Cambridge University Press
978-1-107-01665-1 — The Physics of Energy
Robert L. Jaffe , Washington Taylor
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Part I

Basic Energy Physics and Uses

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CHAPTER

1

Introduction

Energy is a precious resource for humankind. Throughout history, technological ingenuity and heroic efforts have been devoted to the extraction of energy from moving water, coal, petroleum, uranium, sunlight, wind, and other **primary energy** sources. We hear constantly of the rate at which we "consume" energy – to power our cars, heat our homes, and wash our clothes. From a scientific point of view, however, energy is not lost when we use it. Indeed, the essence of energy is that it is *conserved*.

Energy is not easy to define – we return to this subject in §21 – but for now we observe that in any physical system free from outside influences, *energy* does not change with time. This fact is referred to as **conservation of energy**, and this is energy's most fundamental attribute. In fact, energy is important in science precisely because it is conserved. While it moves easily and often from one system to another and changes form in ways that are sometimes difficult to follow, energy can neither be created nor destroyed. It is possible to understand the behavior of most physical systems by following the flow of energy through them.

When we say casually that energy has been "consumed," what we mean more precisely is that it has been degraded into less useful forms – particularly into thermal energy that merely increases the ambient temperature. What exactly is meant by a "less useful form" of energy is a theme that plays an important role throughout this book, beginning with the introduction of the notion of *entropy* in §8, and continuing through the discussion of *exergy* in §36.

Energy is ubiquitous. We see it in the motion of the world around us – the flow of water, wind, and waves, the violence of volcanic eruptions and the intense activity of small animals – and we feel it in the warmth of the air and water in our environment. Most of the energy that powers organisms, ecosystems, and air and water circulation on Earth arrived here as solar radiation produced by *nuclear fusion* within the Sun. Just one hundredth of one percent (1 part in 10 000) of the solar energy that hits the Earth would be sufficient to supply all current human energy needs, if this energy could be effectively harnessed. Even greater quantities of energy are contained in the physical objects that surround us, as matter itself is a form of energy. From Albert Einstein's famous relation $E = mc^2$, it is easy to compute that the mass of a pair of typical pickup trucks ($\sim$2750 kg each) contains enough energy to power human civilization for a year. This type of energy, however, is impossible to extract and put to use with any current or foreseeable technology. (One would need a matching pair of pickup trucks made of *antimatter*.)

> **The Universe is Full of Energy**
>
> There is no shortage of energy in the world around us. Energy in solar radiation hits the Earth at a steady rate 10 000 times greater than the rate at which humanity uses energy. The challenge is to find practical and economical ways of channeling energy to human use from its natural state.

The energy problem, then, is not a shortage of energy, but rather a shortage of *usable* energy. The challenge for humanity is to identify mechanisms for transforming solar and other large repositories of available energy into useful forms in an economically and technologically practical fashion.

The flow of energy through human activities, from sources to end uses and through all the conversions in between, forms a complicated system with many interdependencies (see Figure 1.2). Understanding human energy use requires understanding not only each individual part of the energy system but also how these parts are connected. Physical principles place limits not only on how much

Figure 1.1 On Earth energy is at work around us all the time. (Waterfall image by Stefan Krasowski, hummingbird image by Brady Smith).

energy is available from each possible resource, but also on the efficiency with which energy can be converted from one form to another. For example, only about 25% of the thermal energy released in a typical automobile engine is actually used to power the car; the remainder is lost to the environment as heat. Understanding the physical limitations on energy conversion efficiencies helps to guide efforts to improve the efficiency of existing systems.

Beyond economic and technological limitations, there are also broader impacts associated with the use of energy from some sources. The burning of fossil fuels leads to emission of *carbon dioxide* (CO_2). Atmospheric CO_2 absorbs outgoing infrared radiation, affecting the global radiation budget and Earth's climate. Use of nuclear power generates radioactive waste and can lead to accidents in which substantial quantities of radiation and/or radioactive material are released into the environment. Mining and burning coal can have serious effects on human health and the local environment. Most renewable resources, such as solar and wind power, are relatively diffuse, so that large-scale reliance on these resources will require substantial land areas, potentially conflicting with other human activities and native ecosystems. Sensible energy choices involve a careful weighing and balancing of these

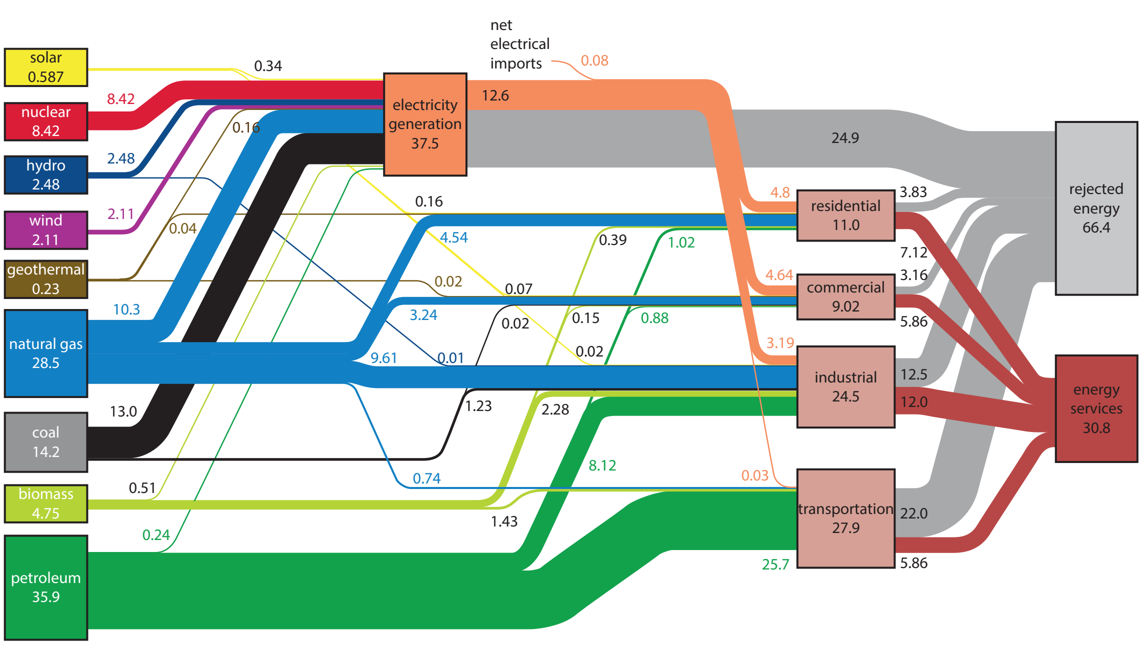

Figure 1.2 Energy flow from sources to end uses in the US for the year 2016. Many physical processes are involved in this complex flow. A substantial fraction of the energy extracted is lost. In some cases, physical principles limit the fraction of energy that can be transformed into useful form. The units in this figure are *quads*; see Table C.1 for translation of quads to other units. Redrawn from [11].

kinds of broader impacts and risk against the advantages of any given energy source.

The rate at which humanity uses energy has increased steadily and rapidly over the last century (see Figure 1.3). As population continues to grow, and per capita energy use increases, global demands on limited energy resources become more intense. Unless a dramatic, sudden, and unexpected change occurs in the human population or human energy use patterns, the quest for usable energy to power human society will be a dominant theme throughout the twenty-first century.

Many of the questions and issues related to energy choices are fundamentally economic and political in nature. To understand energy systems and to make rational economic and political choices regarding energy, however, requires a clear understanding of the science of energy. Without understanding how energy systems work, how they are connected, and the relative scope and limitations of different energy processes and resources, it is impossible to make informed and intelligent decisions regarding extraction, transformation, or utilization of energy resources on any scale large or small. This book is devoted to explaining the scientific principles underlying energy systems, with a focus on how these general principles apply in specific and practical energy-related contexts, and on the interconnections among the variety of terrestrial energy systems. Economic and political aspects of energy systems are generally avoided in this book.

1.1 Units and Energy Quantities

To engage in any meaningful discussion of energy, it is necessary to use a system of units for computation and communication. Reflecting its many forms, energy is perhaps the single quantity for which the widest variety of distinct units are currently used. For example, *calories*, *electron volts*, *British Thermal Units* (BTU), *kilowatt hours*, and *barrels of oil equivalent* are all standard energy units in widespread use. A summary of many different units used for energy can be found in Appendix C (see Table C.1), along with conversion factors, fundamental constants, and other useful data.

In this book we use the **SI** (**Système International**) unit system, known colloquially in the US as the **metric system**. This unit system is in general use throughout the world (except in Liberia, Myanmar, and the US) and is used globally for scientific work. It has the convenient feature that standard units for any physical quantity differ by powers of ten in a common fashion denoted by prefixes, so that even unfamiliar units are readily manipulated with a small amount of practice (see Table C.4).

Science, Economics, and Policy

The scientific, social, economic, and political aspects of human energy use are deeply interconnected. We put economics and policy aside in this book, not because these issues are unimportant, but because we believe that understanding the science of energy is a precondition for an intelligent discussion of policy and action.

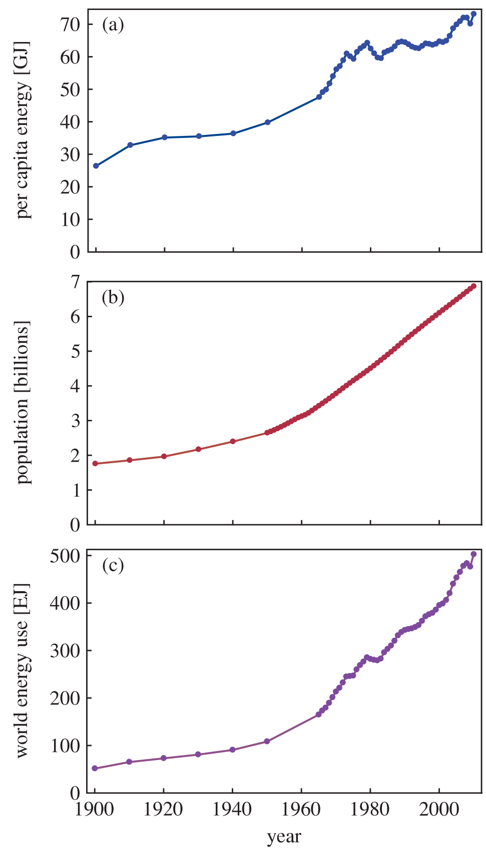

Figure 1.3 Graphs of (a) yearly global energy use per capita; (b) total human population; (c) yearly total global energy use, which is the product of the preceding two quantities. Data cover the last century, over which energy use per person has nearly tripled and population has quadrupled, giving a factor of twelve increase in total energy use. Data on population since 1950 from [8], energy use since 1965 from [9], estimates for earlier years from [5, 10].

Basic SI units for time, length, and mass are the *second*, *meter*, and *kilogram*. The **second** (s) is defined as the time required for a fixed number of oscillations of the electromagnetic wave emitted when a specific *quantum transition* (§7) occurs in a cesium atom. The **meter** (m) is *defined* so that the speed of light in a vacuum (§4) is precisely

$$c = 2.997\,924\,58 \times 10^8 \text{ m/s}\,. \tag{1.1}$$

The **kilogram** (kg) is a mass equal to that of a specific sample of material kept by the International Bureau of Weights and Measures in France, though this may change in the near future.

Given units of length, time, and mass, we can define the fundamental SI unit of energy, the **joule** (J),

$$1 \text{ joule} = 1 \text{ kg m}^2/\text{s}^2\,. \tag{1.2}$$

One joule is roughly equivalent to the *kinetic energy* (§2) of a tennis ball (mass $\cong 0.057$ kg) after falling from a height of 2 m.

Dimensional analysis is a useful approach to understanding qualitative features of many physical systems and relationships between quantities based on their unit structure. We denote the units associated with a given quantity by putting the quantity in brackets. For example, the units of energy are

$$[\text{energy}] = [\text{mass}] \times [\text{distance}]^2/[\text{time}]^2. \tag{1.3}$$

A *force* has units known as **newtons** (N); in terms of the basic units of length, time, and mass, $1 \text{ newton} = 1 \text{ kg m/s}^2$, and we write

$$[\text{force}] = [\text{mass}] \times [\text{distance}]/[\text{time}]^2. \tag{1.4}$$

Multiplying a force by a distance gives us a quantity with units of energy. This is one of the basic equations of elementary mechanics: *work* = *force* × *distance*. As we review in the next chapter, work represents a transfer of energy from one system to another.

Another important quantity in the discussion of energy is **power**. Power is the rate at which energy is used, or transformed from one form to another. It has units of energy per unit time,

$$\begin{aligned}[\text{power}] &= [\text{energy}]/[\text{time}] \\ &= [\text{mass}] \times [\text{distance}]^2/[\text{time}]^3. \end{aligned} \tag{1.5}$$

The SI unit of power is the **watt** (W),

$$1 \text{ W} = 1 \text{ J/s} = 1 \text{ kg m}^2/\text{s}^3. \tag{1.6}$$

It is important to keep units of energy distinct from units of power. For example, a refrigerator that uses electrical power at an average of 300 W will use roughly $300 \text{ W} \times 24 \text{ h} \times 3600 \text{ s/h} = 25\,920\,000 \text{ J} \cong 26 \text{ MJ}$ of energy each day. A popular unit of energy is the **kilowatt-hour** (kWh),

$$1 \text{ kWh} = (1 \text{ kW}) \times (3600 \text{ s}) = 3.6 \text{ MJ}\,. \tag{1.7}$$

> **SI Units**
>
> The SI international unit system is used globally in scientific work. Basic SI units include the meter, second, and kilogram. The SI unit of energy is the *joule* ($1 \text{ J} = 1 \text{ kg m}^2/\text{s}^2$); the unit of power is the *watt* ($1 \text{ W} = 1 \text{ J/s} = 1 \text{ kg m}^2/\text{s}^3$).

One further quantity that arises frequently in energy systems, and that illustrates the utility of dimensional analysis, is **pressure**. Pressure is a force per unit area acting at right angles to a surface. The units of pressure are also the units of energy per unit volume,

$$\begin{aligned}[\text{pressure}] &= [\text{force}]/[\text{area}] = \frac{[\text{mass}]}{[\text{distance}][\text{time}]^2} \\ &= [\text{energy}]/[\text{volume}]\,. \end{aligned} \tag{1.8}$$

The connection between force per unit area and energy per unit volume, which is suggested by their units, figures in the dynamics of gases and liquids (see §5 and §29). The SI unit of pressure is the **pascal** (Pa),

$$1 \text{ pascal} = 1 \text{ N/m}^2 = 1 \text{ kg/m s}^2. \tag{1.9}$$

One **atmosphere** (atm) of pressure is defined as

$$1 \text{ atm} = 101\,325 \text{ Pa}\,. \tag{1.10}$$

This is roughly the average pressure exerted by Earth's atmosphere at sea level.

The SI units for many other quantities, ranging from familiar ones such as temperature (degrees Centigrade or Kelvins) to specialized ones such as permeability (darcys), are introduced as the physics that requires them is encountered throughout the book.

1.2 Types of Energy

Energy is present in the world in many different forms. While chemical energy, thermal energy, mass energy, and potential energy may seem intuitively very different from the simple notion of kinetic energy of a falling tennis ball, they all represent a common physical currency. Each form of energy can be measured in joules, and, with less or more effort, each form of energy can be converted into every other form. Much of the first part of this book is devoted to a systematic development of the physical principles underlying the varied forms of energy and the application of these principles to understanding a variety of energy systems. We briefly summarize some of the principal forms of energy here and point forward to the chapters where each form is introduced and described in further detail.

Mechanical kinetic and potential energy Kinetic energy, mentioned above, is the energy that an object has by virtue of its motion. The kinetic energy of an object of mass m moving at a speed v is

$$\text{kinetic energy} = \frac{1}{2}mv^2 \,. \tag{1.11}$$

For example, the kinetic energy of a 3000 kg rhinoceros charging at 50 km/hour ($\cong$ 14 m/s $\cong$ 30 miles/hour) is roughly 300 kJ (see Figure 1.4).

Potential energy is energy stored in a configuration of objects that interact through a force such as the gravitational force. For example, when the tennis ball discussed above is held at a height of 2 m above the ground, it has potential energy. When the ball is released and falls under the influence of the gravitational force, this potential energy is converted to kinetic energy. Mechanical kinetic and potential energies are reviewed in §2.

Thermal energy Thermal energy is energy contained in the microscopic dynamics of a large number of molecules, atoms, or other constituents of a macroscopic material or fluid. Thus, for example, the thermal energy of the air in a room includes the kinetic energy of all the moving air molecules, as well as energy in the vibration and rotation of the individual molecules. Temperature provides a measure of thermal energy, with increasing temperature indicating greater thermal energy content. As an example, the thermal energy of a kilogram of water just below the boiling point (100 °C) is greater than the thermal energy at room temperature (20 °C) by roughly 335 kJ. Thermal energy is introduced in §5, and temperature is defined more precisely in §8.

Electromagnetic energy Electromagnetism is one of the four fundamental forces in nature; the other three are gravity and the strong and weak nuclear forces. (We give a short introduction to the four forces in §14.) Electrically charged particles produce electric and magnetic fields that in turn exert forces on other charged particles. Electromagnetic energy can be stored in a configuration of charged particles such as electrons and protons in much the same way that gravitational potential energy is stored in a configuration of massive objects. Electromagnetic energy can be transmitted through electrical circuits, and provides a convenient way to distribute energy from power plants to homes, businesses, and industries over great distances. More fundamentally, electromagnetic energy is contained in electric and magnetic fields, and can propagate through space in the form of electromagnetic radiation such as visible light.

A light bulb provides a simple example of several aspects of electromagnetic energy. A 100 W incandescent bulb draws 100 J of energy per second from the electric grid. This energy is converted into thermal energy by the electrical resistance of the filament in the bulb; the heated filament then radiates energy as visible light at around 2.6 W, and the remainder of the energy is lost as heat. By comparison, a compact fluorescent light (CFL) can produce the same amount of energy in visible light while drawing 20 to 30 W from the grid, and a light emitting

Figure 1.4 A charging rhino carries a lot of kinetic energy. Pushing a boulder uphill stores potential energy.

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Figure 1.5 Incandescent, LED, and fluorescent bulbs, all with roughly the same output of energy as visible light, draw 100 W, 16 W, and 27 W respectively from an electrical circuit.

diode (LED) emits roughly the same amount of visible light, but draws only 16 W (see Figure 1.5). We cover basic aspects of electromagnetism and electromagnetic energy in §3 and §4, including electromagnetic fields, charges, circuits, electrical resistance, and electromagnetic waves. Thermal radiation is described in later chapters.

Chemical energy Chemical energy is energy stored in chemical bonds within a material. The energy in these bonds originates in the electromagnetic interactions between atoms at the molecular level, which must be described in the framework of quantum mechanics. We introduce some basic notions of quantum mechanics in §7, and describe chemical energy in §9. A simple example of chemical energy is the energy contained in hydrocarbon bonds in food and fossil fuels. Most of the chemical energy in an apple or a liter of gasoline is contained in the bonds connecting carbon atoms within the material to other carbon atoms or to hydrogen atoms. When the apple is eaten or the gasoline is burned, this energy is released and can be used to power a person walking down the street or an automobile driving along a highway. The energy in a typical chemical bond is a few *electron volts*, where an **electron volt** (eV) is the energy needed to move a single electron across a one volt electric potential difference (electric potentials are reviewed in §3),

$$1\,\text{eV} = 1.602\,18 \times 10^{-19}\,\text{J}\,. \tag{1.12}$$

In contrast, the standard unit of energy in food is the **kilocalorie** (kcal) or **Calorie** (Cal), with 1 kcal = 1 Cal = 4.1868 kJ. Thus, consuming one Calorie of food energy corresponds to harvesting the energy in something like 10^{22} chemical bonds. One kilogram of apples contains roughly 500 Cal $\cong$ 2.1 MJ of energy, while one kilogram of gasoline contains roughly 44 MJ of energy. While the chemical bonds in these materials are similar, apples are about 85% water, which is why – among other reasons – we do not burn apples in our cars.

Nuclear binding energy Just as the atoms in a molecule are held together by electromagnetic forces, similarly the protons and neutrons in an atomic nucleus are held together by the strong nuclear force. Nuclear binding energies are roughly a million times greater than molecular bond energies, so typical nuclear processes emit and absorb millions of electron volts (10^6 eV = 1 **MeV**) of energy.

Small nuclei can fuse together, releasing energy in the process. *Nuclear fusion* in the core of the Sun combines four hydrogen nuclei (protons) into a helium nucleus, generating heat that in turn produces solar radiation. The part of this solar radiation that reaches Earth powers photosynthesis and drives biological processes and the dynamics of the atmosphere and oceans.

Larger nuclei, such as uranium nuclei, become unstable as the electromagnetic repulsion between charged protons opposes the strong nuclear binding force. Their decay into smaller parts – a process known as *nuclear fission* – provides a compact and carbon-free power source when harnessed in a nuclear reactor.

The ideas of quantum physics developed in §7 and §9 are elaborated further in §15, and used as the basis for understanding the physics of nuclear, solar, and geothermal power in later chapters.

Mass energy Mass itself is a form of energy. According to quantum physics, each particle is an excitation of a quantum field, just as a single photon of light is a quantum excitation of the electromagnetic field. It is difficult to convert mass energy into useful form. This can be done by bringing a particle in contact with an *antiparticle* of the same type. The particle and antiparticle then annihilate and liberate some of their mass energy as electromagnetic radiation and/or as kinetic energy of less massive particles that are products of the annihilation reaction. Antimatter is not found naturally in the solar system, however, so mass energy does not represent a practical energy source.

Einstein's formula gives the energy equivalent of a mass m,

$$E = mc^2\,, \tag{1.13}$$

where c is the speed of light from eq. (1.1). Thus, for example, the energy released when a proton (mass $M_p \cong$

1.67×10^{-27} kg) and an antiproton (of the same mass) annihilate is

$$E_{p+\bar{p}} = 2M_p c^2 \cong 3 \times 10^{-10}\,\text{J} \cong 1877\,\text{MeV}\,. \quad (1.14)$$

While irrelevant for most day-to-day purposes, mass energy is important in understanding nuclear processes and nuclear power. Because the energies involved in nuclear binding are a noticeable fraction of the masses involved, it has become conventional to measure nuclear masses in terms of their energy equivalent. The systematics of mass energy and nuclear binding are developed in §15 and §17, and eq. (1.13) is explained in §21.

The zero of energy Although we often talk about energy in absolute terms, in practical situations we only measure or need to consider **energy differences**. When we talk about the potential energy of a tennis ball held 2 m above the ground, for example, we are referring to the *difference* between its energies in two places. When we talk about the binding energy of an atom or a nucleus, we refer to its energy compared to that of its isolated constituents. So the proper answer to a question like "What is the energy of a bucket of water?," is "It depends." We return to this question in §9 (see Question 1.5). Situations (such as astrophysics and cosmology) in which an absolute scale for energy is relevant are discussed in §21.

1.3 Scales of Energy

As we study different energy systems through this book, it will be helpful if the reader can develop an intuition for energy quantities at different scales. Some energy systems function at a scale relevant to an individual human. Other energy systems operate at a scale relevant for a country or the planet as a whole. Still other energy systems are microscopic, and are best understood on a molecular or atomic scale. We conclude this chapter with a brief survey of some energy quantities characteristic of these scales.

Energy at the human scale Energies that a person might encounter in day-to-day life are generally in the range from joules to gigajoules (1 GJ = 10^9 J). The falling tennis ball discussed above has kinetic energy of 1 joule, while the average daily energy use for a US citizen in 2010 was roughly 1 GJ. The global average per capita energy use in 2010 was roughly 200 MJ/day. A number that may give a qualitative feel for human energy scales is the food energy eaten by a single person in a day. A 2400 Calorie diet corresponds to just over 10 MJ/day. Much of this food energy is used for basic metabolism – like the automobile engine that we discuss in the next chapter, our bodies can only transform a fraction of food energy (roughly 25%) into mechanical work. A manual laborer who works at a rate of 100 W for eight hours does just under 3 MJ of work per day (and probably needs more than 2400 Calories/day to comfortably sustain this level of output). One can thus think of modern technology as a way of harnessing the energy equivalent of 60 or 70 servants to work for each individual on the planet (200 MJ/3 MJ ≅ 66).

Scales of Energy

Some useful energy numbers to remember are (in round numbers, circa 2010):

10 MJ:	daily human food intake (2400 Cal)
200 MJ:	average daily human energy use
500 EJ:	yearly global energy use
15 TW:	average global power use

Energy at the global scale Energy quantities at the global scale are measured in large units like exajoules (1 EJ = 10^{18} J) or **quads** (1 quad = 10^{15} Btu = 1.055 EJ), and power is measured in terawatts (1 TW = 10^{12} W). Total world oil consumption in 2014, for example, was about 196 EJ. The total energy used by humanity in that year was close to 576 EJ. This represents a sustained power usage of around 17 TW. Energy flow through many natural systems at the global scale is conveniently measured in units of terawatts as well. For example, solar energy hits the Earth at a rate of roughly 173 000 TW (§22). The total rate at which wave energy hits all the world's shores is only a few (roughly 3) TW (§31.2).

Energy at the micro scale To understand many energy systems, such as photovoltaic cells, chemical fuels, and nuclear power plants, it is helpful to understand the physics of microscopic processes involving individual molecules, atoms, electrons, or photons of light. The electron volt (1.12) is the standard unit for the micro world. When an atom of carbon in coal combines with oxygen to form CO_2, for example, about 4 eV ($\cong 6.4 \times 10^{-19}$ J) of energy is liberated. Another example at the electron volt scale is a single photon of green light, which carries energy ≅ 2.5 eV. Photovoltaic cells capture energy from individual photons of light, as we describe in detail in §25.

Discussion/Investigation Questions

1.1 Given that energy is everywhere, and cannot be destroyed, try to articulate some reasons why it is so hard to get useful energy from natural systems in a clean and affordable way. (This question may be worth revisiting occasionally as you make your way through the book.)

1.2 A residential photovoltaic installation is described as producing "5000 kilowatt hours per year." What is a kilowatt hour per year in SI units? What might be the purpose of using kWh/y rather than the equivalent SI unit?

1.3 Try to describe the flow of energy through various systems before and after you use it in a light bulb in your house. Which of the various forms of energy discussed in the chapter does the energy pass through?

1.4 Give examples of each of the types of energy described in §1.2.

1.5 Discuss some possible answers, depending on the context, to the question posed in the text, "What is the energy of a bucket of water?"

1.6 Compare the global average rate of energy use per person to typical human food energy consumption. What does this say about the viability of biologically produced energy as a principal energy solution for the future?

Problems

1.1 Confirm eq. (1.14) and the estimate for the rhinoceros's kinetic energy below eq. (1.11) by explicit calculation.

1.2 How much energy would a 100 W light bulb consume if left on for 10 hours?

1.3 In a typical mid-latitude location, incident solar energy averages around 200 W/m^2 over a 24-hour cycle. Compute the land area needed to supply the average person's energy use of 200 MJ/day if solar panels convert a net 5% of the energy incident over a large area of land to useful electrical energy. Multiply by world population to get an estimate of total land area needed to supply the world energy needs from solar power under these assumptions. Compare this land area to some relevant reference areas – the Sahara Desert, your native country, etc.

1.4 The US total energy consumption in 2014 was 98.0 quads. What is this quantity in joules? About 83% of US energy comes from fossil fuels. If the whole 83% came from oil, how many tons of oil equivalent (toe) would this have been? How many barrels of oil (bbl) is this equivalent to?

1.5 The gravitational potential energy of an object of mass m at a distance h above ground is given by $E = mgh$. Use dimensional analysis to compute the units of g. What does this result suggest about the behavior of objects near Earth's surface?

1.6 The energy emitted or absorbed in chemical processes is often quoted in kilojoules per *mole* (abbreviated mol) of reactants, where a mole contains $N_A \cong 6.022 \times 10^{23}$ (*Avogadro's number*) molecules (§5). Derive the conversion factor from eV/molecule to kJ/mol.

1.7 The energy available from one kilogram of ^{235}U is 82 TJ. Energy is released when each uranium nucleus splits, or *fissions*. (The fission process is described in §16, but you do not need to know anything about the process for this problem.) 235 grams of ^{235}U contain approximately Avagadro's number (see Problem 1.6) atoms of ^{235}U. How many millions of electron volts (MeV) of energy are released, on average, when a ^{235}U nucleus fissions? How many kilograms of gasoline have the same energy content as one kilogram of ^{235}U?

1.8 The US total electrical power consumption in 2010 was 3.9 TkWh. Utilities try to maintain a capacity that is twice the average power consumption to allow for high demand on hot summer days. What installed generating capacity does this imply?