel varies widely with time and location of its use, as well as on the 'quality' of the fuel. In the past twenty years, the cost of a barrel of crude oil has fluctuated between about \$2 per barrel and nearly \$40 per barrel. A coal from North Dakota or Texas might sell for about \$10 per ton, while premium domestic heating coal from Pennsylvania might sell at the same time for about \$100 per ton. To make the most precise comparisons, the economic calculations need to specify the time, the location, and the fuel quality for which the cost data were obtained. For example, as a prospective homeowner trying to make a decision on the choice of a home heating/cooling system, it is wise for the reader to get information on fuel prices from local consumer organizations or from the state government's energy office. With this information, the illustration above can be followed to compare fuel costs per million BTU. This is then a comparison of apples and apples that will allow the reader to make informed energy-related decisions. These issues are presented in more detail in Chapters 19-21.

REVIEW QUESTIONS

6-1. A representative sample of coal from Pennsylvania was found to have the following elemental composition (by mass): 80% carbon, 10% oxygen, 5% hydrogen, 2% nitrogen and 3% sulfur. How many O, H, N and S atoms are there for every 100 carbon atoms in this coal?

6-2. A representative sample of wood has a heating value of 20,000 kJ/kg. (a) How much is that in the more common units of BTU/cord? A cord is a unit of volume, with 1 cord being equal to 128 cubic feet. (b) Show that 1 cord is equivalent to 1.25 short tons (1 short ton = 2000 pounds). The density of wood is about 20 lb/ft³.

6-3. (a) The principal component of diesel fuel is cetane, a compound whose formula is C₁₆H₃₄. Calculate the molar mass of cetane. (b) The oxygen-containing compounds methanol and ethanol are often mentioned as possible substitutes for gasoline in our cars. Their formulas are CH₄O and C₂H₆O. Determine their molar masses.

6-4. We saw on pp. 102-103 that for every molecule of methane consumed, one molecule of carbon dioxide is produced. (a) How many grams of carbon dioxide are produced for

every gram of methane consumed? (b) How many tons of carbon dioxide are produced for every ton of methane consumed?

6-5. In Illustration 6-1 we saw that the molar mass of octane is 114 grams. When octane burns, for every molecule of octane consumed, 8 molecules of CO_2 are produced. How many tons of carbon dioxide are produced for every ton of octane consumed?

6-6. Compare methane, octane, methanol and ethanol in terms of the quantities of CO_2 that these fuel produce when they burn. Express these quantities as tons of CO_2 produced per ton of fuel consumed.

INVESTIGATIONS

6-1. In a letter to the *Economist* of 8/6/94, C. J. Campbell challenges the assertion that “there are 1.5 trillion barrels of oil in the earth's crust, enough to last 60 years at today's rate of consumption.” He argues that the point of decline (see Figure 6-6) has already been passed in several countries such as the United States and is not far away for the world as a whole. Is the quoted number (1.5 trillion barrels) in the right “ball park”? Compare it with the information provided in Figure 8-1.

6-2. Visit the Web site mentioned on p. 108. Find out what the most recent estimates of fossil fuel reserves are. Have they increased or decreased with respect to previous estimates?