Chapter 5

ENERGY: SUPPLY AND DEMAND

This book is about much more than the (im)balance between gasoline demand and oil supply illustrated on the previous page. But our awareness of general issues of energy supply and demand typically starts with the realization that oil supplies may not keep up with gasoline demand. We may be running out of (cheap) oil. But are we running out of energy too?

We saw in Chapter 2 that the source of most of the energy on earth is the sun. Approximately 220 watts are available on each square meter of our planet when the sun shines. A simple calculation shows (see Illustration 15-1) that this influx of energy, while apparently small (because a light bulb consumes about 100 watts), is equivalent to the output of millions of electric power plants.

Illustration 5-1. If solar radiation reaching the earth's surface could be converted to electricity at 30% efficiency, calculate how many electric power plants could run on solar energy. Assume that the average output of an electric power plant is 1000 megawatts.

Solution.
We can assume for this calculation that the earth is a sphere with a radius (R) of about 4000 miles, or 6400 kilometers. The irradiated earth's surface area is of the order of R^2 or $1.25\text{x}10^{14}\ \text{m}^2$. (This is about 10 times the area of the continental United States.) The total power input from the sun is then:

$$\text{Solar power input} = \left(220\ \frac{\text{W}}{\text{m}^2}\right)\left(1.25\text{x}10^{14}\ \text{m}^2\right) = 2.8\text{x}10^{16}\ \text{W}$$

If each power plant had an overall efficiency of 30%, the number of power plants running on solar energy would be:

$$\text{Number of (hypothetical) power plants} = \frac{\{2.8\text{x}10^{16}\ \text{W(solar)}\}\{\frac{0.30\ \text{W(electric)}}{1\ \text{W(solar)}}\}}{\{\frac{10^{9}\ \text{W(electric)}}{1\ \text{plant}}\}} =$$

$$= 8.5\text{x}10^{6}\ (!)$$

Compare this with some 2000 1000-MW plants that provide electricity to the world today (see Chapter 18).

The main point of Illustration 5-1 is to show that we shall not run out of energy any time soon. Today's electricity needs of the world are satisfied by a much, much smaller number of power plants. The supply of energy – in the form of solar radiation – will be plentiful for millennia to come. Unfortunately, however, this energy does not come in forms that society needs most. At the present time, we do not really know how to harness the sun efficiently. We do not know how to convert all the solar radiation into electricity, for example. We shall see in Chapter 17 that significant progress is being made in this direction but that solar energy will not be a major energy source until well into the 21st century. In the meantime, we have to rely on solar energy that was stored in the earth's crust millions of years ago, in the form of fossil fuels.

We do not need to spend much time, therefore, discussing the supply of energy; we do need to spend a lot of time discussing the supply of fossil fuels. Therein, as the reader probably knows already, lies the cause of the energy problem and of the much publicized "energy crises" of the 1970s. We shall explore this issue in due time (Chapters 6-11).

The demand for energy in our society is the only real issue. How much are we consuming today? How much energy shall we need in the future? These are the main questions of interest here.

Exponential Growth: Population and Energy Consumption

Figures 5-1, 5-2 and 5-3 are representative illustrations of the growth of energy consumption in different time periods, expressed in different energy units. Figure 5-1 shows the tremendous growth of petroleum (crude oil) consumption since it was first drilled in Pennsylvania in 1859 until World War II. Note that the contribution of the Middle East was very small in this entire period. Note also how 'sensitive' such graphs are: the effect of the Great Depression is shown as a marked decrease in oil production (and consumption). Still, in the first four decades of the 20th century both the U.S. and world production increased by one order of magnitude (a factor of ten or so).

Figures 5-2 and 5-3 illustrate the same general trend until the 1970s. The reader should check the agreement of the information obtained from different sources (see Review Question 5-3). For example, it took less than 15 years for the world consumption to double, from 2500 mtce in 1950 to about 5000 mtce in 1964. It also took some 20 years for U.S. consumption to double, from 35 to 70 quadrillion BTU (quads). The relative stagnation periods in early 1970s and early 1980s, in both the world and the U.S., are referred to as the 1st and 2nd "energy crises." They will be discussed in more detail in Chapter 21.

Figure 5-4 summarizes the growth in world population since World War II. It took less than 40 years for the population to double, from 2.5 billion in 1950 to more than 5 billion in 1990. Most of the growth is seen to have occurred in Africa, Asia and Latin America.

The dominant patterns in Figures 5-1, 5-2, 5-3 and 5-4 are examples of a very common type of growth, where the more one has, or the larger the quantity that one produces or consumes, the greater the increase will be. This is called *exponential growth.* Both the world's population and its energy consumption have been increasing exponentially.

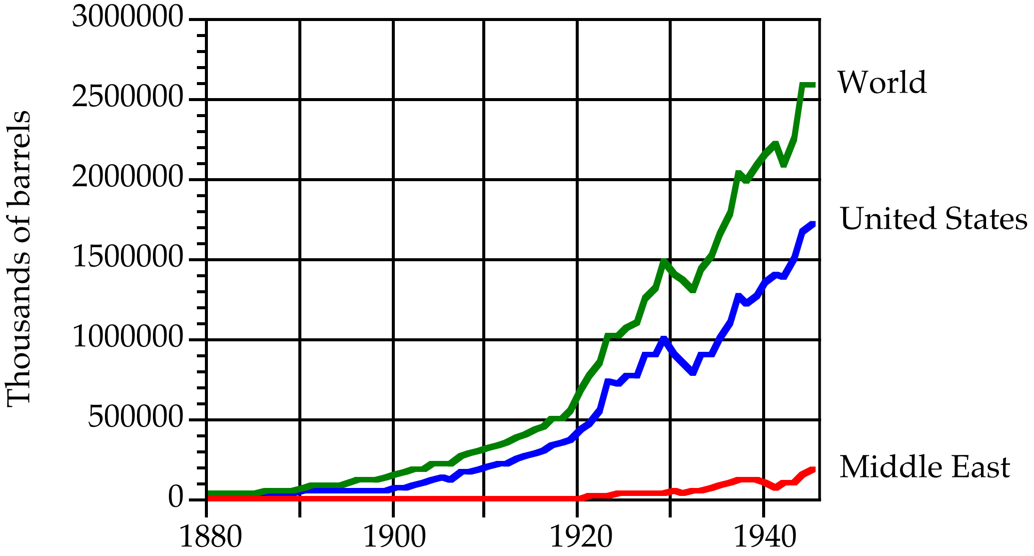
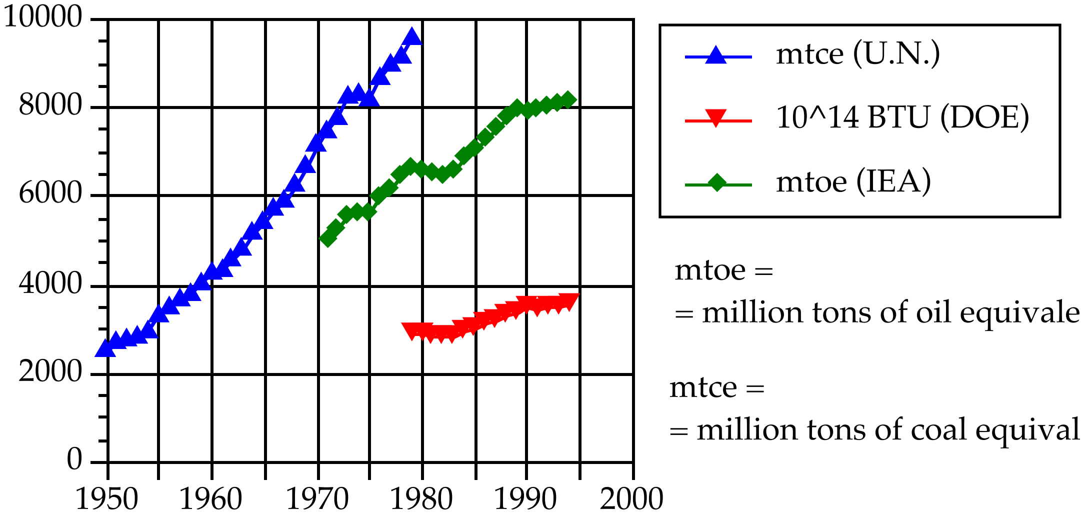


FIGURE 5-1. Growth of crude oil production in the U.S. and the world. [Source: American Petroleum Institute, “Basic Petroleum Data Book,” July 1995.]



mtoe =
= million tons of oil equivalent

mtce =
= million tons of coal equivalent

FIGURE 5-2. World energy production (consumption) trends in the post-World War II period. [Sources: U.S. DOE, United Nations, International Energy Agency.]

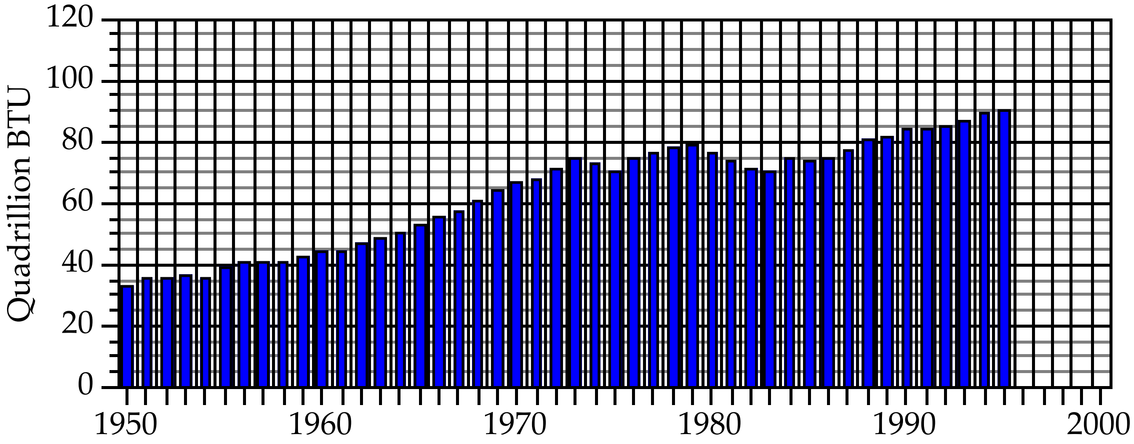


FIGURE 5-3. U.S. energy consumption in the post-World War II period. [Source: Energy Information Administration.]

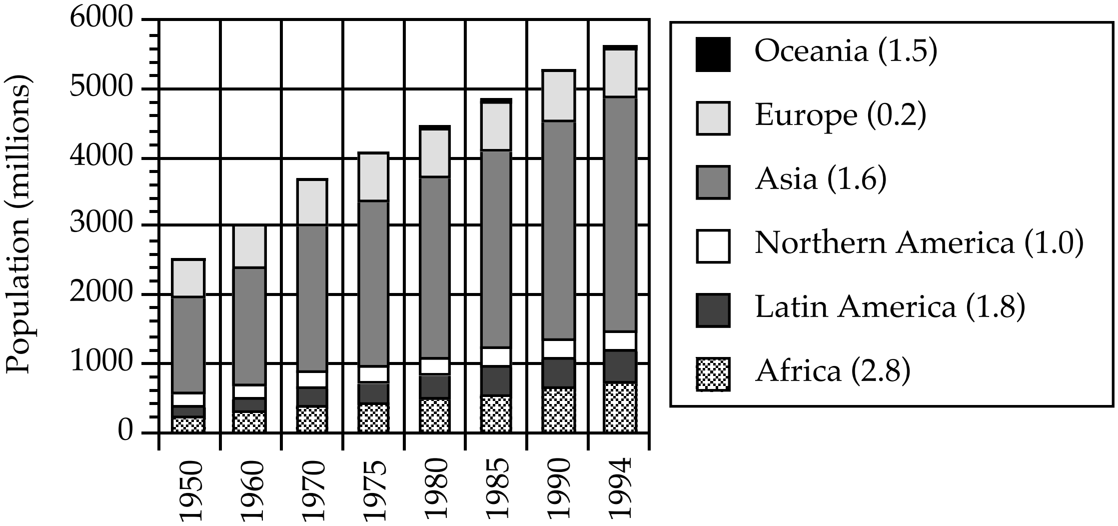


FIGURE 5-4. Recent trends in world population. Annual growth rates for 1990-95 are given in parentheses. [Source: United Nations Demographic Yearbook, 1996.]

For our discussion of energy demand, it is essential that we quantify this rate of growth. A familiar example should be helpful: our savings account. Its growth is illustrated in Figure 5-5. When the axes are given in normal (linear) units, as shown in Figure 5-5a, exponential growth is characterized by the “J curve:” initially the growth is slow, but as the quantity (slowly) grows, its rate of growth (or the slope of this curve) increases. If the y-axis is changed from linear units to logarithmic units, the J-curve becomes a straight line, as shown in Figure 5-5b.

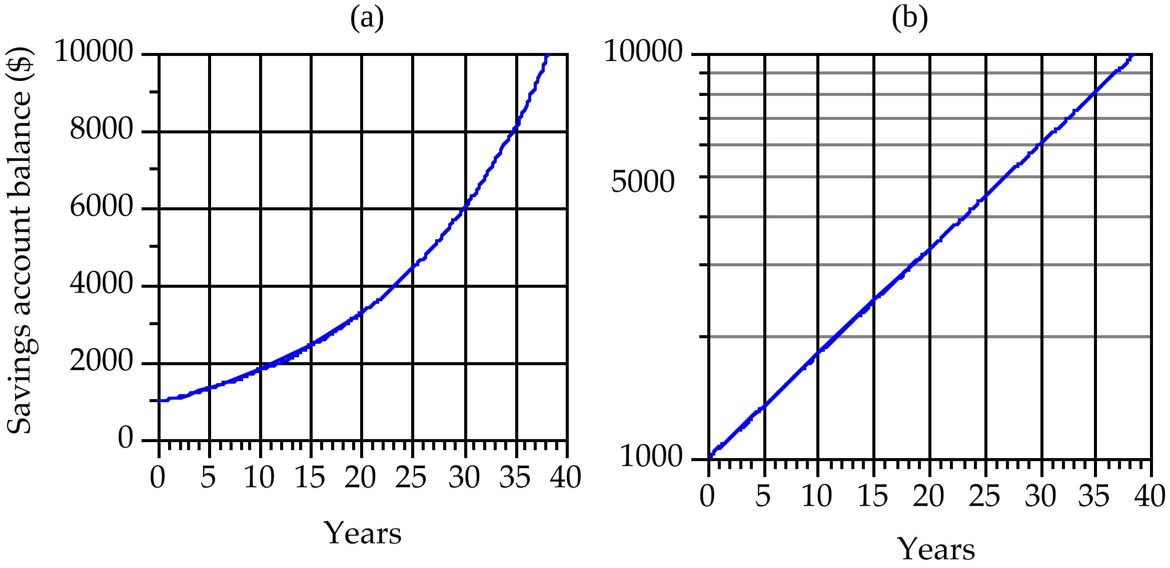


FIGURE 5-5. Example of exponential growth curves in linear (left) and semilogarithmic (right) coordinates: a savings account.

In mathematical terms, exponential growth is expressed in the following way. Let us suppose that we initially have $1000 ($N_o$) and we put it into a savings account in a bank that gives an interest rate (r) of 6% per year. After one year, we shall have an amount N:

$$N = N_o + 0.06N_o = 1000 + (0.06)(1000) = \$1060$$

After two years, we shall have (N):

$$N = N_o + 0.06N_o + 0.06(N_o + 0.06N_o) =$$

$$= 1000 + 60 + (0.06)[(1{,}000 + (0.06)(1000)] = \$1{,}123.60$$

For any period of time (t), and $r < 40\%$, this exponential growth is given by the following expression:

$$N = N_o [e^{rt}] = N_o [\exp(r\,t)]$$

You may remember that e is the number that forms the basis of natural logarithms. (Its value is 2.718, but all calculators have it; so there is no need to remember it.) Thus, for example, after two years, $N = (1000)\{\exp[(0.06)(2)]\} = \$1,127.50$, which is close enough to the number given above.

Of particular interest is the time during which the initial quantity increases by a factor of two, or doubles (t_d). In other words, when $N = 2N_o$,

$$\exp(r\, t_d) = 2$$

or

$$(\text{Rate of growth})\ (\text{Doubling time}) = r\, t_d = 0.7$$

Whenever the product of the rate of growth and the growth interval is 0.7, the initial quantity will double in time. This interval is appropriately called the *doubling time*. (For the analogous concept of half-life of radioactive isotopes, see Chapter 15.)

Note that the product of the growth rate and the growth interval is a dimensionless number. These two quantities must be expressed in the same time units. For example, if the growth rate is expressed on an annual basis, the growth interval is given in years. Note also that the doubling time does not depend on the initial amount.

Illustration 5-2. In 1990 the populations of United States and Mexico were about 250 and 90 million. The annual rates of population growth are 0.6 and 2.6%, respectively. Determine how long it will take in each case for the population to double. When will the population of Mexico become larger than that of the U.S. if these trends continue?

Solution.

$$\text{Doubling time} = \frac{0.7}{\text{Rate of growth}}$$

$$\text{U.S.} \qquad t_d = \frac{0.7}{0.006} = 117 \text{ years}$$

$$\text{Mexico} \qquad t_d = \frac{0.7}{0.026} = 27 \text{ years}$$

So in 2017 the population of Mexico would be 180 million, in 2044 it would be 360 million and in 2071 it would be 720 million. The United States would have 500 million inhabitants in 2107.

Illustration 5-3. Show that the rate of growth of world energy consumption in the period 1950-1965 was roughly 5% per year.

Solution.
From $N = N_o[\exp(rt)]$, we have that

$$rt = \ln\left(\frac{N}{N_o}\right) \quad \text{or} \quad r = \left(\frac{1}{t}\right)\left[\ln\left(\frac{N}{N_o}\right)\right]$$

From the data in Figure 5-2, we have

$$r\ (\text{world}) = \frac{1}{15}\ \ln\left(\frac{5400}{2400}\right) = 0.054\ (\sim 5\%)$$

Energy Consumption and Economic Development

In addition to the intuitively obvious dependence of energy consumption on population, there exists a well-established correlation between energy consumption and the economic well-being of a nation. This is shown in Figure 5-6, where representative energy and economic data for most of the countries in the world are summarized. Electricity occupies a special place among energy forms, because of its versatility and convenience (see Chapter 18). In general, its production is seen to be proportional to the gross national product (GNP), which represents the total market value of goods and services produced by a nation in a year. This is particularly true for the less developed (so-called “third world”) countries (Figure 5-6a), whose GNP per capita is smaller than $10000. For the vast majority of them, it is seen that 1 kilowatthour of generated electricity produces about 2 GNP dollars. (Today's economic data are more often provided in terms of the gross domestic product (GDP), which differs from GNP in that it does not include the net income from investments made abroad.)

A closer look at the relationship between economic development and energy consumption reveals important differences. In Figure 5-6b it is seen, for example, that Switzerland has a 45% larger GNP than the United States, while consuming the same amount of electricity. On the other hand, Norway generates the same GNP with twice as much electricity. Hence, there is some flexibility in this relationship, and some potential for conservation of energy (see Figure 5-6 below).

Figure 5-7 shows the relationship between total energy consumption and economic development in the last quarter of a century. In the early sixties, for every dollar of GNP produced, United States consumed twice as much energy as the rest of the world. Because the increased cost of energy over the last two decades stimulated conservation, the energy intensity (consumption divided by GNP) has been decreasing in the industrialized world in

(a)

(b)

FIGURE 5-6. Relationship between electricity production and the gross national product of less developed (a) and most (b) nations of the world. [Source: World Almanac, 1991].

Illustration 5-4. Show that the information given in Figure 5-6 for the U.S. is essentially the same as that given in Figure 5-7 if the electricity produced in the U.S. represents about 10% of the total energy consumption (see Figure 5-14 below).

Solution. From Figure 5-6b, if electricity production per capita is about 10,000 kWh per person per year, and this is 10% of total energy consumption, the energy consumption in the U.S. is about 100,000 kWh/person/year. Therefore, for a GNP of about 18,000 dollars per person per year, we have:

$$\text{Energy intensity} = \frac{\left(\frac{10^5\ \text{kWh}}{\text{year person}}\right)\left(\frac{3.6\ \text{MJ}}{1\ \text{kWh}}\right)}{\frac{\$1.8\text{x}10^4}{\text{person year}}} = 20\ \text{MJ/\$ (GNP)}$$

This is essentially the same number as that shown in Figure 5-7.

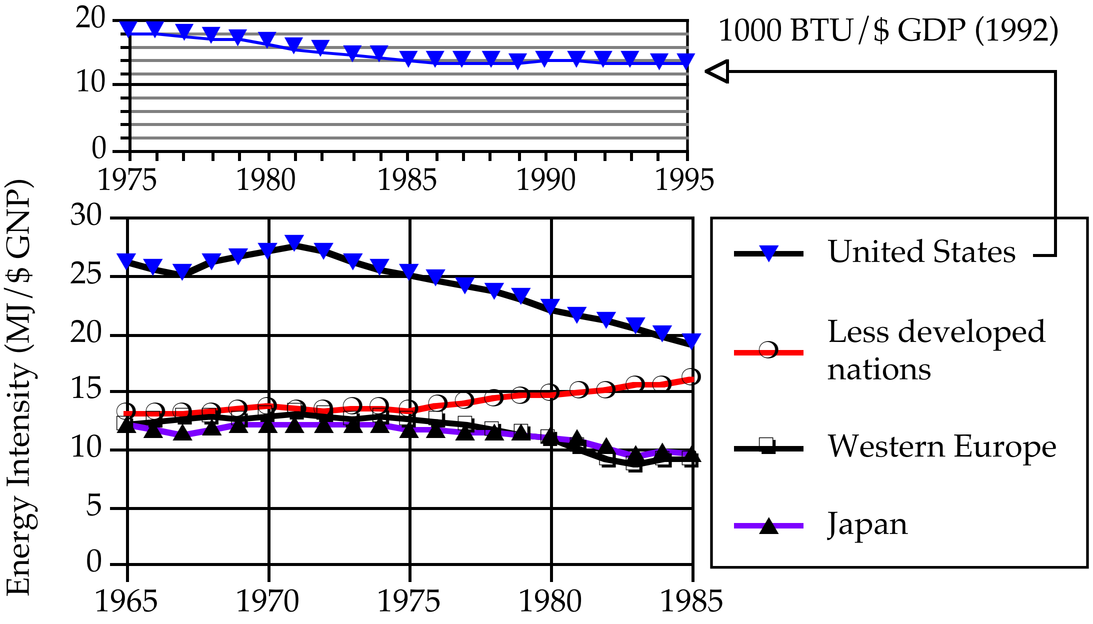


FIGURE 5-7. Energy intensity of various (groups of) nations during the period 1965-1985 and an update for the United States. [Sources: J.H. Gibbons et al., *Scientific American*, September 1989, p. 136; Energy Information Administration.]

general and in United States in particular. In the less developed countries the energy intensity increased in the same period. (When little is consumed – see Figure 5-6 – there is less room for conservation.) When compared with Western Europe and Japan, the United States still has plenty of opportunity for energy conservation (see Chapters 18-20). In the last ten years the desirable decreasing trend has not continued. This is shown in the insert in Figure 5-7 (1000 BTU is roughly equal to 1 MJ).

Renewable and Nonrenewable Energy

In discussing energy supply (Part II), it will be important to make a distinction between two types of energy. Some of the energy forms introduced in Chapter 2 are continuously available. As long as the solar system exists, society can count on them. They are *renewable* or nondepletable. Other energy forms exist on earth in finite quantities and are thus *nonrenewable* or depletable.

If the supply (production) of an energy form is much larger than its demand (consumption), that energy form is considered to be nondepletable. If the demand (in BTU per year) is such that the total supply (in BTU) is consumed within a finite time frame (for example, several hundred years or less), such energy form is considered to be depletable. A simple example will illustrate the difference between these two concepts.

Illustration 5-5. The rate of formation of fossil fuels (coal, petroleum, natural gas) is estimated to be about 4 billion kW. Show that the rate of consumption of fossil fuels is of the same order of magnitude and that these energy sources are therefore nonrenewable.

Solution.

Today's world consumption of energy is of the order of 10^{17} BTU/year, as shown in Figure 2-3. This number needs to be converted into kW.

$$10^{17}\,\frac{\text{BTU}}{\text{year}} = \left(10^{17}\,\frac{\text{BTU}}{\text{year}}\right)\left(\frac{1055\ \text{J}}{1\ \text{BTU}}\right)\left(\frac{1\ \text{year}}{3.15\text{x}10^{7}\ \text{s}}\right) = 3\text{x}10^{12}\ \text{W} = 3\text{x}10^{9}\ \text{kW}$$

So, the rate of consumption of fossil fuels is estimated to be of the same order of magnitude as the rate of their formation (in photosynthesis).

In Chapter 2 we introduced the primitive energy forms. Gravitational and solar energy are nondepletable; they are discussed in Chapters 16 and 17. Conventional (fission-based) nuclear energy is depletable; this is taken up in Chapter 13. With new technology (such as breeder reactors and fusion), it too becomes nondepletable; this is discussed in Chapters 13 and 14. In contrast, the chemical energy of fossil fuels, on which society relies so much today, is a depletable energy form. This fact will be illustrated in Chapters 6-10.

Resources and Reserves

The supply of the various nonrenewable (depletable) energy sources is discussed in terms of reserves and resources. It is important to distinguish between these two concepts. Figure 5-8 illustrates the key difference between them. The two criteria for their distinction are the degree of certainty of their existence (from assurances by geologists) and the profitability (economic feasibility) of their recovery.

The term *reserves* refers to the quantity identified by detailed exploration. The reserves thus represent the quantity of an energy source that is known to exist and that can be recovered economically with existing technology. They are further classified as possible, probable or proved, depending on how sure the geologists are of their estimates.

The term *resources* is much broader. It refers to the quantity of an energy source known or even suspected to exist, regardless of the cost or the technology required to recover it. For example, conditional resources are known to exist but the cost of their recovery is too high at current prices and with existing technology.

(paste)

FIGURE 5-8
Comparison between reserves and resources of a depletable energy source.

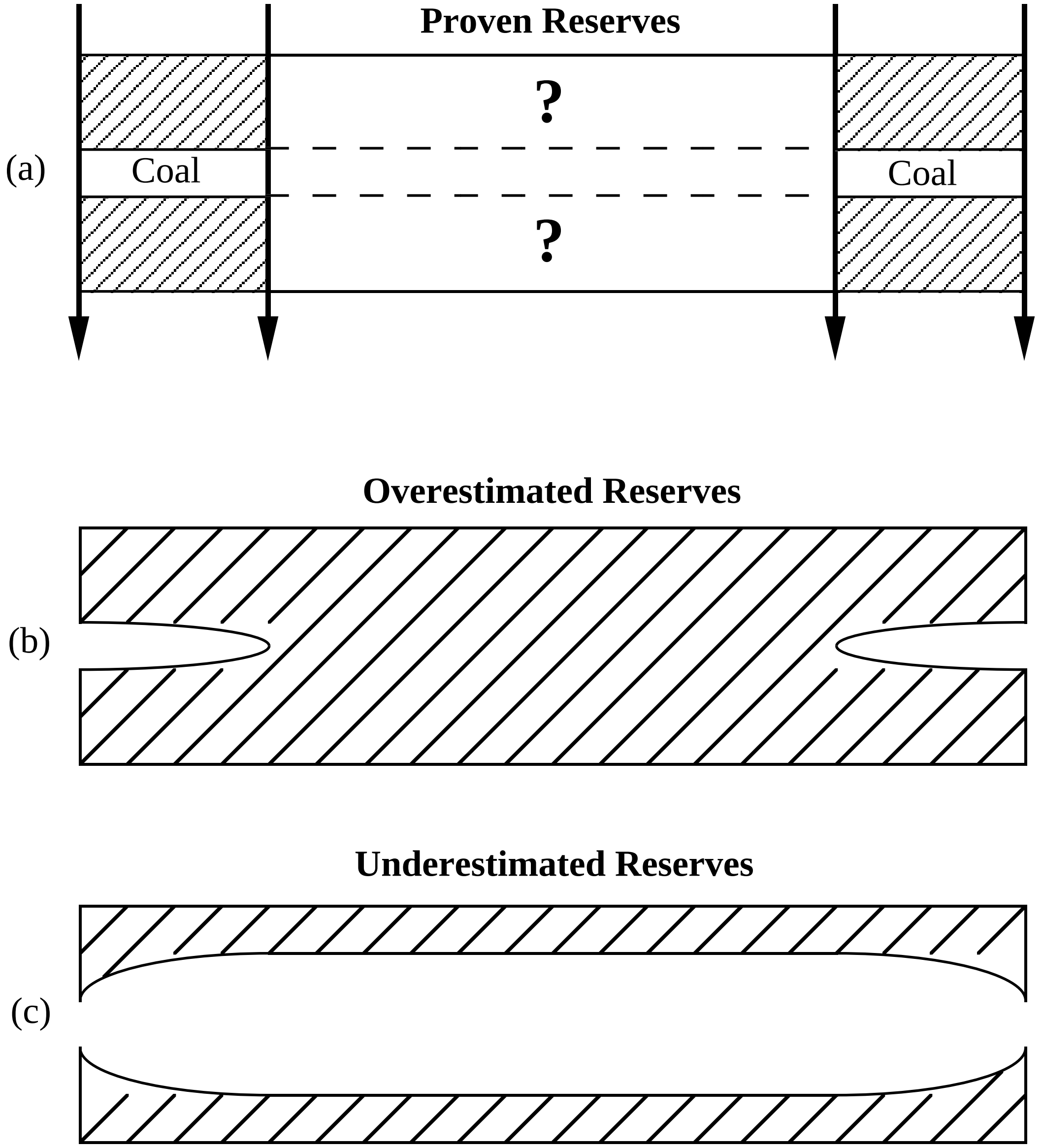


FIGURE 5-9
Schematic representation of estimated reserves of a fossil fuel (e.g., coal). Hatched areas represent non-fuel rock; white areas represent reserves actually recovered.

An analogy to reserves and resources, in the form of our personal finances, is helpful to provide a clearer distinction. Our reserves represent the money we are sure we can get our hands on. This would be the cash we have plus what is in our checking and savings accounts plus any cash advance we can get with credit cards. Our resources represent all the money that we could possibly get hold of: our reserves plus what we can get by selling personal valuables (car, stereo, etc.) plus the cash value of any investment (stocks, bonds, etc.) plus whatever money could be ‘extracted’ from relatives or friends.

Obviously, there are problems in making reliable estimates of resources. The estimated values are continually adjusted upward or downward as more and better information becomes available. In exploring for coal, for example, geologists may drill into the earth's crust at intervals of, say, two miles. If two drill tests both strike a coal seam, we can make the assumption that the seam is continuous and of about the same thickness between the sites where drill tests were made. This is illustrated in Figure 5-9a. However, as more information becomes available (by drilling at half-mile intervals, for example), we might find out that the seam actually looks either as in Figure 5-9b, where there would be much less coal than estimated based on previous information, or as in Figure 5-9c, in which case there would be much more coal than inferred from Figure 5-9a.

Of course there is also a relationship between profit and exploration. As the cost of petroleum increases, there is greater incentive to explore and (hopefully) find more. Also, as cost increases some resources that were classified as conditional (see Figure 5-8) become economically viable. In both cases, these resources become reserves.

We saw earlier in this chapter that the supply of energy is essentially limitless. In discussing the supply of specific energy forms, however, it is very important to make sure that one is not comparing ‘apples’ and ‘oranges’, for example the proven reserves of coal vs. the proven reserves plus undiscovered resources of petroleum. When ‘apples’ and ‘apples’ are compared (e.g., proven reserves of coal vs. proven reserves of oil or natural gas), large differences in supply are found. This fact represents a potential threat to the normal functioning of our oil-dominated modern society. Whether it will result in serious energy supply/demand imbalances, as it already has on several occasions in the past, depends on supply and demand projections for the future.

Population and Energy Demand Growth: Projections

Much has been written and intense debate is still going on about how fast the population, the economy and our energy consumption will grow in the years and decades to come. Even Nobel prize-winning economic analysts and forecasters have often been wrong on this matter. The projections are mutually interdependent and each one of them is dependent on many additional factors. To cite just one simple example, when the population increases so does the energy demand while the GDP per capita will decrease if GDP growth is not as fast as population growth (and this is a typical case in developing nations).

With regard to population, the only statement that can be made safely is that the growth will be larger in the less developed countries than in the developed countries. This is illustrated in Figure 5-10 by showing the trends in selected 'representative' countries. The improvement in the living conditions in the developed countries has led to steady decreases in their death rate over the last century and a half. The birth rate has also been decreasing, at about the same rate, so that today the population growth (the difference between birth rate and death rate) is about 0.4% per year in the industrialized world. In the less developed countries, the decrease in birth rate has occurred only in the last half century. Furthermore, their development has resulted in a greater decrease in death rate. Thus, their average population growth has increased from about 1% per year fifty years ago to about 2.1% per year today. Now, the population of the less developed countries (which include China and India) is about 4 billion (75% of total world population) and that of the developed countries is about 1.2 billion (25% of the total). Therefore, overall, the world population has been growing at an annual rate of 1.7% (0.75x2.1 + 0.25x0.4).

FIGURE 5-10. Historical trends in population growth rates in developing and developed nations of the world. [Source: United Nations.]

Figures 5-11 and 5-12 show the historical trends and summarize a large number of projected scenarios for energy consumption in the United States and the world. Most energy forecasts predict moderate-to-large increases, at rates that are equal or somewhat inferior to the ones experienced in the last three decades. If this indeed happens, adjustments will be necessary in the supply/demand patterns. Note that some projections envision a decrease in energy use in the U.S. In contrast, world energy consumption is expected to grow, mainly because of the expected strong economic growth of densely populated developing nations such as China, India and Nigeria, to name just a few.

More detailed projections were made by Amory Lovins in 1976 in his landmark book "Soft Energy Paths" (see Investigations 1-2 and 5-6 as well as Chapter 21).

FIGURE 5-11. Past and projected energy consumption in the United States by end-use sector. [Source: National Energy Strategy, U.S. Department of Energy, 1991.]

FIGURE 5-12. Past and projected energy consumption in the world by source. [Source: National Energy Strategy, U.S. Department of Energy, 1991.]

Finally, Figures 5-13 and 5-14 show the characteristic energy supply/demand patterns (also called energy input/output diagrams) in the world and the United States. They are seen to be quite similar, in the sense that fossil fuels (coal, petroleum and natural gas) are responsible for most of the energy supply and that the transportation sector of the economy is ‘hooked’ on petroleum. In particular, the transportation sector of the U.S. economy depends to a large extent on imported petroleum. Furthermore, the high ‘tax’ that nature imposes on the conversion of heat to electricity is evident. The average efficiency of electric power plants in the world is 15/48 = 31.3%. In the United States it was somewhat higher in 1994, 9.9/30.7 = 32.2%. In Part II of this book we analyze in detail the energy supply. In Part III, we discuss the energy demand. Finally, in Part IV we briefly discuss the possible strategies to resolve some of the anticipated supply/demand imbalances, as well as to minimize the environmental impact of energy use.

FIGURE 5-13. World energy flows (in 10^6 barrels of oil equivalent per day) for 1985. [From “Energy for Planet Earth,” by G.R. Davis. Copyright © 1990 by Scientific American, Inc. All rights reserved.]

FIGURE 5-14. U.S. energy supply/demand diagram (in quadrillion BTU) for 1994. [Source: Energy Information Administration.]

REVIEW QUESTIONS

5-1. Using the figures provided in this chapter, estimate the rate of growth of population and energy consumption in as many time intervals as you can.

5-2. The U.S. reserves of oil and coal are estimated as 300 and 6000 quadrillion BTU. The annual consumptions are given in Figure 5-14. Determine their depletion times if current consumption levels are maintained.

5-3. Compare the values of world energy consumption in 1979 shown in Figure 5-2. Is the agreement between these *different* sources satisfactory? Compare it with the recent data for 1994 from the *same* source ("1994 Energy Statistics Yearbook," United Nations, 1996): 329,945 thousand terajoules vs. 11,258 mtce vs. 7881 mtoe. One ton of coal-equivalent (tce) is defined as 0.0293076 TJ. One ton of oil-equivalent (toe) is defined as 0.041868 TJ.

5-4. Note that the consumption of energy shown in the various figures in this chapter is given in many different units. This is a true reflection of how energy information is presented both in the media and in statistical sources. It is important that you become comfortable, therefore, with the required unit conversions. As an example, show how good is the agreement between the world energy consumption data provided in Figure 5-13 and Figure 5-2. (Assume that one toe is equivalent to 7.32 barrels.)

5-5. Are the following statements true or false?
(a) The per capita energy consumption in the world is larger than the per capita energy consumption in the U.S.
(b) If the rate of growth of energy consumption is 5% per year, it takes 20 years for the amount consumed to increase by a factor of two.
(c) A general correlation typically exists between the economic well being of a nation and its energy consumption.
(d) Energy intensity is an important index of economic activity of a nation. It is obtained when the gross national (or domestic) product is multiplied by the energy consumption.
(e) By proven reserves we mean the quantities of a resource that are known to exist including those that are not economically recoverable.

INVESTIGATIONS

5-1. The *Economist* of 5/27/95 ("Emerging-market indicators") provides information about the consumption of energy per person and per $1000 of gross domestic product (GDP) in a number of nations. The following table summarizes some of the information. Compare this information with as many pieces of information provided in the figures in this chapter and comment on the degree of (dis)agreement. (See the definition of one ton of coal equivalent in Review Question 5-3.)

Country	Energy consumption, tons of coal equivalent (1992)	
	per capita	per $1000 (GDP)
Singapore	8500	0.43
USA	10,700	-
China	~1000	1.67
Russia	~7300	3.15
Europe (average)	5200	-

5-2. Consult the World Almanac and update the information on electricity production and GDP per capita for Norway, Switzerland and the United States (see Figure 5-6). Verify the information provided below and add the appropriate points to the graph in Figure 5-6.

Country	Population	Electricity production, kWh	GDP, US$
USA	263,814,032	3,230,000,000,000	6,380,000,000,000
Norway	4,330,951	111,000,000,000	89,500,000,000
Switzerland	7,084,984	56,000,000,000	149,100,000,000

5-3. The *Economist* of 4/29/95 published projections of population growth in 25 urban areas around the world. Assuming exponential growth and using the expression for doubling time, estimate the projected growth rate of Tokyo, New York, Bombay and Lagos.

5-4. The *Economist* of 4/15/95 (p. 98) contains information on the phenomenal growth of the Internet. Prepare a semilogarithmic plot of these data and determine the annual growth rate of this new form of communication.

5-5. How ‘correct’ were the predictions for the U.S. energy consumption made by the National Energy Strategy. Compare Figures 5-11 and 5-14.

5-6. Amory Lovins is the main proponent of a “soft path” to the U.S. energy future (see Investigation 1-2). Compare the 1994 consumption information (Figure 5-14) with his projections, which were (approximately) as follows:
“Soft path” – Total consumption, 100 quads (coal, 25%; oil and gas, 40%; ‘soft’ technologies, 35%).
“Hard path” – Total consumption, 150 quads (coal, 35%; oil and gas, 45%; nuclear, 20%).
(a) What are the differences in energy distribution?
(b) Was Lovins off mark with respect to the total energy consumption as well?

5-7. In a 1971 *Scientific American* article (“The Flow of Energy in an Industrial Society,” September issue, p. 135), Earl Cook provided the following graph of U.S. energy consumption and population trends in the last 200 years. Trace the actual trends since 1970 and comment on the degree of (dis)agreement with Cook's predictions.