SUSTAINABLE ENERGY

SECOND EDITION

Richard A. Dunlap

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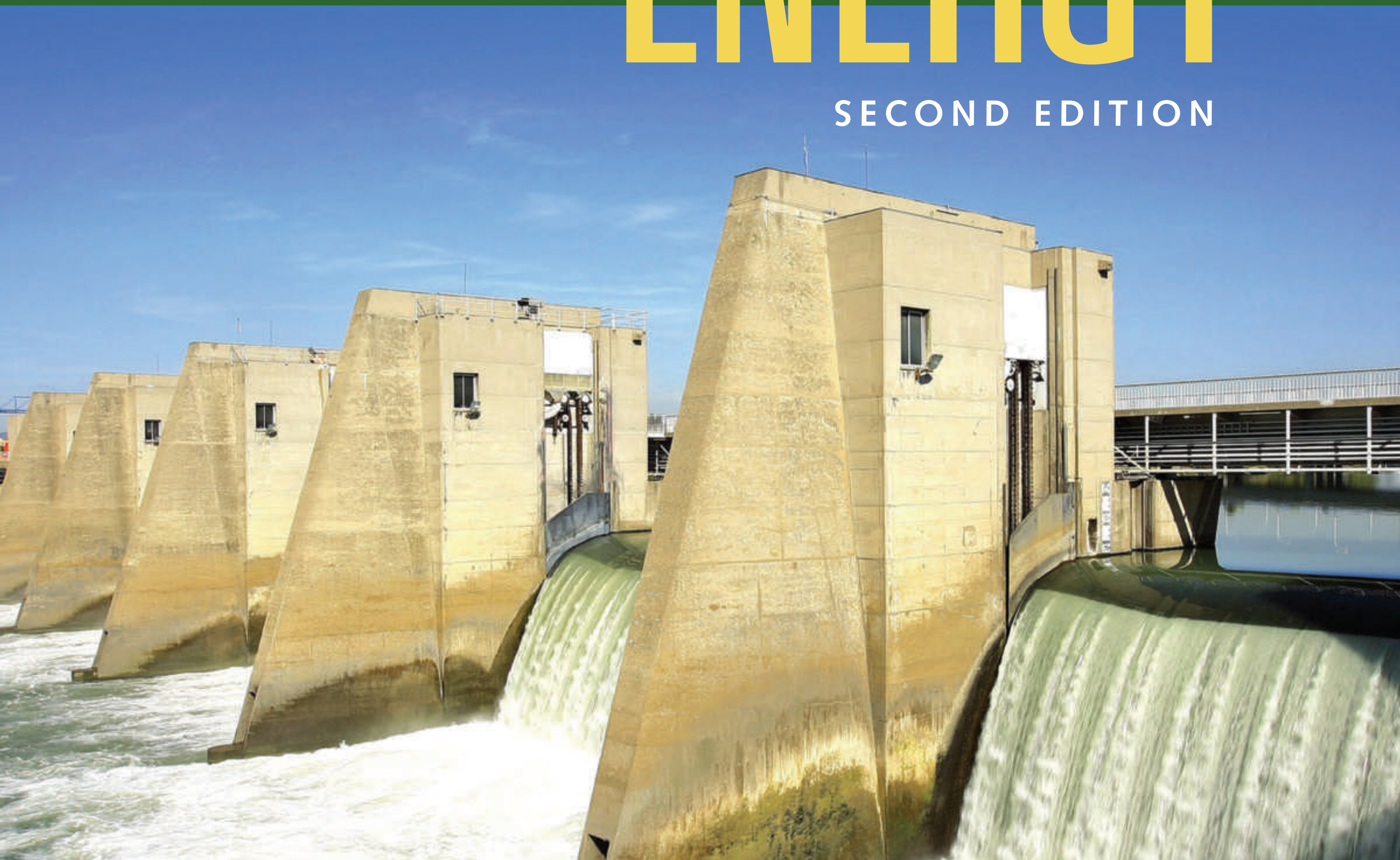

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In Memory of my Father

Robert Bennett Dunlap

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PREFACE

Our society uses substantial quantities of energy. This energy use amounts to about 6.1×10^{20} J, or 570 quads (1 quad = 10^{15} Btu), per year worldwide, or an average of 8.1×10^{10} J (or 7.7×10^{7} Btu) per year per person. Between 80 and 85% of the world's energy comes from fossil fuels, which are preferred because they are inexpensive (relatively speaking), are readily available (at least at present), and have a high energy density. As a result, an enormous infrastructure has been established for the location, production, and use of fossil fuels. The fuel of choice is oil because it is convenient, and the gasoline and diesel fuel it produces are portable and constitute our major source of fuel for transportation.

For the purpose of planning for methods to meet our future energy needs, it is important to begin by asking two questions: How long will our fossil fuel reserves last? Is it wise, from an environmental perspective, to continue to use fossil fuels?

The answers to both questions are not simple. The answer to the first question can be several tens of years or several hundreds of years depending on the conditions that are put on our fossil fuel use. Will fossil fuels continue to supply 80 to 85% of our energy needs? Will a fossil fuel–derived product be required to fulfill our needs for a portable transportation fuel? Perhaps most importantly, how much are we willing to pay for fuel? There is certainly some limit to how much we, as individuals, are willing or able to pay for the gasoline for our automobiles or for the oil or natural gas to heat our homes. However, it is important to realize that the cost of fuel is not only a financial cost. Producing fossil fuels in a form that is suitable for our needs requires energy input in order to undertake exploration to locate new fuel reserves, the extraction of the fuel from those reserves, and the subsequent processing of the fuel. If the energy needed to produce a liter of fuel is greater than the energy we obtain from burning it, then the process is not only economically unattractive but is ultimately not energy productive. If only the use of oil in the traditional sense, from known and economically recoverable reserves, is considered, then the longevity of fossil fuels will certainly be at the low end of the timescale. If coal and less traditional oil reserves are also considered, then the answer can be near the upper end of the timescale. This will be especially true if alternative sources are used to supply a substantial fraction of our energy needs.

The answer to the second question is also not straightforward. There is overwhelming evidence that the emission of greenhouse gases that results from the burning of fossil fuels has a severe impact on the environment. The magnitude and the timescale of this impact are not fully understood. If the use of fossil fuels continues for an extended period of time, then our willingness or even our ability to take steps to mitigate the effects on the environment are also unclear.

To ensure an adequate supply of energy in the future and to avoid causing a negative impact on our environment, it is important to understand how energy is utilized at present, our future energy needs, and the options for fulfilling these needs. Designing an appropriate energy structure for the future requires, not only a consideration of appropriate energy sources, but the implementation of suitable strategies to minimize energy requirements through conservation efforts.

In terms of our reliance on fossil fuels, two extreme approaches can be taken: to stop using fossil fuels now or to stop using fossil fuels when our supply is exhausted. The first approach would certainly minimize the environmental impact of fossil fuel use but would be impossible to implement because of our lack of infrastructure for the use of other energy sources. The latter approach would maximize the environmental effects and would best make use of the resources available. Whatever the final course of events, it is essential that steps toward eliminating our dependence on fossil fuel be taken immediately by developing and implementing alternative energy sources so that the environmental impact of our fossil fuel use is minimized. The latter would involve the reduction in greenhouse gas emissions by not only a reduction in fossil fuel use but also by processes such as carbon sequestration.

To put the magnitude of this task (however it is approached) into perspective, it is necessary to consider the current world power requirement of about 1.9×10^{13} W. In 50 years (roughly the time scale set by the recent Paris Agreement for a carbon neutral society), the world power requirement might be more than twice the current amount (primarily as a result of increased energy needs in developing countries). This is a rough goal that should be kept in mind when assessing the viability of any energy policy. These power requirements can be related to the output of a typical large electric generating station. These stations most commonly use fossil fuels (mostly coal and natural gas) to produce electricity and might have a typical output of about 10^9 W. The conversion to a nonfossil fuel energy economy on a timescale of about 50 years will require the construction of about $(4 \times 10^{13}\ \text{W})/(10^9\ \text{W}) = 40{,}000$ large replacement facilities (or a corresponding number of smaller facilities). These might be large nuclear power plants, large hydroelectric stations, or equivalent-capacity facilities utilizing solar energy, wave energy, wind energy, and other sources. This amounts to the construction of more than two major nonfossil fuel power stations every day for the next five decades. Clearly, this task requires a substantial commitment.

Sustainable Energy's Purpose

The textbook *Sustainable Energy* considers in detail our present and future energy needs, options for continued use of fossil fuels, and options for establishing an alternative energy economy. This text was developed out of a course entitled "Energy and the Environment" that has been taught in the Department of Physics and Atmospheric Science at Dalhousie University since 2003. This one-semester introductory course is aimed at undergraduate science and engineering students and is taught at the sophomore level. Most students have taken freshman-level chemistry and physics, and most have had some introductory calculus. These prior courses make a suitable prerequisite for a course taught from the present text. The course at Dalhousie is taught as a follow-up to a course on climate change to give students the overall picture of how humanity interacts with the environment, although this previous course is not a necessary prerequisite for a course taught from *Sustainable Energy*. Although such a course is intended to be introductory, there is enough technical detail that upper-level science or engineering will find it a useful and informative elective.

The purpose of this textbook is to fill a niche between a significant number of texts on similar topics at a very descriptive level intended for freshmen survey courses and a few advanced (and often fairly specialized) texts aimed at senior undergraduate or beginning graduate students in engineering. The textbook is useful for science and engineering students with an interest in energy-related matters, particularly those looking to pursue a professional career in a related field, to take an introductory energy course with some reasonable technical content. In addition to filling a mostly unfilled gap in the field, the present text also provides an up-to-date introduction to a fairly rapidly changing field.

Organization

This text begins with an overview of the basic science needed for the remainder of the book, as well as a summary of our past, present, and anticipated future energy needs. The technologies currently in use to meet our energy needs are described, and the need for the development of new energy technologies on the basis of future resource availability and environmental concerns is emphasized. The text includes a separate chapter on every future renewable energy technology that could be viewed as a viable option for the production of a significant portion of our energy needs. How these developing technologies can be integrated efficiently with existing technologies is discussed, as well as approaches to conserving available energy resources. Finally, the text considers options for perhaps our greatest energy-related challenge: transportation. The viability of any alternative energy technologies is determined by its ability to fulfill various criteria. The important criteria are described in this text by the acronym CURVE, for *c*lean, *u*nlimited, *r*enewable, *v*ersatile, and *e*conomical. This acronym makes it easy for students to appreciate how different technologies may, or may not, play an important role in our future energy production. The final chapter of the book summarizes the various alternative energy sources that have been presented and analyzes how these different technologies succeed or fail in satisfying the various CURVE criteria.

Throughout the text, the complexity of energy issues is emphasized, as is the need for a multidisciplinary approach to solving our energy problems. This approach provides students with an appreciation for the real problems that are encountered in the understanding of how we produce and use energy, as well as the realization that, while exact calculations are important and necessary, a broadly based analysis is often most appropriate. The text also stresses the fact that solutions to our energy problems, both now and in the future, are not straightforward and do not have simple, well-defined solutions, and that the way ahead is far from certain. The book contains enough material for a typical one-semester (12- to 14-week) course with about 20% excess material to allow the instructor some flexibility in course design. This coverage of material allows about 2–3 hours of lecture, on average, per chapter. Instructors may also focus on specific topics to provide a more in-depth picture of certain aspects of energy. This approach may include a more detailed and probing look at some of the topics presented in the Energy Extra boxes and may require the omission of other components of the text. Some chapters from the text can be covered in less detail and/or even eliminated. Chapters 7, 12, 13, 14, and 20 can be skipped with minimal effect on continuity. Certain approaches to sustainable energy may be more or less relevant from some national and/or regional perspectives and may warrant more or less detailed course coverage.

Finally, Chapter 21 acts as a summary of the ideas presented in the text and shows how they can be integrated into our approach to future energy production. This chapter includes a number of research and design projects that provide the student with the challenge of integrating information presented throughout the text to the solution of practical problem related to energy production and use. These projects give the student the opportunity to assess information and to make decisions about the most reasonable approach to energy production and use. Such decisions often involve a consideration of scientific, technological, environmental, and economic factors and illustrate not only the complexity but the multidisciplinary nature of sustainable energy.

Chapter Pedagogical Elements

- **Learning Objectives**. Each chapter starts with a bulleted list of learning objectives, making it very clear to both instructors and students what is covered in the chapter.
- **Examples**: The text includes numerous worked examples to provide the student with the basic approach to deal with end-of-chapter problems
- **Energy Extra Boxes**. Energy Extra boxes are included in nearly all chapters. These boxes provide insight into details of specific aspects of energy and often emphasize the complex nature of the decisions required to plan for our future energy needs. They also stress that ostensibly advantageous approaches to energy are often not as beneficial as they seem and that a critical analysis is necessary to understand all aspects of the topic.
- **End-of-chapter Problems**. The end-of-chapter problems are predominantly quantitative in nature. However, most are not straightforward calculations based on substituting values from the chapter into the appropriate formulas. The problems are designed to require the students to analyze information, to make use of material from previous chapters, to correlate data from various sources (not only from the textbook itself but from library, Internet, or other sources), and in many cases to estimate quantities based on interpretation of graphical data, interpolation of values, and sometimes just plain common sense.

New to This Edition

- Updated data tables and graphs with the most current information and developments.
- Doubled the number of end-of-chapter exercises for each chapter.
- Developed more than 30 new examples throughout the text.
- Added new Energy Extra boxes.
- Expanded coverage of alternative energy methods and feasibility analysis.

New additions to each chapter include:

Chapter 1: New content on diesel generators.
Chapter 2: Energy Extra box on rare earth elements.
Chapter 3: Added operation of an oil well, transport methods for oil and natural gas, and expanded application of the Hubbert model.
Chapter 4: Added discussion on acid rain and ocean acidification; added Energy Extra box on natural vs anthropogenic climate change, added new sections on methanol production from CO_2 and international climate change initiatives.
Chapter 6: Added Energy Extra boxes on Watts Bar Reactor, and thorium reactors and the Indian reactor program, expanded sections on fast breeder reactors.
Chapter 7: Expanded section on design of inertial confinement fusion reactors.
Chapter 8: Added Energy Extra box on evacuated tube solar collectors; and added section on transpired solar collectors.

Chapter 9: Expanded discussion of parabolic trough collectors; expanded section on central receivers; added section on solar ponds; added Energy Extra box on solar updraft towers.
Chapter 10: Added Energy Extra box on wind turbine safety.
Chapter 12: Added discussion on integrated wind/wave generation.
Chapter 13: Added discussion on Sihwa Lake Tidal Station.
Chapter 14: Added section on details of physical principles of ocean thermal energy conversion.
Chapter 16: Added section on biogas.
Chapter 17: Added Energy Extra boxes on cogeneration in Iceland and thermoelectric generators; expanded section on hybrid vehicles.
Chapter 19: Expanded section on commercial availability of battery electric vehicles.
Chapter 20: Added Energy Extra box on hydrogen storage in fullerenes; Expanded section on commercial availability of fuel cell vehicles.

Ancillaries

A variety of ancillaries are available to accompany this book to supplement your course. These supplements include:

- An *Instructor's Solution Manual*.
- *Annotated Lecture Note PowerPoint Slides*, which include suggestions for teaching the material in the book.
- Sample test items for instructors.
- Additional practice problems for students.
- *Image Bank* of figures and tables from the book.

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Would you prefer to easily create your own personalized text, choosing the elements that best serve your course's unique learning objectives?

Cengage's Compose platform provides the full range of Cengage content, allowing you to create exactly the textbook you need. The Compose website lets you quickly review materials to select everything you need for your text. You can even seamlessly add your own materials, like exercises, notes, and handouts! Easily assemble a new print or eBook and then preview it on our site.

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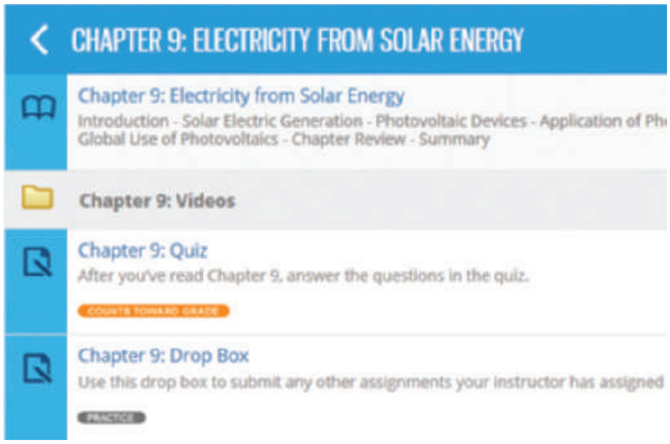

Sustainable Energy, 2e is also available with **MindTap,** Cengage's digital learning experience. The textbook's carefully-crafted pedagogy and exercises are made even more effective by an interactive, customizable eBook accompanied by automatically graded assessments and a full suite of study tools.

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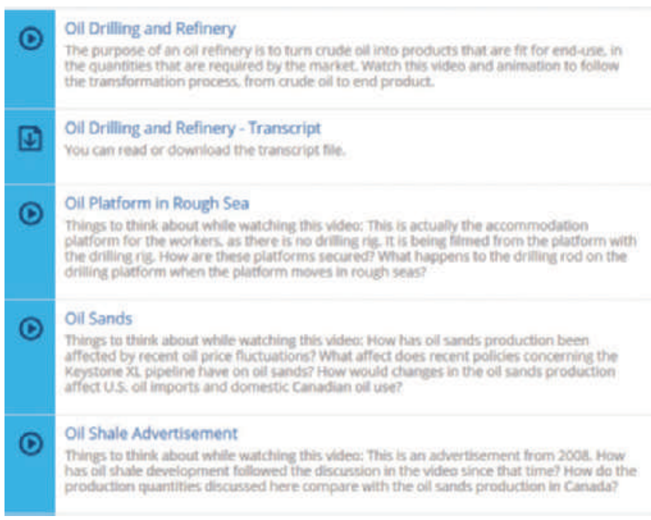

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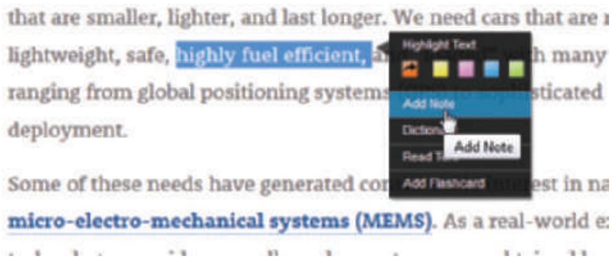

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PART I

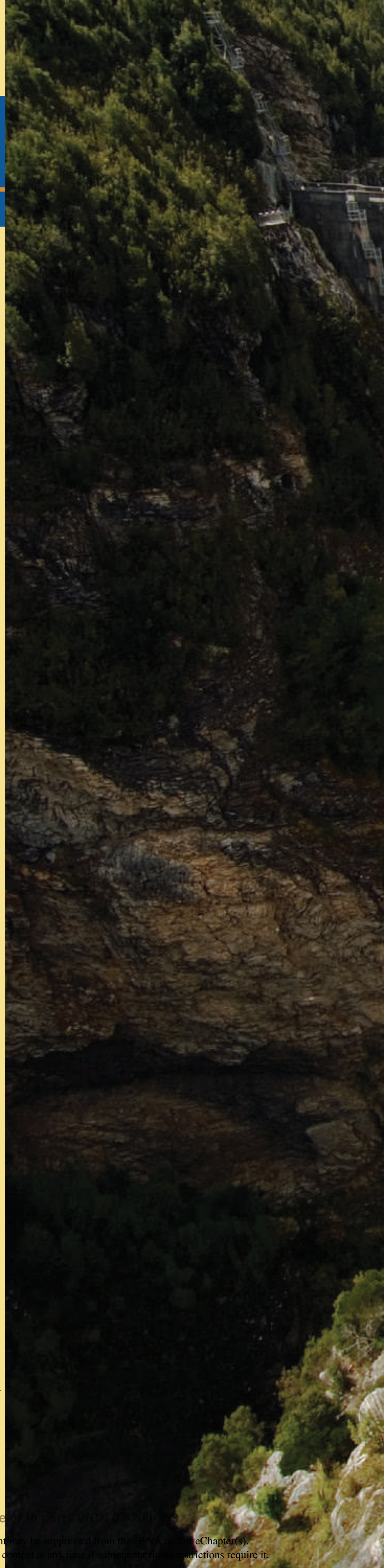
Background

Energy is an essential component of our daily lives. Throughout human history, our energy use has increased, and we now depend on a complex energy infrastructure to meet our needs for heating, lighting, transportation, and the production and distribution of all manufactured materials. Our increased energy needs have put increasing demands on the earth's resources and have had increasingly adverse effects on our environment. We are now at a stage of human development where our energy use must be critically analyzed to determine suitable future approaches to the production and use of this vital component of our lives.

Chapter 1 of this text begins with an overview of the basic scientific principles related to energy and a description of the quantitative scientific tools needed to analyze our energy use. This overview includes a summary of the various forms of energy and a quantitative description of the processes by which energy can be converted from one form to another. Also included is a survey of fundamental thermodynamics and a description of the basic principles of electricity distribution.

An overview of energy use throughout history is presented in Chapter 2. The chapter also provides the mathematical basis needed to assess future energy needs and a summary of the factors that need to be evaluated when considering possible future energy production methods.

The photograph at the beginning of this part of the text shows the Gordon Dam in Tasmania. This high head hydroelectric dam is 192 m long and 140 m high and has a maximum capacity of 432 MW_e. It became operational in 1978 and was one of the last major hydroelectric facilities to be constructed during an era of hydroelectric power development in Tasmania that began in the 1950s and continued until the 1980s. This trend in major hydroelectric development is paralleled in many other parts of the world. ■



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CHAPTER 1

Energy Basics

Learning Objectives: After reading the material in Chapter 1, you should understand:

- The relationship between energy and power.
- The forms of energy.
- The laws of thermodynamics.
- Heat engines and their Carnot efficiency.
- Heat pumps and their coefficient of performance.
- How electricity is generated and distributed.

1.1 Introduction

Energy may be categorized in different ways. One approach is to classify energy as either kinetic or potential. From a classical point of view, *kinetic* energy is merely the energy associated with the motion of a body. *Potential* energy may be described in terms of the nature of the interactions in a system. For example, gravitational potential energy arises from the gravitational interaction between two masses. The potential energy of water in an elevated reservoir may be converted into kinetic energy, which can be utilized to turn a turbine.

From a practical standpoint, however, it is convenient to describe the forms of energy according to how they are produced and utilized. It is also crucial to understand how one form of energy can be converted into another. In fact, when one says that energy is "produced" (e.g., by a nuclear reactor), one refers to the conversion of one form of energy that is not suitable for our needs (i.e., nuclear binding energy) into another form (e.g., electrical energy) that is more readily utilized. Energy that is extracted from our environment is *primary* energy; for example, chemical energy in the form of fossil fuels, kinetic energy in the wind, potential energy of water in a reservoir, or incident solar energy. To utilize energy, it is nearly always necessary to convert primary energy into a form that suits our needs. In this chapter, some of the basic physics of energy are explained, as well as the characteristics of some forms of energy and their conversions.

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1.2 Work, Energy, and Power

Energy, E, is defined as the ability to do work, W. *Work* is the consequence of the expenditure of energy and is defined as the product of a force, F, acting on an object times the distance, d, that the object moves. This relationship can be written as

$$W = Fd. \tag{1.1}$$

This expression assumes that the force acting on the object is a constant over the time during which the object moves a distance, d, and that the force is acting in the same direction as the displacement. The units of work are the same as the units of energy. In the metric system, the standard unit of energy is the *joule* (J) when the force is expressed in *newtons* (N) and the displacement in *meters* (m). In terms of fundamental metric units, the *joule* is equal to $kg{\cdot}m^2{\cdot}s^{-2}$. The British unit of energy, which is often used in engineering in the United States, is the *British thermal unit* (Btu, 1 Btu = 1055 J). The Btu is commonly used to designate thermal energy.

It is perhaps convenient to think of the concept expressed in equation (1.1) in terms of a mechanical system. An object with a mass, m, lying at rest on the floor exerts a force (the gravitational force), mg (here g is the gravitational acceleration), downward on the floor. The floor exerts a force, mg, upward on the mass (the normal force) that cancels out the gravitational force. The net vertical force on the object is zero, and, from Newton's law,

$$F = ma, \tag{1.2}$$

the acceleration is zero, and the object does not move. The work done is zero because the distance that the object travels is zero. If an external vertical force that is equal to (or greater than) mg is exerted on the object, then the object can be lifted from the floor. If the object is lifted to a height h, then the work done, from equation (1.1), is the force times the distance, or

$$W = mgh. \tag{1.3}$$

According to the law of conservation of energy, this work is converted into gravitational potential energy, also equal to mgh. The work done is independent of how long the process takes or of the path taken to reach height h. Because of this latter property, the gravitational force is said to be *conservative*.

It is sometimes convenient to deal with power rather than with energy or work. *Power*, P, is the rate at which work is done (or the rate at which energy is expended). Power is measured in *watts* (W), and the watt is defined as 1 joule per second. The British unit of power is *horsepower* (hp), where 1 hp = 746 W. Assuming that power is a constant in time, t, then the total energy utilized is

$$E = Pt. \tag{1.4}$$

This definition shows that $1\ W{\cdot}s = 1\ J$. Total energy is the power integrated over time so that producing (or using) 1000 W of power for 1 second represents the same amount of energy as producing (or using) 1 W of power for 1000 seconds. Equation (1.4) provides the basis for an alternative unit for the measurement of energy, the *kilowatt-hour* (kWh). The kWh is defined as the energy corresponding to a power of 1 kilowatt (1000 W) over a period of 1 hour (3600 s) so that $1\ kWh = (1000\ W) \times (3600\ s) = 3.6 \times 10^6\ J$.

Example 1.1

If a system produces 1 Btu of energy every minute, what is the power produced in watts?

Solution

One Btu is equivalent to 1055 J. If a Btu is released over a period of 60 seconds, then the energy per unit time in joules per second, which is equivalent to watts, is

$$P = E/t = (1055\ \text{J})/(60\ \text{s}) = 17.6\ \text{W}.$$

1.3 Forms of Energy

Energy can take on many forms:

- *Kinetic energy* (e.g., of a moving automobile).
- *Gravitational potential energy* (e.g., of water in a reservoir).
- *Thermal energy* (e.g., in a pot of boiling water).
- *Chemical energy* (e.g., stored in a liter of gasoline).
- *Nuclear energy* (e.g., stored in a gram of uranium).
- *Electrical energy* (e.g., used by a light bulb).
- *Electromagnetic energy* (e.g., that associated with a beam of sunlight).

As explained, these categories of energy are merely convenient ways of describing energy from different sources. They are not necessarily unique or mutually exclusive, nor is the list necessarily comprehensive. For example, thermal energy might be thought of as the microscopic kinetic energy of the molecules of a material. Both chemical energy and nuclear energy can be viewed as manifestations of the mass-energy associated with bonds in a material. However, these seven categories are a convenient way of defining the forms of energy from a practical standpoint.

To make use of energy, it is generally necessary to convert energy from the form in which it is obtained to a form that is compatible with our needs. For example, the stored chemical energy in a liter of gasoline can be converted to heat and then into mechanical energy to move a vehicle. Energy conversions are an important aspect of the utilization of any energy source, and the efficiency of these conversions is crucial to the viable utilization of the energy source. In any process, energy is always conserved. (In nuclear physics, the conservation of mass-energy, rather than the conservation of energy itself, is employed because there is an equivalence between these two quantities.) However, in any energy conversion process, all of the energy does not end up in the form needed. Each of these forms will now be discussed briefly.

1.3a Kinetic Energy

Kinetic energy is most obviously associated with moving objects. For an object of mass, m, moving at a velocity, v, the kinetic energy is

$$E = \frac{1}{2} mv^2. \tag{1.5}$$

In the metric system, m is in kilograms (kg), v is in meters per second (m/s), and the resulting energy is in joules ($\text{kg}\cdot\text{m}^2\cdot\text{s}^{-2}$).

Example 1.2

What is the kinetic energy associated with a 1500-kg automobile traveling at 100 km/h?

Solution

The velocity converted to m/s is (100 km/h) × (1000 m/km)/(3600 s/h) = 27.8 m/s. Using equation (1.5), the energy is given as

$$E = \frac{1}{2}mv^2 = (0.5) \times (1500\text{ kg}) \times (27.8\text{ m/s})^2 = 5.8 \times 10^5\text{ kg·m}^2/\text{s}^2 = 5.8 \times 10^5\text{ J}.$$

Kinetic energy is also associated with the rotational motion of rotating objects. The energy is given as

$$E = \frac{1}{2}I\omega^2, \tag{1.6}$$

where I is the moment of inertia of the object, and ω is its angular velocity. (The moment of inertia of an object and further details of rotational motion will be discussed in Chapter 18.) The moment of inertia is given in units of kg·m^2, and the angular velocity is given in units of s^{-1}. As before, the energy is measured in joules. Objects that have both translational motion and rotational motion have both translational kinetic energy, as given by equation (1.5), and rotational kinetic energy, as given by equation (1.6).

Example 1.3

A wheel in the form of a solid disk with a mass of $m = 400$ kg, a diameter of $d = 0.85$ m and a moment of inertia of $I = md^2/8 = mr^2/2$ rolls without slipping. The velocity of its center of mass is 30 m/s. This is a rough approximation of a wheel on a freight train. Compare the wheel's translational kinetic energy to its rotational energy.

Solution

From equation (1.5), its translational kinetic energy is

$$E_{\text{kinetic}} = \frac{1}{2}mv^2 = (0.5) \times (400\text{ kg}) \times (30\text{ m/s})^2 = 1.8 \times 10^5\text{ J}.$$

If the wheel rolls without slipping, then its angular velocity is related to the velocity of its center of mass, v, and its radius, r, because $\omega = v/r$. Substituting for ω and I in equation (1.6) gives

$$E_{\text{rotational}} = \frac{1}{2}\left(\frac{mr^2}{2}\right)\left(\frac{v}{r}\right)^2 = \frac{1}{4}mv^2.$$

Substituting these values,

$$E_{\text{rotational}} = \frac{1}{4}mv^2 = (0.25)\times(400\text{ kg})\times(30\text{ m/s})^2 = 9.0 \times 10^4\text{ J}.$$

Note that the rotational energy is independent of the wheel diameter and is exactly one-half of the translational kinetic energy. These features are basic characteristics of a solid disk that rolls without slipping.

1.3b Potential Energy

Potential energy is most conveniently thought of in terms of gravitational potential, as explained. The concept of potential energy also applies to other situations, such as the energy contained in a compressed spring. In the case of gravitational potential energy, an object of mass, m, at a height h has potential energy given by

$$E = mgh. \tag{1.7}$$

This potential energy can be converted into kinetic energy by allowing the object to fall through the distance h (assuming there are no drag forces), yielding

$$E = \frac{1}{2} mv^2 = mgh. \tag{1.8}$$

The velocity of the object may thus be calculated to be

$$v = \sqrt{2gh}. \tag{1.9}$$

Example 1.4

A 75-kg person walks up a flight of stairs with a vertical height of 3 m. What is the change in that person's potential energy?

Solution

From equation (1.7),

$$E = mgh = (75\text{ kg}) \times (9.8\text{ m/s}^2) \times (3\text{ m}) = 2.2 \times 10^3\text{ J}.$$

1.3c Thermal Energy

The *thermal energy* of a gas results from the kinetic energy of the microscopic movement of the molecules. Each molecule of gas has a kinetic energy associated with it that is given by equation (1.5), where m is the mass of the molecule, and v is its average velocity. It can be shown by applying ideal gas theory that the right-hand side of equation (1.5) can be expressed in terms of the temperature of the gas as

$$\frac{1}{2} mv^2 = \frac{3}{2} k_B T. \tag{1.10}$$

Here k_B is *Boltzmann's constant* with a value of 1.3806×10^{-23} J/K, and T is the absolute temperature in Kelvin (K) (more on this in Section 1.4). The total internal energy of a collection of gas molecules is obtained from equation (1.10) by multiplying the right-hand side by the number of gas molecules present. From a practical standpoint, it is convenient to deal with macroscopic quantities such as the number of moles of gas. Thus

$$E = \frac{3}{2} nRT, \tag{1.11}$$

where n is the number of moles of gas, and R is the *universal gas constant*; $R = N_A k_B = 8.315$ J/(mol·K). *NA* is *Avogadro's number* (6.022×10^{23} mol^{-1}).

It is sometimes convenient (particularly for solids and liquids) to describe changes in the macroscopic thermal energy of the material in terms of the *specific heat*, C, of the material. If a quantity of energy, Q, is supplied to a piece of material of mass, m, then its temperature will increase by an amount, ΔT, given by

$$\Delta T = \frac{Q}{mC}. \tag{1.12}$$

Materials with a large specific heat require a large amount of energy per unit mass to raise their temperature by a given amount. On the other hand, these materials are able to store large amounts of thermal energy per unit mass when its temperature is raised by a relatively small amount. (The utilization of these principles is discussed in detail in Chapter 8.) If a solid is heated to its melting point, then additional energy must be provided to melt it. This energy is used to break the chemical bonds holding the solid together and is referred to as the *latent heat of fusion*. The term *latent heat* is used to distinguish it from *sensible heat* because latent heat does not change the temperature of a solid. When a liquid is heated to its boiling point, then additional energy, the *latent heat of vaporization*, is needed to cause the material to undergo a phase transition and become a gas.

Example 1.5

The specific heat of water is 4180 J/(kg·°C). Calculate the energy required to heat 500 g of water from 20°C to 80°C.

Solution

Rearranging equation (1.12) to solve for the heat gives

$$Q = mC\Delta T.$$

Using $m = 0.5$ kg, $C = 4180$ J/(kg·°C), and $\Delta T = (80°C - 20°C) = 60°C$, then

$$Q = (0.5 \text{ kg}) \times [4180 \text{ J/(kg·°C)}] \times (60°C) = 1.25 \times 105 \text{ J}.$$

1.3d Chemical Energy

Chemical energy is the energy associated with chemical bonds, that is, the interaction energy between atomic electrons in a material. Energy can be absorbed or released during a chemical reaction as a result of changes in the bonds between the atoms. If a process requires energy to be input for the reaction to occur, then the process is referred to as *endothermic*. In general, these types of processes are not useful in the production of energy, although they can be useful in the storage of it. The dissociation of water (into hydrogen and oxygen) is of interest in this respect and will be discussed in more detail in Chapter 20.

Processes that release energy are referred to as *exothermic* and are of interest in this discussion. In general, oxidation reactions (i.e., the burning of materials) fall into this category. Some of the most relevant for the production of energy are reactions