Energy Units

Introduction

Many sorts of units are used in energy discussions. They fall into two broad categories: (a) those whose definition is not related to a particular fuel, which we here term "basic" units; and (b) those whose definition is related to idealized properties of a specific fuel, which we here term "source-based" units. These units, along with special topics related to electricity, are discussed in succeeding sections. Table 1 gives conversion factors between units, as well as the energy content of specific fuels.

Basic Units

Joule (J).

This is the basic energy unit of the metric system, or in a later more comprehensive formulation, the International System of Units (SI). It is ultimately defined in terms of the meter, kilogram, and second.

Calorie (cal).

Historically the calorie was defined in terms of the heating of water. Thus, in a traditional definition, one calorie is the amount of heat required to raise the temperature of 1 gram of water by 1°C, from 14.5 °C to 15.5 °C. (This is sometimes referred to as the 15 °C calorie, and differs slightly from the "calorie" measured for other temperature intervals.) More recently the calorie has been defined in terms of the joule; the equivalence between the calorie and joule is historically known as the mechanical equivalent of heat.

Several definitions of the calorie are now in common use, including (2):

thermochemical calorie	1 cal = 4.184	J (exact)
15 °C calorie	1 cal = 4.1858	J
International Table calorie	1 cal = 4.1868	J (exact)
mean calorie	1 cal = 4.1900	J

The International Table (IT) calorie has been adopted in the publications of the Energy Information Administration of the U.S. Department of Energy (DOE/EIA) (3) and of the International Energy Agency of the Organization for Economic Co-operation and Development (OECD/IEA) (4). In view of the importance of these publications, it is reasonable to view the IT calorie as being the preferred unit for discussions of energy production and use, but there is no universally adopted practice (see also the discussion of Btu, below).

Sometimes a capitalized version, Calorie, is used to denoted the kilocalorie (kcal). In discussing food, the "calorie," capitalized or not, is always the kilocalorie.

British thermal unit (Btu).

This is the English system analog of the calorie. For specific heat capacities to be the same, whether expressed in Btu/lb-°F or in cal/gm-°C:

1 Btu = 251.9958 cal.

As for the calorie, there is a family of "Btu's" in relatively common use, including:

thermochemical Btu	1 Btu = 1054.35	J
59 °F (15 °C) Btu	1 Btu = 1054.80	J
International Table Btu	1 Btu = 1055.06	J
mean Btu	1 Btu = 1055.87	J

Again, the IT unit is the one used in DOE/EIA publications.

Kilowatt-hour (kWh).

The kilowatt-hour is a standard unit of electricity production and consumption. By definition, noting that 1 kilowatt = 1000 watts:

$$1 \text{ kWh} = 3.6 \times 10^{6} \text{ J (exact).}$$

The relationship between the kWh and the Btu depends upon which "Btu" is used. It is common, although not universal, to use the equivalence:

1 kWh = 3412 Btu.

This corresponds to the International Table Btu. [More precisely, 1 kWh = 3412.14 Btu (IT).]

Large-scale units.

In describing national or global energy budgets, it is common practice to use large-scale units based upon the joule, Btu, and kWh:

Exajoule (EJ):

1 EJ = 10^{18} J

Quadrillion Btu(quad):

1 quad = 10^{15} Btu = 1.055 EJ

Terawatt-year (TWyr):

1 TWyr = 8.76 x 10^{12} kWh = 31.54 EJ = 29.89 quad

Source based conversion factors and units

Actual energy content and nominal equivalents. In discussing the production and use of energy it is often convenient to speak in terms of the bulk amount of fuel, e.g. a barrel of oil or a ton of coal. These terms are sometimes used not only to denote a volume or mass, but also to represent an amount of energy. While useful in putting a primary focus on the fuel of interest, there is an intrinsic imprecision in such an approach because "oil" and "coal" embrace a variety of products, with different energy contents per unit mass. The differences can be large. The heat content for several common fuels, as well as the weighted averages for petroleum, coal and natural gas consumed in the U.S. in 1995, are listed in Table 1, using data from Ref. (3).

Given the wide variations in the actual heat content of fuels, especially oil and coal, it is common to introduce a nominal energy equivalent that reflects a typical energy content of the given fuel, but is decoupled from the variations that occur in actual fuels . The energy equivalent can be considered to be an alternate energy unit, precisely related to units such as the joule, calorie, or Btu. Energy equivalents for oil and coal are discussed in succeeding paragraphs, below, and are listed in Table 1.

Conversion factors for oil. The heat content of crude oil from different countries varies from about 5.6 million Btu (MBtu) per barrel to about 6.3 MBtu (5). The heat content of typical petroleum products varies even more (see Table 1). A nominal conversion factor is sometimes used for a barrel of crude oil, which is close to its actual average energy content:

1 barrel of oil equivalent = 5.80 MBtu.

With this definition, a correspondence can be established between millions of barrels of oil per day (Mbd) and quads per year:

1 Mbd = 0.0058 x 365 = 2.12 quad/yr.

which is sometimes rounded off to: 1 Mbd = 2 quad/yr.

An energy equivalence for oil can also be specified in terms of energy per metric ton (tonne). [For oil, unlike coal, mass is commonly specified in tonnes even in U.S. literature (5).] The number of barrels of crude oil per tonne varies widely, depending upon the source. For 1993, the EIA has reported values varying from well under 7 barrels/tonne for some countries of origin to over 8 barrels/tonne for others (5). For the United States, the average was 7.33 barrels/tonne. This average, together with the nominal equivalence of 5.8 MBtu/bbl, corresponds to a heat content for crude oil of 42.5 MBtu/tonne.

There are differing definitions in the literature of a *tonne of oil equivalent* (toe). In OECD/IEA publications it is set equal to 10.0 kcal (IT) (4), while in other publications it is set equal to 10.7 x 10^6 kcal (thermochemical) [e.g., Ref. 6] . These choices correspond, respectively, to:

$$1 \text{ toe} = 1.00 \times 10^{10} \text{ cal (IT)} = 41.868 \text{ GJ} = 39.68 \text{ MBtu (IT)}$$

and

$$1 \text{ toe} = 1.07 \times 10^{10} \text{ cal (thermochemical)} = 44.769 \text{ GJ} = 42.46 \text{ MBtu (thermochemical).}$$

In OECD/IEA tabulations, the *megatonne of oil equivalent* (Mtoe), equal to 4.1868 x 10^{16} J, is used as the general unit to describe the energy content of all fuels. A corresponding larger unit, the *gigatonne of oil equivalent* (Gtoe) can be related to the exajoule and quad:

1 Gtoe = 41.868 EJ = 39.68 quad.

Conversion factors for coal. Amounts of coal are described both in short tons and metric tons. Heat contents vary widely among countries, averaging less than 10 MBtu/ton for some regions and up to about 30 MBtu/ton for others, where low heat content corresponds to a large lignite fraction (5). For the United States in 1995, the average was 20.9 MBtu/ton (3).

In a fairly widely used specification of a nominal value, the energy content of 1 *tonne of coal equivalent* is set equal to 7 x 10^9 calories [e.g., Ref. 6]. Then, at a level of precision that makes the particular choice of "calorie" irrelevant:

1 tonne of coal (equiv) = 29.3 GJ = 27.8 MBtu

1 ton of coal (equiv) = 26.6 GJ = 25.2 MBtu.

As seen in Table 1, this nominal heat content is considerably higher than the average heat content of coal as presently consumed in the United States; it is, however, fairly close to the average heat content of coal used in the early 1950s (3).

Conversion factors for natural gas. Natural gas is made up largely, but not entirely, of methane (CH_4) and its energy content is more uniform than that of coal. For the large majority of sources the gross heat content of dry natural gas lies between 900 Btu/ft^3 and 1100 Btu/ft^3 (5). For the U.S. in 1995, it averaged 1028 Btu/ft^3 (3).

There is no widely used equivalent unit of energy specifically based on natural gas, although the heat content of natural gas is often approximated by the rounded value of 1000 Btu/ft^3. In discussions of natural gas production and consumption it is also common to use the unit *therm*, where

1 therm = 100,000 Btu.

Special topics relating to electricity

Gross and net electricity production. The gross electricity generation (for example, in kWh) is the amount of energy measured at the terminals of the generating unit. The net generation is measured at the output transformer of the power plant. They differ by the amount of electricity consumed within the plant itself, roughly 4%.

Electricity sales. Electricity sales differ from net generation due to transmission losses. In standard tabulations, such as those of the DOE/EIA, there may be further differences due to imports, exports, time lags between generation and billing, and the inclusion in utility sales of amounts of electricity purchased by utilities from non-utility producers for resale. In 1993, for example, the ratio of U.S. utility sales to net utility generation was 0.99. Transmission and distribution losses amounted to about 8%, but this was largely balanced by purchases from non-utility electricity producers and, secondarily, imports (3).

Efficiency for fossil fuel and nuclear sources. At 100% efficiency, the conversion from heat to electricity is at a rate of 3412 Btu per kWh. Actual generation efficiencies, limited by the Second Law of Thermodynamics and design practicalities, fall short of this. More specifically, for U.S. power plants during recent years the average heat input per kWh of net generation was in the neighborhood of 10,300 Btu/kWh for fossil-fuel steam plants and of 10,700 Btu/kWh for nuclear plants, corresponding to thermal conversion efficiencies of 33% and 32%, respectively (3). [It is expected that future plants, especially those based on gas turbine systems, often will have higher efficiencies, in some cases exceeding 50%.]

Primary energy and end-use energy. In considering energy consumption for electricity generation, a separation is sometimes made between the electrical energy consumed at the point of use (converted from electricity sales at the rate of 3412 Btu/kWh) and the energy lost to heat in electricity generation and transmission. The end-use energy and the energy losses are then individually tabulated, with the losses roughly twice as great as the end-use energy. However, this separation creates a possibly misleading asymmetry in comparisons among modes of energy use, because end-use losses are neglected for fossil fuels used directly and these losses sometimes are substantial.

From the standpoint of energy resources, the interesting number is the primary energy---the total energy consumed at the generating plant, whether used efficiently or wasted. Thus, it is usually desirable to consider energy budgets in terms of the energy content of the resource originally consumed, i.e., the primary energy and not the end-use energy. When this is done, the energy corresponding to 1 kWh of electricity depends upon the conversion efficiency, and is typically above 10,000 Btu.

Energy equivalent for non-fossil fuel sources. To facilitate comparisons between different energy sources, a conversion factor is assigned to non-fossil fuel sources which relates electricity generated to a nominal primary energy. For nuclear energy, this is done on the basis of the heat content of the steam produced (3). A similar approach can be used for geothermal plants.

For the various renewable energy sources, the primary energy cannot be readily established and often is irrelevant. Instead, a "primary energy" is assigned by adopting a standard conversion factor---equivalent to adopting a nominal efficiency, where 100% efficiency corresponds to 3412 Btu per kWh. In DOE/EIA publications, the nominal efficiency for renewable energy sources (hydroelectric, biomass, wind, photovoltaic, and solar thermal) is taken to be the same as the efficiency of fossil-fuel steam electric plants, namely 33.2% (3). [More precisely, the conversion factor is set at 10,272 Btu/kWh.] In OECD/IEA publications, on the other hand, the efficiency is taken to be 100% for hydroelectric, wind, and direct solar sources; for geothermal sources it is taken to be 10% (4). Thus, compared to DOE/EIA publications, the OECD/IEA publications underestimate the primary energy consumed for hydroelectric power and overestimate the primary energy consumed for geothermal power. [The DOE/EIA and OECD/IEA assumptions are summarized in Table 1.]

Gigawatt-year (GWyr). Large individual plants have capacities in the neighborhood of 1 GW of electrical output (GWe). This makes the gigawatt-year (GWyr) a natural unit to use in discussions of total electricity production. By definition:

1 GWyr = 8.76 x 10^9 kWh.

It is to be noted that a 1 GWe plant does not normally generate 1 GWyr of electricity per year. The ratio of the actual electricity generated to the amount which would be generated were the plant to operate at full capacity for one year is the *capacity factor.* Typical coal and nuclear plants operate at capacity factors between about 60% and 80%.

For a plant with a conversion efficiency of 33%, an electrical output of 1 GWyr (3.15 x 10^{16} J) corresponds to a thermal output of 9.5 x 10^{16} J, or 0.090 quad. Thus, typically, the relation between primary energy used and electricity produced is approximately:

1 quad ---> 11 GWyr.

Table IV.4.1. Units and conversion factors (see text).

General
1 short ton (ton) = 2000 lb
1 metric ton (tonne) = 1000 kg
1 ton = 0.907185 tonne
1 barrel = 42 U.S. gallons = 159.0 liters
1 barrel of crude oil ~ 0.136 tonne
1 square mile = 640 acres = 2.590 km^2
1 hectare = 10^{-2} km^2 = 2.471 acres

Energy units
1 calorie (thermochemical) = 4.184 J
1 calorie (15 °C) = 4.1858 J
1 calorie (IT) = 4.1868 J
1 calorie (mean) = 4.1900 J
1 Btu = 251.9958 calories
1 Btu (thermochemical) = 1054.35 J
1 Btu (59 °F) = 1054.80 J
1 Btu (IT) = 1055.06 J
1 Btu (mean) = 1055.87 J
1 kilowatt-hour (kWh) = 3.6 x 10^6 J
1 kilowatt-hour (kWh) = 3412 Btu (IT)
1 therm = 100,000 Btu
1 electron-volt = 1.6022 x 10^{-19} J

Large-scale units
1 quad = 10^9 MBtu = 10^{15} Btu
1 exajoule (EJ) = 10^{18} J
1 terawatt-year (TWyr) = 8.76 x 10^{12} kWh

	Quad[a]	EJ
1 quad	1.000	1.055
1 EJ	0.948	1.000
1 TWyr (100% effic)	29.89	31.54
1 TWyr (33% effic)	90.6	95.6
10^9 tonne coal equiv	27.76	29.29
10^9 barrel oil equiv	5.80	6.12
10^9 tonne oil equiv[b]	39.68	41.87
10^9 tonne oil equiv[c]	42.43	44.77

a. Based on IT Btu.
b. As used by OECD/IEA (Ref. 4).
c. As used in Ref. 6.

Units of power
1 watt (W) = 1 J/sec
1 horsepower = 746 W
10^6 bbl of crude oil/day ~ 2.12 quad/yr

Assumed efficiency in electricity generation
(for calculating "primary energy")

Source	DOE/EIA	OECD/IEA
nuclear power	0.320	0.33
hydroelectric	0.332[a]	1.00
biomass	0.332[a]	
wind and solar	0.332[a]	1.00
geothermal	0.163	0.10

a. Set equal to efficiency for fossil fuels.

Heat content of fuels

	MBtu[a]	GJ[a]
Nominal equivalents:		
1 barrel of crude oil	5.80	6.12
1 tonne of crude oil	39.68	41.87
1 short ton of coal	25.18	26.57
1000 ft^3 of natural gas	1.000	1.055
Average for U.S., 1995:		
1 bbl petroleum prod	5.358	5.653
1 ton coal	20.852	22.000
1000 ft^{3}of natural gas	1.028	1.085
1 bbl petroleum products:		
propane	3.836	4.047
aviation gasoline	5.048	5.326
motor gasoline	5.253	5.542
distillate fuel oil	5.825	6.146
residual fuel oil	6.287	6.633
Other:		
1 cord dry wood[b]	21.5	22.7
1 tonne ^{235}U[c]	8 x 10^7	8 x 10^7

a. 1 MBtu = 10^6 Btu (IT); 1 GJ = 10^9 J
b. 1 cord of dry wood = 1.25 ton
c. Ignoring n-capture in ^{235}U and ^{238}U.

References

* This chapter is based, to a large extent, on Reference 1.

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