

Chapter 2

CONCEPT OF ENERGY

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Beetle Bailey is not the only one who wants to save energy. Energy conservation and efficiency is on many people's minds lately, especially when energy becomes expensive. Are energy conservation and modern energy-guzzling society compatible? To begin to answer this question, we must first define energy (Chapter 2 and 3) and then see what we mean by energy efficiency (Chapter 3 and 4).

Qualitative Definition of Energy

Most dictionaries define energy as “the capacity to do work.” This implies that energy is a more abstract concept than work. The definition is correct, of course, but it is incomplete. *Work* is certainly an important ‘manifestation’ of energy; indeed, the Industrial Revolution went into full swing in late eighteenth century when breakthroughs were achieved in converting other forms of energy into work. But work is not the only ‘palpable’ form of energy. *Heat* is another important energy form; a lot of effort and expense is made by society to remove heat from our homes and offices in the summer and to bring it to them in the winter. And *radiation* too, for better or for worse, is energy that we can sense. Hence, a more complete definition is the following:

Energy is a property of matter that can be converted into work, heat or radiation.

Strictly speaking, both work and heat are processes by which energy can be changed but we don't need to worry about this subtlety here. A good analogy is that energy is like money in the bank, while heat, work and radiation are like cash, checks and money orders.

Most dictionaries cite the year 1599 as the date of the earliest recorded use of the term ‘energy’ in English. This may be so, but it took another two and a half centuries for its meaning to be understood completely. Indeed, its precise definition, together with that of entropy (see Chapter 3), is one of the greatest intellectual achievements of mankind.

An instructive analogy can be drawn between the rather abstract concept of energy and another more or less abstract but familiar property of (living) matter: our health. Health is a God-given property that we have, to which we often pay little attention, until we lose it. Similarly, energy is a property that humans and others – both living and nonliving matter – possess to a greater or lesser extent; we are pretty much unaware of its existence, however, until it is converted into work, heat or radiation.

The above definition of energy highlights the fact that energy *conversion* is essential for energy utilization. We shall discuss this in detail. We shall see that the quantity of energy available in the universe is constant. It cannot be created or destroyed; it is only transformed from one form to another. In other words, it is conserved in all these transformations. Work and heat (as well as some types of radiation) are forms of energy that society needs. These are also the energy forms used today for the production of electric energy (or electricity). Unfortunately, however, these are not the *primitive* forms of

energy. They are not the energy forms that are readily available on our planet. The primitive and less palpable forms of energy – such as solar, gravitational, chemical and nuclear energy – need to be converted to work, heat and useful radiation. The entire problem of energy availability can be reduced to that of conversion of abundant but less convenient forms of energy into scarce and more convenient forms which our society needs most. A few examples are outlined below. We shall examine them in more detail in Chapter 3.

Energy: Evolution of a concept

Historians of science have probably written more essays on the development of the concept of energy than on any other subject. This concept has evolved from those of the archaic *fire*, the more modern *vis viva* (“living force”), which was dominant until the nineteenth century, and *force*, which persisted well into the 19th century and today has a much narrower scope. It was Aristotle (384-322 BC) who developed the concept of ‘fire’ as one of four basic ‘elements’ of nature first described by Empedocles (490-430 BC), the other three being earth, water and air. This view remained unchallenged for the next two thousand years. The largely apathetic and deeply religious ‘scientists’ of the Dark and Middle Ages did not seem to care to clarify it. The age of Enlightenment had to come eventually, and it did in the late seventeenth century. The inquiry into the how's and the why's of this world was then not only resurrected but it was systematized into what we today know as the *scientific method*. This allowed Leibniz (1646-1716) to champion the idea that the *vis viva* of a body is its mass times the square of its speed (what we now know to be twice the kinetic energy of a body). In the ensuing 150 years or so, the rapidly growing scientific community was successful in drawing a clear distinction between the more abstract concepts of force and energy and the less abstract concepts of heat and work. The invention of the thermometer – as early as in 1592 by Galileo Galilei (1564-1642) and then by Fahrenheit (1686-1736) in the early eighteenth century – first helped to clarify the distinction between temperature and heat. The detailed studies of heat by Joseph Black (1728-1799) then inspired James Watt (1736-1819) to develop the first modern steam engine which propelled the Industrial Revolution throughout the nineteenth century and beyond. This crucial technological development in turn inspired the scientific community to unravel the laws that govern the conversion of heat to work (see Chapter 3).

In contrast to the early human realization that mass is conserved in all earthly and heavenly phenomena (for an important exception, see Chapter 12), the fact that conservation of energy is an even more basic law of the universe did not become clear until mid-nineteenth century, when the science of thermodynamics was developed. The key players in this fascinating story of simultaneous discoveries are the Englishmen Thomas Young (1773-1829) and James Joule (1818-1889), the American-born Benjamin Thompson (1753-1814), the Germans Robert Mayer (1814-1878) and Hermann Helmholtz (1821-1894), the Frenchman Séguin (1786-1875) and the Dane Ludvig Colding (1815-

1888). While Young is better known for having demonstrated the wave-like character of light and for his research on the elasticity of materials, he is often credited for being the first, in 1807, to use the word *energy* in its modern scientific sense. Thompson, better known as Count Rumford – a remarkable personality, very popular among historians for his military and political adventures which earned him nobility in both England and Bavaria – clarified the nature of *heat* by showing in 1804 that it is not a fluid-like substance, as widely believed until then. This realization and the analysis of interconversion between heat and work by Séguin, Mayer, Colding and especially Joule, in the period 1839-1849, clarified the relationship between heat and work, as two qualitatively different but quantitatively equivalent forms of energy. Finally, in 1847 the inspired young Helmholtz generalized this principle of conservation of energy into a universal law of nature, which came to be known as the First Law of Thermodynamics.

There is some irony in these historical developments: just before major social upheavals were to spread throughout most of Europe in the revolutions of 1848, the collective efforts of the European scientific community brought about one of the major intellectual syntheses of all time.

Energy in Its Various Forms: First approximation

Work. When we lift an object (this book, for example) from one level to another (say, from the floor to a shelf on the wall), we expend our energy – by doing work – to increase the energy stored in the object. (This energy can be converted back into work, for example, if we let the book fall back to the floor.) In this transformation, the *chemical energy* stored in our muscles is converted to work, or more precisely to mechanical energy, and work is converted into the *potential energy* stored in the object (while it sits on the shelf).

Heat. When we put a kettle filled with water on an electric stove, the temperature of the water increases, typically from 60 to 200 degrees Fahrenheit. The energy of the water (sometimes called thermal energy) increases, and we can dissolve coffee and sugar in it. In this transformation, *electric energy* is expended, it is transformed into heat, which in turn is transferred to the water. On a larger scale, in an electric power plant, the water is heated (for example, by burning coal) to a much higher temperature (say, 600 degrees Fahrenheit) and thus acquires sufficient energy to produce electricity (by turning the turbines within the magnetic field of an electric generator). In this transformation, the chemical energy stored in coal is converted to thermal energy of water vapor, which in turn is converted to mechanical energy (work) of the rotating turbine, which is finally converted to electricity.

Radiation. Life on earth is possible because of the sun, and most of earth's energy comes from the sun. The energy from the sun reaches our planet in the form of a very wide spectrum of rays (or waves) of different intensity, which we call solar radiation. Most of it

is benign, like radio waves and light (or visible radiation), and some can be harmful (for example, ultraviolet rays). Both evolution and technological development have made possible the detection of this energy. At one extreme, the first organisms that “have seen the light” lived on Earth some 500 million years ago. At the other extreme, the detection and production of TV and FM waves is only several decades old.

In addition to radiation from outer space, radiation can also come from the tiniest constituents of matter. As we shall see in more detail in Chapter 12, all matter (living and nonliving) is made of atoms, with their protons and neutrons in the nucleus and their electrons revolving around the nucleus. Energy is also stored in atoms, mainly in their nucleus (hence the name *nuclear* energy). When a nucleus (for example, of uranium) is split into smaller fragments, part of its energy is converted into the desired heat, while another part is converted to different forms of radiation, some of which have potentially damaging effects.

In the above examples, several different forms of energy are mentioned. Their interconversion is the subject of much of this book. We thus need to introduce and define some of them more precisely. Work and heat deserve particular attention; they are discussed in detail in Chapter 3.

Gravitational (Potential) Energy. All matter on our planet is subject to the force of gravity, which – as we know well from the times of Galileo and Isaac Newton (1642-1727) – pulls objects toward the earth's center. Overcoming the force of gravity requires expending energy. Therefore, the farther (or higher) an object is from the earth's surface, the greater its gravitational, or potential, energy will be. The change in the gravitational energy of the object is thus proportional to the change in its *vertical* position. A body on top of Mount Everest, Nepal (29,028 feet high), has a higher potential energy than the same body on top of Mount McKinley, Alaska (20,320 feet), which in turn has a higher potential energy than the same body at sea level (0 feet). Also, the larger the mass of an object is, the greater its potential energy will be. Finally, the third factor that defines potential energy is the acceleration due to gravity. This is a relatively constant number on our planet; it represents an increase in speed of about 10 meters per second for every second of free fall. Thus, the gravitational potential energy is defined as follows:

$$\text{Potential Energy} = [\text{Mass}] [\text{Acceleration (due to gravity)}] [\text{Height}]$$

In Chapter 16 we shall see how hydroelectric power plants take advantage of the high potential energy of some of the world's rivers and convert water's gravitational energy into huge quantities of electricity.

Nuclear Energy. It is not indispensable to take a physics course to understand the most important issues surrounding this controversial energy form. We shall discuss these issues in Chapters 12-15. For now, let us just introduce nuclear energy by saying that an enormous quantity of energy is stored in the fundamental particles which make up all

matter, and which we call atoms (from the Greek word 'atomos', meaning indivisible). In spite of the name given to them, we have known for the last hundred years that the atoms are in fact divisible. The splitting of their nucleus is called *fission*. The nuclei of identical or different atoms can also join together. This process is called *fusion*. In both these processes, part of the atomic mass is converted to energy, according to the famous Einstein equation:

$$\text{Energy} = [\text{Mass}] [(\text{Speed of light})^2]$$

Solar Energy. Practically all forms of energy available to us on earth – except gravitational and nuclear – come from the sun. In Chapter 17 we shall see that the sun itself is a giant nuclear reactor in which fusion reactions take place and huge quantities of radiation are emitted in all directions. Part of this energy reaches our planet. It travels in waves that possess a characteristic wavelength (see Figure 2-1). The number of wave crests that pass by a given point in space in a second is called the frequency of the wave. The shorter the wavelength of radiation is, the higher its frequency (see Figure 2-2) and the more intense the radiation will be.

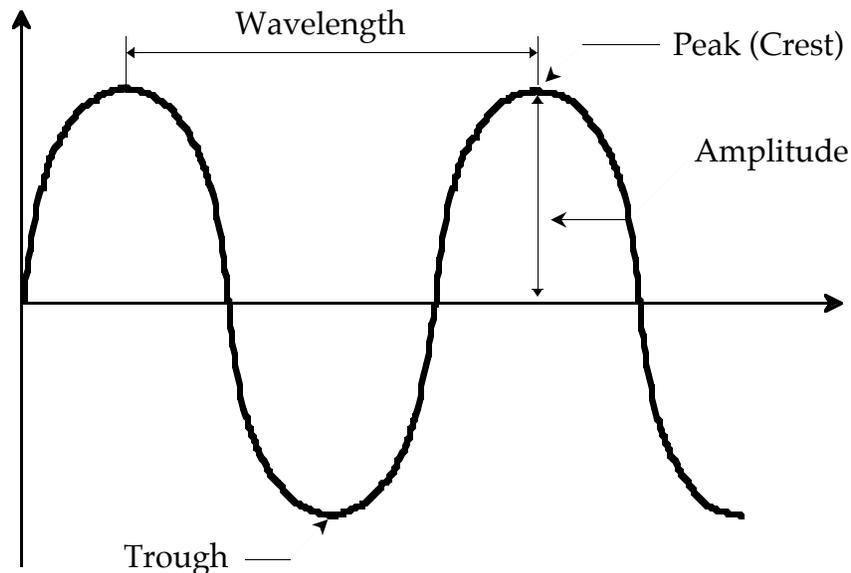


FIGURE 2-1. Principal characteristics of a radiation wave.

FIGURE 2-2. The ‘electromagnetic’ spectrum of energy radiation. The indicated transitions from one form of radiation to another are only approximate. (For a reminder of power-of-ten notation, see Table 2-1 in the next section.)

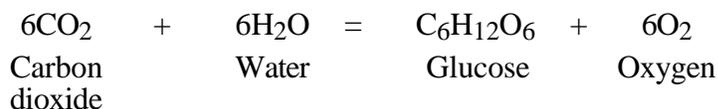
It is seen that only a small portion of this so-called *electromagnetic spectrum* corresponds to ‘sunlight,’ or visible radiation. Radiation of higher intensity – for example, ultraviolet rays, x-rays and gamma-rays – can be harmful, as we shall see in Chapter 15. At the opposite end, low-intensity radio waves (standard AM broadcast), TV signals, FM waves and microwaves are relatively harmless; in fact, they are purposely produced in the myriad electronic devices that characterize modern society.

The following fundamental relationship between frequency and wavelength of electromagnetic waves defines the speed of light:

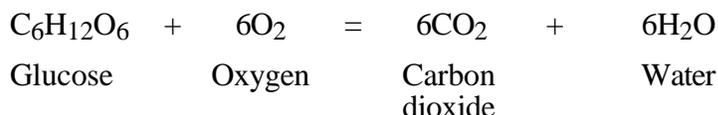
$$\text{Speed of light} = [\text{Wavelength}] [\text{Frequency}]$$

In Figure 2-2 it can be confirmed easily that the order of magnitude of this universal constant is a hundred million meters per second. Its approximate and convenient value is 300,000,000 meters per second (some 670,000,000 miles per hour).

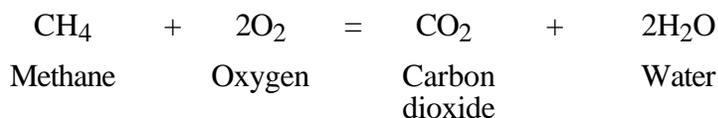
Chemical Energy. Life on earth is the consequence of many chemical processes. For example, carbon dioxide and water combine in green plants – with the help of sunlight – to form more complex molecules such as carbohydrates and proteins. This process is called *photosynthesis*. A typical example is the formation of a sugar (glucose), according to the following chemical equation:



Here the atoms of carbon (C), hydrogen (H) and oxygen (O) are seen to redistribute themselves among different molecules. Depending upon the nature of the rearrangement, energy may be either consumed or released in a chemical process. In the above example of sugar formation, the energy provided by the sunlight is consumed. Of special interest to us are those chemical processes in which certain molecules (called fuels) combine with oxygen from the air. One example is the reverse of the above process:



A more important one for our purposes is the combustion of natural gas (methane):



These processes are invariably *exothermic*; in other words, energy is released (or produced) when they take place. They are an essential part of the functioning ('metabolism') of living organisms and explain why oxygen is needed for survival. For example, they provide the energy of the muscles in our illustration of the concept of work. We shall see in Chapter 6 that this same chemical energy accounts today for the overwhelming majority of world's energy consumption.

Electric Energy (Electricity). This energy form has often been called the 'all-American' energy because after World War II, and even today, Americans consume so much of it and so much more than almost everybody else. Electricity is an intermediate energy form. Once it is produced, its usefulness resides in the fact that it can be converted easily to other energy forms. It is a remarkable fact that as much as 70% of the energy that society uses to produce electricity is wasted. Quite a bit of air pollution is produced in the process too. Only the remaining 30% of the energy expended is actually utilized, and sometimes squandered, in our homes, offices and factories. In Chapters 3 and 4 we shall show why this is so.

Much of this book deals with these blessings and curses of electricity. The entire Chapter 18 is devoted to it.

An Elementary Mathematical Prelude

Energy issues cannot be understood without developing a feel for the amount of energy that is available or is consumed. This turns out to be quite simple, and does not involve any math beyond the four basic operations.

Any quantity of energy has *units* associated with it, for example barrels of oil, kilowatthours of electricity, millicuries of radiation, etc. In Chapters 3 and 4 we shall see that, in contrast to currency exchange rates, there is a definite relationship between the various quantities of energy; in other words, a quantity of energy expressed with a given unit of measurement can be *converted* to an equivalent number expressed with another unit of measurement. In much of this book, and as we read the media reports, we shall see that energy quantities are expressed in a seemingly bewildering variety of units. We shall also see that the understanding of energy issues requires that comparisons be made between 'apples' and 'apples' (and not between 'apples' and 'oranges', as is too often the case). This is possible only if the appropriate conversion of units is performed before making the comparisons. In this chapter we thus take some time to become comfortable with, and indeed proficient in, these conversions. We won't worry for the moment about the important concept of efficiency of conversion, to which entire Chapter 4 is devoted.

Two familiar examples illustrate the procedure involved in all conversions of units. We do not need to perform a step-by-step calculation to know that if one has ten dollars and goes to a bank to exchange them for Mexican pesos, and if the exchange rate is

$$1 \text{ U.S. dollar} = 2500 \text{ Mexican pesos,}$$

the number of Mexican pesos that one will get from the clerk is 25,000. It is also very simple to calculate, when we stop at the gasoline station to fill the tank of our car, that if the tank capacity is 10 gallons, and if a gallon costs \$1.25, we have to pay \$12.50 to fill it up. Let us formalize the thought process involved in these calculations.

In the case of the currency exchange, we start with the quantity that we originally have, \$10, and we multiply it by the number of new units that are equivalent to one original unit (2500 pesos per dollar):

$$(10 \text{ dollars}) \left(\frac{2500 \text{ pesos}}{1 \text{ dollar}} \right) = 25,000 \text{ pesos.}$$

We note two important points in this simple calculation. First, the conversion involves the *cancellation of units*; for this to be possible, if the dollar units are in the numerator in the first term on the left-hand-side of the above expression, they must be in the denominator in the other term. Second, multiplication by the currency *equivalence* – 2500 pesos per dollar (expressed as shown above in the same way as, for example, one percent is expressed as 1/100) – does not change the quantity of money; it only changes the money units. This is

easily understood by noting that if 2500 pesos = 1 dollar, then, by dividing both sides of this expression either by 2500 pesos or by one dollar, we have

$$\frac{2500 \text{ pesos}}{2500 \text{ pesos}} = \frac{1 \text{ dollar}}{2500 \text{ pesos}} = 1,$$

or

$$\frac{2500 \text{ pesos}}{1 \text{ dollar}} = \frac{1 \text{ dollar}}{1 \text{ dollar}} = 1.$$

We see that this currency equivalence has no units; it is unity (or one). Multiplication or division by unity (one) does not change the quantity involved, of course; but it does change the units in which a quantity (of money in this case, or of energy) is expressed.

In the example of tank filling with gasoline, the energy/currency equivalence is

$$1 \text{ dollar} = 1 \text{ gallon of gasoline},$$

and the calculation is as follows:

$$(10 \text{ gallons}) \left(\frac{1 \text{ dollar}}{1 \text{ gallon}} \right) = 10 \text{ dollars}.$$

All the calculations done in this book, even the most complex ones that show us how to make important energy-related decisions, are performed using this simple ‘technique’ of conversion of energy units. This is further shown in Illustration 2-1.

It should be noted in Illustration 2-1C that no effort was made to give the *exact* solution. This is part of what we mean when we say that in this book we want the reader to develop a feel for the amounts of energy that are available or are consumed. We shall see that many of the quantities involved are not known precisely. Therefore we shall often be interested only in the order of magnitude of certain quantities, especially those that are expressed as very large numbers.

So at times we shall be interested just in ‘ball-park’ figures, that is, in orders of magnitude. For example, when comparing the amount of solar energy reaching earth with the amount of energy consumed in the world today, it will be sufficient to say that the former is roughly 4-5 orders of magnitude larger to conclude that we shall not run out of energy any time soon. Other times, we shall need to be more precise, well within an order of magnitude. For example, energy consumption per capita in the U.S. is approximately 5 times larger than in the world as a whole. Still other times, it will be important to distinguish between, say, a 32% and a 33% efficiency of an electric power plant; this is so because, as we shall see, a 1% increase in power plant efficiency usually translates into million-dollar savings.

Illustration 2-1a. Use the approach outlined above to determine how many dollars one should get for one million Japanese yen, if the current exchange rate is:

$$1 \text{ dollar} = 110 \text{ yen}$$

(Answer: \$9,090.91)

Illustration 2-1b. Show that the value of the speed of light is 671,224,363 miles per hour.

Solution.

$$\begin{aligned} \text{Speed of light} &= (300,000,000 \frac{\text{meters}}{\text{second}}) (\frac{1 \text{ mile}}{1609 \text{ meters}}) (\frac{3600 \text{ seconds}}{1 \text{ hour}}) = \\ &= 671,224,363 \frac{\text{miles}}{\text{hour}} \end{aligned}$$

Illustration 2-1c. The total amount of energy consumed in the U.S. in 1990 was about 80 quadrillion British thermal units. If one British thermal unit is equivalent to 1055 joules, express this annual energy consumption in joules.

Solution.

U.S. energy consumption =

$$80 \times 10^{15} \text{ BTU} = (80 \times 10^{15} \text{ BTU}) (\frac{1055 \text{ joules}}{1 \text{ BTU}}) = 8.4 \times 10^{19} \text{ joules}$$

Quantitative Definition of Energy

We cannot overemphasize the fact that most energy issues are issues of balance, or lack thereof, between supply and demand. To reach this balance or to understand the imbalance, energy in its various forms needs to be quantified. This requires a scale, such as the one shown in Figure 2-3.

The energy yardstick shown on this scale is one of the most commonly used energy units in the U.S., the BTU (British thermal unit).

One BTU is equivalent to the energy required to raise the temperature of one pound of water by one degree Fahrenheit.

A related unit is one calorie (1 cal), equivalent to the energy required to raise the temperature of one gram of water by one degree Centigrade. The international standard unit is the joule, in honor of James Joule (see p. 9). The most precise definition of a BTU is that it is equivalent to 1055 joules.

We should note from the above definitions that the temperature of a substance is a measure of its (thermal) energy. Indeed, the higher the temperature of a substance is, the more energy it possesses. We shall discuss this in detail in Chapter 3. For now, we need to remind ourselves of the following relationship between degrees Fahrenheit ($^{\circ}\text{F}$) and degrees Centigrade or Celsius ($^{\circ}\text{C}$):

$$\text{Temperature, } ^{\circ}\text{F} = 32 + [\text{Temperature, } ^{\circ}\text{C}] \left(\frac{9}{5}\right)$$

An easy way to remember this is by recalling that 0°C (the temperature at which water freezes) corresponds to 32°F and that 100°C (the normal boiling point of water) corresponds to 212°F . Indeed,

$$32^{\circ}\text{F} = 32 + (0) \left(\frac{9}{5}\right)$$

$$212^{\circ}\text{F} = 32 + (100) \left(\frac{9}{5}\right)$$

We see in Figure 2-3 that one BTU is a relatively small quantity of energy. The average daily energy consumption (food intake) of an adult person, expressed in these units, is about 12,000 BTU. As mentioned in Illustration 2-1C, the annual consumption of energy in the U.S. has been about 80,000,000,000,000,000 (eighty quadrillion) BTU in recent years. Obviously, a more convenient way to express these quantities is needed. The convenient power-of-ten notation is summarized in Table 2-1. Some of the abbreviations commonly used can be recognized from the familiar jargon of personal computers. (For example, a 760-kb floppy diskette contains 760,000 bytes of storage space. A 400-Mb hard disk drive can store 400,000,000 bytes of information.)

Large numbers are best expressed using this notation. The digit in the exponent simply represents the number of zeros to be placed after the one. For example, 10^9 means that there are nine zeros after the one, giving a billion, that is 1,000,000,000. This is particularly useful when one is interested primarily in orders of magnitude, as we shall be in many instances. In the examples given above, we have

$$\begin{aligned} 12,000 \text{ BTU} &= 1.2 \times 10^4 \text{ BTU} \\ 80,000,000,000,000,000 \text{ BTU} &= 8 \times 10^{16} \text{ BTU} (= 80 \times 10^{15} \text{ BTU}) \end{aligned}$$

Expressed as orders of magnitude, the above two numbers would be roughly 10^4 ($\sim 10^4$) and $\sim 10^{17}$, respectively. Sometimes our calculations or estimates are not very accurate, and the above approximations are sufficient.

FIGURE 2-3. Energy scale showing the approximate energy equivalents (in BTU) for a variety of processes.

Illustration 2-2. As shown in Figure 2-3, the average daily human food intake is some 10^4 BTU. Convert this quantity into the more familiar dietary calories.

Solution. Using Table 2-2 we have

$$10,000 \text{ BTU} = 10,000 \text{ BTU} \left(\frac{1 \text{ J}}{9.478 \times 10^{-4} \text{ BTU}} \right) \left(\frac{2.39 \times 10^{-4} \text{ Cal}}{1 \text{ J}} \right) = 2522 \text{ Cal}$$

This quantity and its order of magnitude are very familiar to a diet-conscious reader. Note that a dietary calorie is equivalent to one thousand calories.

TABLE 2-1
Reminder of large numbers (power-of-ten notation)

Power of 10 Notation	Designation (Prefix)	Abbreviation
10^{-12}	(pico)	p
10^{-9}	(nano)	n
10^{-6}	(micro)	μ
10^{-3}	(milli)	m
10^0	one	-
10^1	ten	-
10^2	hundred	-
10^3	thousand (kilo)	k
10^4	ten thousand	10k
10^5	hundred thousand	100k
10^6	million (mega)	M
10^7	ten million	10M
10^8	hundred million	100M
10^9	billion (giga)	B (G)
10^{10}	ten billion	10B
10^{11}	hundred billion	100B
10^{12}	trillion (tera)	T
10^{13}	ten trillion	10T
10^{14}	hundred trillion	100T
10^{15}	quadrillion	quad

Table 2-2 summarizes all the commonly used energy units. As we read about energy utilization either in newspapers or in specialized publications, sooner or later we shall encounter each one of them. So it is important to be able to express energy quantities in different units. Illustrations 2-2 and 2-3 show the procedure to follow when using these conversion factors.

Illustration 2-3. Trinitrotoluene (TNT) is an explosive. When it explodes, it releases energy, which (for convenience) is measured in units of mass of TNT. How many joules of energy are released by the explosion of 1 kg of TNT?

Solution. Using Table 2-2 we have

$$\begin{aligned} \text{Energy in 1 kg of TNT} &= (1 \text{ kg TNT}) \left(\frac{1 \text{ J}}{2.381 \times 10^{-10} \text{ tons TNT}} \right) \left(\frac{1 \text{ ton}}{1000 \text{ kg}} \right) = \\ &= 4.2 \times 10^6 \text{ J} \end{aligned}$$

Note: This calculation will be used in Chapter 15, to place into perspective the destructive power of nuclear weapons.

TABLE 2-2
Conversion of energy units

1 joule	= 1 J = (1 W) (1 s) = 1 kg $\frac{\text{m}^2}{\text{s}^2}$
	= 6.242 x 10 ¹⁸ electron volts (eV)
	= 10 ⁷ ergs
	= 0.2388 calories (cal)
	= 2.39 x 10 ⁻⁴ diet calories (Cal)
	= 9.478 x 10 ⁻⁴ British thermal units (BTU)
	= 2.778 x 10 ⁻⁷ kilowatthours (kWh)
	= 0.735 footpounds (ft lb)
	= 2.381 x 10 ⁻¹⁰ tons of TNT

Note: The reader is not expected, of course, to memorize any of the numbers in Table 2-2. All the conversion factors required can be derived easily by referring to this table (see Review Question 2-1).

Power

A concept very much related to energy, but not to be confused with it, is that of *power*. An analogy should help to understand the difference. We are intuitively familiar with the time value of money: if a car bought for cash costs 10,000 dollars, it may end up costing 15,000 (current) dollars if paid over a four-year period. The time interval during which energy is produced or consumed is of equal importance. Some energy-consuming devices are more 'energy-intensive' than others. These devices have more power: they consume the same amount of energy in a shorter time interval. By analogy with the interest rate (for example, 10 percent per year), this *rate of consumption (or production) of energy* is called power.

$$\text{Power} = \frac{\text{Energy}}{\text{Time}},$$

or

$$\text{Energy} = [\text{Power}] [\text{Time}].$$

The familiar example of the acceleration of an automobile can further clarify the difference between the two concepts. A certain amount of energy is required to accelerate the car from its position at rest to a movement at a constant speed of, say, 60 miles per hour. If car A, having a power P_1 , can achieve this acceleration in 20 seconds, car B needs a power equivalent to $2xP_1$ in order to achieve the same acceleration in 10 seconds (and the same total amount of energy is consumed in both cases).

Table 2-3 summarizes all the important units of power. A familiar though inconvenient unit is the historically significant horsepower (hp). The most convenient and also familiar unit (e.g., from the ratings of light bulbs, hair driers, loudspeakers, etc.) is the watt (W), in honor of James Watt (see p. 9) defined as

$$1 \text{ watt} = \frac{1 \text{ joule}}{1 \text{ second}}, \quad \text{i.e.,} \quad 1 \text{ W} = \frac{1 \text{ J}}{1 \text{ s}}.$$

TABLE 2-3
Interconversion of power units

$ \begin{aligned} 1 \text{ watt} &= 1 \text{ W} = \frac{1 \text{ J}}{1 \text{ s}} = 10^{-3} \text{ kW} = 10^{-6} \text{ MW} \\ &= 3.412 \text{ BTU/h} \\ &= 0.001341 \text{ hp (horsepower units)} \end{aligned} $
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The distinction between power and energy is particularly important for energy economics. Remember: *we buy power, but we pay for energy!* In other words, energy-consuming devices come with a certain power rating (for example, a 1200-watt hair drier, a 60-watt light bulb, a 1.5-kilowatt air conditioner). This rating determines how much energy we shall have to consume – and how much money we shall have to spend – in order to be able to use them. Thus, a 1200-W hair drier requires that we supply 1200 joules of energy every second. If we use it for 5 minutes, this amounts to using 360 kilojoules of energy. If we then know how much we pay for the energy we use, in dollars per kilojoule, we are in a position to determine the economics of this and many other energy-consuming devices.

Illustration 2-4a.

An automobile has a horsepower rating (power) of 100 hp. Calculate its power in watts.

Solution.

$$\text{Power} = 100 \text{ hp} = (100 \text{ hp}) \left(\frac{1 \text{ W}}{0.001341 \text{ hp}} \right) = 74,571 \text{ W} = 74.5 \text{ kW}$$

Illustration 2-4b.

Show that 1 kilowatthour (kWh) is equivalent to 3.6 megajoules (MJ).

Solution.

$$1 \text{ kWh} = (1 \text{ kW}) (1 \text{ h}) =$$

$$= (1000 \text{ W}) (1 \text{ h}) = (1000 \text{ Wh}) \left(\frac{3600 \text{ s}}{1 \text{ h}} \right) = 3.6 \times 10^6 \text{ Ws} = 3.6 \times 10^6 \text{ J} = 3.6 \text{ MJ}.$$

Summary

We have briefly introduced the primitive energy forms available on our planet. We have also introduced the forms of energy that are more useful to our modern, high-tech society. For historical reasons and for convenience, the quantities of energy associated with these different energy forms are expressed in different units. We have thus shown how to make the necessary conversions of energy units. We are now ready to discuss the laws that govern these energy conversion.

Illustration 2-5. A 100-W light bulb is left on overnight. How much energy does it consume and how much money does this cost, if electricity costs ten cents per kilowatthour?

Solution.

We know how much power the light bulb draws, and we know the time interval over which it is used, say, 8 hours. So we can calculate the energy consumed. We also know the cost of a unit of energy. Therefore:

Energy consumed = [Power drawn] [Duration of power use]

$$= (100 \text{ W}) (8 \text{ h}) = 800 \text{ Wh} = (800 \text{ Wh}) \left(\frac{1 \text{ kW}}{1000 \text{ W}} \right) = 0.8 \text{ kWh}$$

Cost of energy consumed = [Energy consumed] x [Cost of unit of energy]

$$= (0.8 \text{ kWh}) \left(\frac{\$0.10}{1 \text{ kWh}} \right) = \$0.08$$

REVIEW QUESTIONS

2-1. Using the information in Table 2-2, show that 1 kWh is equivalent to 3412 BTU and that 1 BTU is equivalent to 1055 J.

2-2. The 1994 consumption of energy in the world was 329,945,000 terajoules. Convert this to BTU and show that the order of magnitude indeed corresponds to 10^{17} - 10^{18} BTU shown in Figure 2-3.

2-3. A hair drier (1600 W) is used for 15 minutes. If electricity costs \$0.15 per kWh, show that these 15 minutes of use cost 6 cents.

2-4. Indicate whether the following units represent energy, power or neither of the two: (a) calorie, (b) (BTU) (seconds), (c) (kilowatt) (day), (d) BTU/hour, (e) megawatt/hour, (f) joule/minute, (g) calorie/minute, (h) gigawatt, (i) watt/second.

2-5. Show that the frequency of visible radiation, whose wavelength is 0.4-0.7 micrometers, is indeed of the order of 10^{15} per second.

INVESTIGATIONS

2-1. Find out more about Count Rumford, that “most successful Yank abroad, ever” (see *Smithsonian* magazine of 12/94). Summarize his energy-related accomplishments.

2-2. Spend some time in the library or on the Internet and investigate how G. D. Fahrenheit (1686-1736) came up with the awkward 32 and 212 degrees as reference points on the Fahrenheit temperature scale. Prepare a brief summary (one page maximum) for class discussion. Use *multiple* sources to check your story. See, for example, *Dictionary of Scientific Biography* and *Encyclopedia Britannica* (<http://www.eb.com>). If available, consult also the journals *Isis*, Vol. 4 (1921-22), pages 17-22 and *Nature*, Vol. 137 (1937), pp. 395-398 and 585-586.

2-3. Investigate the role of Benjamin Franklin in the development of electricity as a useful energy form. Prepare a one-page report for class presentation and discussion. Start with the *Encyclopedia Britannica* online (www.eb.com). Use also one of Internet's search engines; simply type in “Benjamin Franklin.”