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Excerpt
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1 Preliminaries

Chop your own wood,
and it will warm you twice.

Henry Ford

Let us begin by describing the sort of energy we are interested in. In this book, our emphasis will be on useful energy, energy that people apply to their purposes, like heat from a wood stove (Figure 1.1) or the energy derived from eating rice (Figure 1.2). Nowadays most of us buy our energy, although some people do split their own firewood. The energy *supply* is the amount that producers sell, like the 562 million tonnes[1] of oil that flowed from Saudi wells in 2017. The energy *demand* is the amount that consumers buy, like gasoline for a car and electricity to light a home. Energy sales are an important part of the economy, and for this reason most countries keep good energy statistics, although they often miss the energy that people generate for themselves, like the firewood they split and the electricity from home solar panels (Figure 1.3). For energy statistics, a useful publication is the BP *Statistical Review of World Energy*, which has been published annually by the oil company since 1951. In recent years, the *Statistical Review* has been a collaborative effort between the economics group at BP and the Heriot-Watt University Centre for Energy Economics Research and Policy. The *Statistical Review* is the most current, most consistent, and most accessible of the energy data sources. Measured in terms of the quantity of data, the US Department of Energy's Energy Information Administration (EIA) comes first. Often one can find arcane numbers in an obscure part of the EIA website that appear nowhere else. For agriculture, the best reference is FAOSTAT, the online database of the United Nations Food and Agriculture Organization, abbreviated FAO. Other energy data sources are listed in the Further Reading section at the end of this chapter. Studying these statistics can help one identify trends and gain perspective on energy issues. In energy, the past is often a good guide to the future and the trends may indicate whether a policy proposal is realistic or not. However, there can be unpredictable shocks because of wars, economic collapse, and new technology. For example,

[1] A tonne is a thousand kilograms. Technical language varies between countries, and this can be confusing. Much of the American energy literature uses the short ton, which is 2,000 pounds. Americans commonly write and say "metric ton" instead of tonne to distinguish it from the short ton.

Figure 1.1 A wood stove for heating a home. This stove, manufactured by the Morso Company in Denmark, produces 6 kilowatts of heat. It has an efficiency of 75%, that is, only a quarter of the heat is lost up the chimney. There is a secondary pre-heated air supply at the top of the fire box that reduces air pollution by making the burn more complete. A wood stove can save money. A 6-kilowatt electric heater might cost a dollar an hour to run. However, it is hard work to saw and split the wood. Photograph by the author.

Figure 1.2 A rice field in Japan. Rice provides one-fifth of the world's food energy. Like wood, rice is primarily made up of carbohydrates, and this gives it a similar energy density. The world food supply was reckoned by the United Nations Food and Agriculture Organization (FAO) in 2013 to be 2,884 food calories per person per day. Credit: Jason Hickey/CC BY 2.0, https://creativecommons.org/licenses/by/2.0/

Figure 1.3 A solar photovoltaic array for a home in the state of New Mexico. There are six panels with a capacity of 190 W each. The array is connected to the electrical grid, which supplies electricity when the sun is not shining. When the array produces more electricity than needed, the electric cooperative buys the surplus. Solar arrays provide electricity without noise or air pollution. The solar panels themselves have become inexpensive, but there are substantial costs associated with the installation and integration into the grid. Germany has been the world leader in solar panel installations, with a capacity of 500 watts per person in 2017. Photograph by the author.

the combination of hydraulic fracturing and horizontal wells, aided by the unusual American system of private mineral rights, has resulted in an astonishing increase in US oil and gas production.

Engineering calculations often start from the principle of energy conservation that is expressed by the First Law of thermodynamics. This law states that when energy is converted from one form to another, it is neither created nor destroyed. So what do we mean when we talk about producing or consuming energy? We are not talking about violating the First Law. Rather, it is an accounting convention where we track useful energy. Consider a computer that is supplied with 100 watts of electricity during an 8-hour workday. During that time electrical energy is converted in the computer to heat in the processor, light in the monitor, and sound in the speakers. That heat, light, and sound energy are no longer available for practical purposes, and we say that the computer consumed 800 watt-hours of electricity. For a production example, consider coal. Coal is a rock that formed over millions of years from plants that were buried by sediment. The energy in sunlight enabled the plants to grow, and heat and pressure in the earth drove the chemical processes that converted the plant remains to coal. When the coal is mined, it is available for burning, and we say that the energy produced is the combustion heat of the coal.

1.1 Plan of the Book

This chapter introduces ideas that we will encounter repeatedly. In the following chapter, we turn to historical energy sources that were important before the transition to coal, considering horses, whale oil, and wood. Then we study the major fossil fuels, coal and hydrocarbons. It is important to get a perspective on the factors that affect fossil-fuel resources and to appreciate the potential of new technology for fossil fuels. We will develop projections for the ultimate production of the fossil fuels.

Next we consider the food supply. Agriculture is both a significant consumer of energy in fertilizer production and a significant producer of energy through biofuels. Its most important impact is the enormous land area needed for agriculture. In some places, like Africa, the yield increase has not been sufficient to prevent significant deforestation. On the oceans, commercial fishing has put severe pressure on many fisheries. However, a transition to aquaculture is underway.

We will consider the role of each of the components of the electricity supply, starting with the fossil fuels and the traditional alternatives, hydroelectric and nuclear power. Many countries are now emphasizing the new alternatives: wind, solar, geothermal, and biofuels for new electricity capacity, so it is important to investigate how the new alternatives will affect the grid.

Stationary demand is industrial energy use, and lighting, heating, and cooling for buildings. The emphasis in many countries has been in making buildings more efficient. Usually the goal has been to reduce energy consumption, but the policy can also make homes more comfortable and make offices better places to work.

In transportation, oil is king, although electric vehicle sales are beginning. It is important to understand the differences between highway and rail networks as infrastructure, and between passenger and freight transportation systems.

We conclude with a discussion of climate change. In contrast to the technical solutions developed for air pollution, there is no quick way to reduce carbon-dioxide emissions from burning fossil fuels. Our discussion will consider the carbon cycle, sea level rise, and the temperature indexes. We will develop an estimate of the long-run temperature sensitivity to ultimate fossil-fuel production.

1.2 Units

The basic energy unit is the *joule*, abbreviated J. It is named after James Joule, an English physicist who in 1845 characterized the conversion of mechanical energy to heat energy. In his measurements, Joule spun a paddle wheel in a can of water. He found that this warmed the water and he measured the temperature rise. Expressed in modern units, the ratio was 4,400 J per kilogram of water per kelvin.[2] This amount of energy is the basis of the *food calorie*, abbreviated Cal. Food calories are used in food content labels in the United States, Canada, and Japan. The modern value of the food calorie is 4,184 J.

Many systems are characterized by how fast energy is produced or consumed. This quantity is the *power*. The unit of power is the watt (W), named after James Watt, a Scottish mechanical engineer who invented the first practical steam engine in 1765. A watt is one joule per second. The maximum transmitter power from cell phones is about a watt. There is also an energy unit that includes "watt" in the name. This is the watt-hour, abbreviated Wh. A watt-hour is the energy delivered by a 1-W source in an hour, or 3,600 J. It is common in media reports to confound watts with watt-hours. This is an easy error to make, but it marks the journalist and the editor as having a weak understanding of energy. We will use the watt-hour only for electricity.

For many energy discussions, both the joule and the watt are small units, and prefixes are applied to indicate larger amounts. The standard SI[3] unit prefixes are given in Table 1.1. Be careful to distinguish the "k" for "kilo" from the "K" for kelvin, the temperature unit. The larger units starting with "M" for "mega" are capitalized. One warning is that in energy writing, you will often see "M" or "m" for one thousand, and "MM" or "mm" for one million. Older dictionaries often show the pronunciation of the first "g" in "giga" as soft, like the word gigantic. However, most people now pronounce both g's hard, as in giggle, and newer dictionaries reflect this. Usually we choose the prefix that leaves the number between 1 and 1,000. For example, we would write 10 kW rather than 10,000 W or 0.01 MW. By convention 1 km^2 is not one thousand square meters but rather a square kilometer. In this book, we freely put prefixes in front of most units but not another prefix. So we write 1 G$ for a billion dollars and 1 Tm^3 for a trillion cubic meters, but 1.5 million km^2 for one million, five hundred thousand square kilometers.

The units we use are shown in Table 1.2. Standard SI units will be used for many calculations in this book. However, energy markets use many non-SI units. International oil prices are commonly quoted in US dollars per barrel. The barrel

[2] Joule expressed the result in British units: 817 foot-pounds per degree Fahrenheit for a pound of water. This amount is the basis for the Btu (British thermal unit), which is equivalent to 1,055 J. Joule's measurement was within 5% of the correct value.

[3] From the French, *Système International d'unités,* based on combinations of the meter, kilogram, and second and the prefixes.

Table 1.1 The standard SI unit prefixes.

Prefix	Pronounced	Meaning
y	yocto	10^{-24}
z	zepto	10^{-21}
a	atto	10^{-18}
f	femto	10^{-15}
p	pico	10^{-12}
n	nano	10^{-9}
μ	micro	10^{-6}
m	milli	10^{-3}
k	kilo	10^{3}
M	mega	10^{6}
G	giga	10^{9}
T	tera	10^{12}
P	peta	10^{15}
E	exa	10^{18}
Z	zetta	10^{21}
Y	yotta	10^{24}

Table 1.2 Units in this book. The abbreviation “p” for person is not standard, but it is convenient.

Symbol	Name	Type	Representative use	Equivalent
$	US dollar	currency	prices	
p	person	population	per-person demand	
H	hash	calculation	transaction validation	
lm	lumen	luminous flux	lamp ratings	
lx	lux	flux density	illumination	1 lm/m^2
°C	degrees Celsius	temperature	reference is freezing water	
°F	degrees Fahrenheit	temperature	annual cooling degree days	
K	kelvin	temperature	temperature changes	
J	joule	energy	basic energy unit	kgm^2/s^2
W	watt	power	basic power unit	J/s
N	newton	force	vehicle drag	J/m
Nm	newton-meter	torque	motor output	J/radian
Wh	watt-hour	energy	electricity	3,600 J/Wh
Btu	British thermal unit	energy	American energy statistics	1,055 J/Btu
Cal	food calorie	energy	food energy	4,184 J/Cal

Table 1.2 (cont.)

Symbol	Name	Type	Representative use	Equivalent
toe	tonne-of-oil equivalent	energy	fuel comparisons	42 GJ/toe
boe	barrel-of-oil equivalent	energy	fuel comparisons	7.33 boe/toe
hp	horsepower	power	motor and engine output	746 W/hp
rpm	revolutions per minute	frequency	motor and engine output	
l	liter	volume	gasoline consumption	1,000 l/m^3
m	meter	length	fundamental SI length unit	
km^2	square kilometer	area	land	10^6 m^2/km^2
m^3	cubic meter	volume	natural gas production	900 toe/Mm^3 (gas)
b	barrel	volume	oil production	7.33 b/t (oil)
kg	kilogram	mass	fundamental SI mass unit	
t	tonne, metric ton	mass	coal production	2 t/toe (world coal)
tC	metric tons of carbon	mass	CO_2 emissions	12/44 tC/tCO_2
Pa	pascal	pressure	atmosphere	N/m^2
V	volt	voltage	electrical circuits	
A	ampere	current	electrical circuits	
Ω	ohm	resistance	electrical circuits	V/A
F	farad	capacitance	electrical circuits	J/V^2
T	tesla	magnetic field	electrical machines	Vs/m^2
Hz	hertz	frequency	AC circuits	cycle per second
s	second	time	fundamental SI time unit	
h	hour	time	electricity production	3,600 s
d	day	time	food supply	24 h
y	year	time	energy production	8,760 h

unit goes back to early oil production in the state of Pennsylvania in the 1800s. It is a volume unit, equal to 42 gallons, or 159 liters. The barrel for whale oil was ten gallons smaller. Oil production may also be quoted in metric tons. The tonne is a unit of mass, and in practice, the density of different grades of oil vary enough that it may take anywhere from six to eight 42-gallon barrels to make up a tonne. We will follow the lead of the BP *Statistical Review* and convert at 7.33 barrels per tonne. The toe, or tonne-of-oil equivalent, is an energy unit equal to 42 GJ. It is useful for comparisons involving different energy sources. The energy density of mined coal varies considerably from mine to mine and from country to country. However, at the world level, the average energy density of mined coal has been relatively stable at 2 t/toe (tonnes per tonne-of-oil equivalent). There are several definitions for horsepower that differ slightly. When it matters, we will use the electrical horsepower that appears in electrical motor and generator ratings for calculations. It has the advantage that the conversion to watts is a whole number, 746 W/hp. The number of hours in a year that is not a leap year, 8,760, is a useful number to remember for converting annual electricity production to average power. In a leap year there are 24 more hours.

1.2.1 Capacity Factors

The power rating for a source is called the *capacity*, or often *nameplate capacity*, because it is common for a generator capacity to be given on an attached metal plate. Capacities vary widely. Each solar panel in the array in Figure 1.3 has a capacity of 190 W, while the Diablo Canyon Nuclear Power Plant in California has a capacity of 2.2 GW. The capacity is specified at standard testing conditions. For example, solar panels are tested in a strong light of 1 kW/m^2 with the panel cooled to 25 °C. However, a panel outdoors will usually be hotter than 25 °C when the sun is shining in the summer, and this reduces the output. For this reason, a solar panel may never actually achieve its power capacity in practice. The capacity of solar farms is often specified as the capacity of the electronic inverters that produce AC electricity for the grid, rather than the total nameplate capacity of the panels. Capacity is what a power company pays for when it buys a generator. However, in making comparisons, one should be aware that the average power from a source may be much less than the capacity. For example, a solar panel will have no output at night and reduced output on cloudy days. We define the *capacity factor* CF as

$$\mathrm{CF} \equiv P_a / P_c \tag{1.1}$$

where ≡ indicates a definition, P_a is the average power and P_c is the nameplate capacity. As an example we will calculate the capacity factor for the six solar panels in Figure 1.3. These have a capacity of 190 W each, or 1.14 kW for the entire array. In one year of production, the array produced 1.52 MWh. The average power is given by

$$P_a = 1.52\,\mathrm{MWh} / 8{,}760\,\mathrm{h} = 174\,\mathrm{W} \tag{1.2}$$

and the capacity factor is given by

$$\mathrm{CF} = 174\,\mathrm{W} / 1.14\,\mathrm{kW} = 15\%. \tag{1.3}$$

In practice the capacity factor of solar panels varies considerably with the location. A solar array in cloudy England may have a 10% CF, while the panels at the Kayenta Solar Facility shown on the cover of this book have a 23% CF. The solar panel CFs are low compared to most other generators. For comparison, the worldwide average CF for nuclear power plants is 80%.

The low capacity factor of solar panels is a fundamental limitation. We cannot command the sun to shine at night or push away clouds over a solar farm. The electrical utility will need to have capacity available to connect to the grid when the solar output drops. This extra capacity is often provided by natural gas generators. In this situation the natural gas generators are not competing with solar farms, but instead are complementary. This means that it may not be appropriate to compare the prices of generation from different sources calculated separately. Consumers are not looking for access to a particular solar farm when the sun is shining. They want continuous access to electricity. The high capacity factor for nuclear plants can also be limiting. The electricity demand varies during the day, and with their enormous steam boilers, nuclear plants are not able to follow this changing load. Generators sell electricity into markets where the prices vary dramatically during the day, even going negative at times. When prices are low, it is difficult for the owners of the nuclear plants who cannot turn them off.

1.2.2 Payback Times

In the United States, when a residential solar array is connected to the grid, the owner receives a federal income tax credit of 30% of the installation price. The utilities charge for the electricity supplied to the residence after the solar generation to the grid has been subtracted. This is called *net metering*. It is equivalent to allowing the electricity meter to run backwards. In net metering, people effectively receive the marginal retail price for the electricity their panels generate. The marginal retail price varies widely so that it may make sense to buy solar panels in some states and not in others. California has price tiers with marginal rates up to 40¢/kWh. However, in other American states customers pay flat rates with marginal prices closer to 10¢/kWh. If an array produces more electricity during a month than the house uses, the utilities may pay a much lower price based on their accounting of the savings in accepting the solar power. These *avoided costs* may be as low as 3¢/kWh.

In Europe the system is different. The utility pays the solar panel owners for the electricity they generate. The price is called the *feed-in-tariff*, or FIT. The FITs are set by the government. The FITs have generally been larger than the retail price, but they have been dropping over time. A major difference between the two systems is who pays. In the US, the main subsidy is the income-tax tax credit, so the burden falls primarily on the high-income taxpayers who pay the majority of income taxes.[4]

[4] In the US, the most important source of tax revenue is the federal income tax. In other countries the value-added-tax may be as important. The US does not have a national value-added-tax. In 2017, the top 20% of households in income, those who reported $150,000 or more on their tax returns, received 52% of the income and paid 87% of the income taxes. For more discussion, see Laura Saunders, "Top 20% of earners pay 87% of income tax" in the *Wall Street Journal*, April 6, 2018.

The effects may not be at all apparent in the utility bills that an American homeowner pays. In Europe the burden effectively falls on the neighbors who do not have solar arrays, and who are likely to have lower incomes than people who do.

We can evaluate a capital investment like a solar array by its payback time T in years, given by

$$T = I / r \tag{1.4}$$

where I is the investment net of subsidies and r is the annual money return after the operating costs are subtracted. For a homeowner, the return r for a solar array might be the reduction in electricity bills. Longer payback times indicate poorer investments, but it is hard to be specific about how short a payback time should be. If the equipment has a limited lifetime, the payback time should certainly be shorter than that lifetime. For example, the manufacturer specifies the performance of the panels in Figure 1.3 only out to 25 years. One should also realize that to be attractive, the return should be larger than the distributions for an alternative investment like stocks. For energy systems, the original investment is lost forever. This is different from stocks, which can ordinarily be sold later, often at a profit. In our examples, we will assume a 10-year payback time.

1.3 Efficiency

When energy is converted from one form to another, the useful output energy will be less than the input energy. This is an informal statement of the Second Law of thermodynamics. We write the *efficiency* η (the Greek letter *eta*) of the conversion as

$$\eta = E_o / E_i \tag{1.5}$$

where E_o is the output energy and E_i is the input energy. In this formula η does not have units, and it is typically expressed as a percentage. For example, for the wood stove in Figure 1.1, the input energy is the combustion heat, and the output energy is the heat that goes into the home. Some heat is lost up the chimney, and we can write an equivalent efficiency formula in terms of the lost energy E_l as

$$\eta = 1 - E_l / E_i \tag{1.6}$$

In some situations, the word efficiency is used in a less precise way. For example, people talk about improving the efficiency of a house by adding insulation in the walls and roof. We define a *thermal resistance* R_t, given by

$$R_t \equiv T / P \tag{1.7}$$