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Ognjen Š. Miljanić and Joseph A. Pratt

Introduction to Energy and Sustainability

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Cover Image: © Jenson/shutterstock

Library of Congress Card No.:
applied for

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <http://dnb.d-nb.de>.

Print ISBN: 978-3-527-34540-3
ePDF ISBN: 978-3-527-81861-7
ePub ISBN: 978-3-527-81863-1

Cover Design ADAM DESIGN, Weinheim, Germany
Typesetting Straive, Chennai, India

Printed on acid-free paper

10 9 8 7 6 5 4 3 2 1

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Preface

Why study energy and sustainability? Why did we decide to write this book, and why do we think you should be reading it?

Energy is one of the key areas of human enterprise and it is so omnipresent that it is often taken for granted. It will sound like a cliché, but energy issues are everywhere around us. Fruits that you may have had for breakfast needed fertilizers (made with natural gas) to grow and were then harvested and transported to your local supermarket using diesel-powered machinery. Once at home, they had to be refrigerated – using electricity from a power plant – until you used them. Energy is consumed to power your daily commute, the lights in your home and classroom, the production of the very building materials from which those were built, and dozens of gadgets that a modern house has. Despite (or perhaps because of) this omnipresence, much of the population does not know where their energy comes from, what is it being used for, how much of it do they use, and how much pollution that use brings with it. This last point is growing into an ever-bigger problem as our energy utilization continues to increase, and such a large-scale production of energy brings large-scale emissions of carbon dioxide and other pollutants. These pollutants cause both acute health problems and long-term consequences in the form of accelerating climate change. Thus, a second focal point of this book will be sustainability: figuring out how to continue the progress of our civilization in a way which our planet, ecosystems, and society can bear in the future.

Energy systems are dynamic and constantly change. Wood was the dominant source of energy for most of our civilization. Then coal replaced it. Then oil replaced coal. Now natural gas and renewable energy sources may replace them both. Or not. Where will our energy come from in the future will depend on the economic, political, and technological choices that will be made. These choices will shape the answers to two fundamental questions: how severe will the impacts of climate change become and what can be done to reduce these impacts? Public policies toward energy and environmental issues will remain important topics to be debated, tested, and either discarded or embedded in energy and environmental laws around the world.

This textbook aims to capture the multidisciplinary and complex nature of modern energy and sustainability issues. As a topic, energy and sustainability are positioned at the intersections of traditional disciplines of natural and social sciences, law, and engineering. This interdisciplinary nature traditionally meant that a student of chemistry or economics would have invariably learned much about energy, but always in the form of side notes and footnotes to whatever the central topic of discussion was. This situation is changing nowadays, as many universities start to invert this paradigm, by creating new courses specifically focused on energy and sustainability. These courses bring in lessons from physics, chemistry, history, economics, engineering, architecture, and many other fields to explain the complex interplay between them in the context of energy and sustainability studies.

Our book is supposed to be a textbook for such courses. Together, we have taught a course entitled *Introduction to Energy and Sustainability* at the University of Houston since 2012. In it, we brought together our very different sets of skills and expertise – Pratt is a historian and Miljanić a chemist – to create a unique classroom experience which saw students from a broad variety of majors participate and learn on a very even footing. In doing so, all of them transcended their majors – and so did we as the teachers. It is our hope that this textbook, written with a balanced view of social, political, scientific, and engineering aspects of energy issues, will serve as an inspiration to many of our colleagues to do the same: start a course for which they felt 80% prepared, and learn the rest from our text.

Energy and sustainability are global issues and will only become more global in the decades to come. Our book will have as its primary focus the United States, but we will also discuss how other nations have responded to the challenges of balancing economic growth, environmental quality, energy security, sustainability, and social equity. In each part, we will choose nations that have been influential and original in global terms. For example, Brazil will be used to illustrate many of the issues related to biofuels. France will be the model on which we will study nuclear power, and Denmark will help introduce us to wind power. Japan's case will illustrate the issues associated with energy efficiency. We hope that this comparative perspective will prove quite valuable – as we in the United States have much to learn from other nations about the effective management of energy and environmental issues. The successes and failures of other nations can also help us understand the constrains that we will face as we pursue environmentally responsible policies in the context of the simultaneous pursuit of economic growth and the realities of democratic politics.

This book is divided into six broad parts. In the first, titled **Introductory Concepts**, we will introduce and define energy, sustainability, heat, work, and thermodynamics and put them on a comparative quantitative footing that will be utilized throughout the remainder of the text. Think of it as the primer of energy – no big stories just yet, but important letters and words that will help you understand the big stories later. The second part, **Energy Production Today**, will describe the technologies currently used to produce the bulk of world's energy: fossil fuels, nuclear energy, and hydroelectric power. We will follow this part with a discussion of how energy is consumed in today's industry, agriculture, and households in a series of chapters focusing on **Energy Consumption Today**.

The trends that we are witnessing today seem to suggest that something will need to change in the way we consume and produce energy. The motivation for these changes is found chiefly in the materializing threat of climate change, but also in the economics and income inequality that are associated with the current system of energy production, allocation, and consumption. This looming change will be examined in the pivotal part of the book, titled **Energy Transition**. The fifth and the sixth parts of the text will parallel the second and the third one. Entitled, respectively, **Energy Production Tomorrow** and **Energy Consumption Tomorrow**, they will examine the use of renewable and other nonemitting fuel sources as alternatives to fossil fuels, and the adaptation of our consumer habits to the world where energy is much more expensive and the environment significantly more fragile than it was in the twentieth century. All chapters will finish with practice problems. Some will have well-defined answers that you can often calculate; those will train you in treating energy and sustainability with quantitative tools. Others will be open-ended, discussion style questions. Those will be useful to spark classroom conversations, or stimulate you to read, research, and think about energy daily and independently.

Ognjen Š. Miljanić and Joseph A. Pratt
Houston and Colorado Springs, in the strange year 2020

Acknowledgments

This book would not have been in your hands were it not for the help, support, and advice of dozens of our colleagues, students, and friends. At our home institution of University of Houston, Prof. Ramanan Krishnamurthy was an unrelentless early supporter of our class and this book project from the very beginning, as was Prof. William Monroe in the latter stages of the project. Our editors Katherine Wong, Pinky Sathishkumar, and Lesley Jebaraj provided the logistical support and the occasionally needed gentle nudge throughout the writing of this manuscript. The marvelously talented Stephanie Romero prepared virtually all the diagrams and graphs in the book. Many of our colleagues, students, and friends provided insights and commented on parts of the book: Prof. Kasper Moth-Paulsen (Chalmers University of Technology), Prof. Šćepan Miljanić (University of Belgrade), Prof. Peter Vollhardt (University of California at Berkeley), the late Prof. François Diederich (Eidgenössische Technische Hochschule Zürich), Prof. Mircea Dincă (Massachusetts Institute of Technology), Dr. Anca Itul (Heidelberg Cement), Prof. Gail Buttorff (University of Houston), Jeremy Baines, Matt Lueck, Michelle Delaney (Neste US Inc.), Dr. Vojislav Srdanov (UC Santa Barbara), Chris Jones, Paul Sabin, and all of the students in our ENRG3310 course who read and commented on parts of this manuscript throughout the years. Shelby Roquemore had the grace and patience to help me in collecting data and photos during our 2019 Europe trip. The teaching assistants for this class – Jami Summey-Rice, Brooks Vasquez, Jacob True Furrh, Dania Fayad, and Maia Mendoza – were of invaluable help with their own suggestions and in collecting students' feedback. Josiah Cherian was a former student in the ENRG3310 class and later an assistant who proofread dozens of pages and collected statistical data for many figures in the text.

Also of great help were the New York University Abu Dhabi (UAE) and Ruprecht-Karls-Universität in Heidelberg (Germany), as well as the Max Kade and the Alexander von Humboldt Foundations, who all allowed Ognjen Š. Miljanić to spend some time away from Houston and focus on the writing of this book. Research Corporation for Science Advancement and Dr. Silvia Ronco – its Senior Program Director – have been of invaluable financial and moral support during this project.

Finally, our families have been both encouraging and very patient with us over the years and months of working on this project, and we owe them our deepest gratitude.

Part I

Introductory Concepts

1

Brief History of Our Relationship with Energy

Since the very beginnings of civilization, humans used energy to power their daily activities. The history of humanity runs parallel with the history of its energy use: as our civilization and population grew, so did our energy usage. Ancient empires fell and gave rise to new ones, and the sources of energy used to power these empires continuously evolved; occasionally, revolutionary advances propelled humanity into a new era. Perhaps the most famous of these shifts was the **Industrial Revolution**, which took place in the second half of the eighteenth century and is associated with James Watt and the introduction of the coal-powered steam engine. However, Industrial Revolution was not the only significant energy transition in human history: many other revolutions preceded and followed it. History of energy is thus very much a history of **energy transitions**. In fact, we are presently finding ourselves in the middle of one such transition: as the environmental consequences of high usage of fossil fuels become more and more dramatic, we are seeking to transition away from them toward energy sources with lower carbon dioxide emissions.

Earth, our home, is 4.5 billion years old. Formed by the accretion of the solar nebula – a disc-shaped cloud of gas and dust left over from the formation of Sun – it slowly cooled and eventually became habitable for life. The process of Earth's formation gave rise to some sources of energy that we use today. Geothermal heat, which we will cover in Chapter 24, stems in part from the leftover heat trapped under the Earth's crust in the process of planetary formation. The uranium and thorium nuclear fuels, which we will return to in Chapter 11, are also as old as the Earth itself – they presumably originated in the explosion of a supernova that gave rise to the material that formed our solar system.

Humanoids like modern-day humans showed up very recently in this long planetary history: they first appeared a mere 2 million years ago in eastern Africa. If the entire 4.5-billion-year history of our planet was condensed into a 24-hour time span, humans would have emerged slightly after 11:59 p.m.! From there, they spread through the remainder of the African continent, and later – through the modern-day Arabian Peninsula – into Eurasia. America was reached last, via the then-frozen Bering land bridge to northeastern Asia, possibly as late as 20 000 BCE.

For a very long period of our history, our ancestors powered all their daily activities using only the energy provided by their muscles. This energy in turn came from digested food. The first major change in this energy consumption pattern – and consequently human civilization – came approx. 500 000 years ago, when our prehistoric ancestors learned to

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control fire. Wood-burning fires allowed them to cook meat and increase their caloric intake, to keep warm during cold spells and at night, and to ultimately manufacture simple tools. With the subsequent domestication of first crops – grains and peas – humans could move away from the hunter-gatherer lifestyle and form more permanent settlements, but also needed more energy to cultivate crops. Most of this energy was provided by the Sun, and some came from human muscles pulling the plows.

The next big jump in our energy consumption came with the **domestication of animals** to be used for work (Figure 1.1). Oxen were domesticated first around 9000 BCE in India and the Middle East. Donkeys (5000 BCE, Egypt), horses (4000 BCE, in Eurasian steppes), and camels (around 3000 BCE, in Somalia and southern Arabia) followed. All these animals were stronger than humans and their usage translated into faster, deeper plowing and higher yields per unit of area. In this early era, domesticated animals were not used as a source of meat nearly as much as they are today – they were too valuable to be simply eaten. Instead, they were needed for labor, milk, cow dung (which was used as fuel), and their hides. Increased use of farm animals allowed the production of more food, increasing human population. More humans required more crops to be grown, which led to further increases in the need for domesticated animals, which in turn needed to be fed too – soon creating a virtuous circle.

The next significant benchmark was the use of wind energy to power transportation, in the form of **sailing ships**. First sailing ships have been documented in Egypt and Phoenicia (present-day coastal Lebanon) around 4000 BCE. These were also the vessels

Figure 1.1 Early prehistoric depictions of ancestors of domesticated horses, found in a cave near Lascaux, France. Domestication of horses and other farm animals helped our ancestors cultivate fields and transport goods. Source: Patrick Janicek, licensed under the Creative Commons Attribution 2.0 Generic license.

capable of transporting many people and significant amounts of cargo, allowing trade and warfare across the Mediterranean. Sailing ships persisted as an important form of transportation until the nineteenth century and were quite efficient in their usage of wind energy – comparable and occasionally better than the modern-day wind turbines. It was this form of energy that allowed the creation of colonial empires and the transfer of goods from one side of the world to the other: the very first seeds of **globalization** (Figure 1.2). Wind also brought Europeans in contact with advanced kingdoms in parts of the world previously unknown to them: Aztecs, Mayas, and Incas in the Americas, or Kongo and Zimbabwe in Africa, to name just a few. Conflicts soon ensued, almost uniformly ending with European military conquests of these nations and ushering in the age of colonial expansion. Wind energy continued to be used on land as well, to power windmills and to pump water.

Pause here for a minute and reflect on the fact that the vast Roman, Mongol, and Spanish empires were built on just three sources of energy: wood, domesticated animals, and wind! All three of them were what we today call **renewable sources of energy**, even though most of the forests cut down in those days were not actively replenished. It was another empire – the British empire – that required a new source of energy. As population growth, industrialization, and maritime trade started significantly depleting British forests, coal became a useful and apparently inexhaustible alternative to wood. The steam engine, made practical in the 1770s by James Watt, accelerated the ascension of coal, a **fossil fuel**, into Britain's most significant energy source. Combustion of coal in the steam engine produced pressurized steam, which could be used to mechanically move pistons of

Figure 1.2 Portuguese explorer Ferdinand Magellan (c. 1480–1521) was the first to circumnavigate the globe in the years before his death. Wind-powered *Victoria*, featuring prominently in this map of the world, was the sole ship of his expedition to complete the journey, opening a new era of colonial expansion of Portugal and other western European powers. Source: Ortelius's map (1590), in public domain because of its age.

Figure 1.3 Coal-powered trains are one of the enduring images of industrialization. Today, however, they are increasingly a tourist attraction: even trains transporting coal to power plants run on – diesel. Source: Pixabay.

an engine. The development of railways followed shortly (Figure 1.3), leading to the creation of an internal transportation infrastructure that could move people and cargo on land. The abundance of coal in Britain allowed the country to become the first true industrial power in the world, spreading its economic and military influence across the globe. However, the mining, transportation, and combustion of coal brought with it the pollution, which was significantly worse than that coming from wood. The beginnings of the Industrial Revolution in Britain were associated with the first concerns about the environmental effects of high energy use.

The beginning of the twentieth century brought two significant advances into the world of energy. First, in the early 1900s, the inventions of Tesla, Westinghouse, and Edison allowed the production and commercial distribution of electricity, opening the way to a myriad of electric appliances we use today. Broad **electrification** became a quick way for countries to industrialize and modernize – a trend that was dramatic in the 1930s' Soviet Union and is currently ongoing in China, India, and many developing countries (Figure 1.4). The second technological leap occurred in 1908, when Henry Ford opened the first production assembly line that mass-produced the now-iconic Ford Model T. While cars existed before Ford, they were expensive, slow to manufacture, and often impractical. The creation of Model T led to a fast increase in the ownership of cars – *individual transportation engines* – and the creation of a complex road infrastructure that we know today. Use of personal automobiles also vastly increased the demand for oil and its light gasoline fraction. Before the advent of the automobile, oil was exploited mostly as a source of lighting fluids: a more reliable and cheaper fuel than the whale oil that dominated the lighting industry before it. The rapid growth in oil consumption accelerated with the creation of airplanes in 1903 and the increased switch to diesel fuel in railway transportation and shipping.

Figure 1.4 Our modern quality of life was largely enabled by the increased use of energy in the form of electricity. Mass electrification begun in the early twentieth century and is still ongoing in some countries. Source: Pixabay.

The middle of the twentieth century saw the development of **nuclear power** – an incredibly concentrated source of energy coming from the atomic nucleus. The first use of nuclear energy was destructive, in the form of the atomic bombs the United States dropped on the Japanese cities of Hiroshima and Nagasaki. However, since the 1950s, nuclear energy was used only peacefully: as a source of electricity that does not generate carbon dioxide and other pollutants. Nevertheless, nuclear energy continues to face strong environmental opposition because of its association with nuclear weapons and the generation of radioactive waste products that must be properly disposed and present a security concern. Additionally, the public worries about the capacity for very rare, but catastrophic accidents, such as the 1986 Chernobyl explosion in the USSR or the 2011 failure of reactors in Fukushima (Japan) because of a tsunami. In the twenty-first century, modern nuclear reactors are again considered as a viable alternative to fossil-fuel-powered electricity generation plants, as they do not emit greenhouse gases.

In parallel with the expansion and diversification of our energy supply, the last 50 years have witnessed increased awareness among the governments and public about the potential pitfalls of using large amounts of energy, especially that derived from fossil fuels. Prolonged smog (Figure 1.5) episodes in the London of 1950s and 1970s' Los Angeles, as well as the rare but dramatic nuclear accidents have largely been responsible for the increased understanding and concern among the citizens about the consequences of their energy use. Modern environmentalist movements were born, and regulatory responses to pollution crises soon followed. This "age of awareness" brought with it the concepts of recycling, energy conservation, and increased research aimed at large-scale commercialization and installation of alternative energy sources: solar, wind, biomass, and geothermal. These sources of energy are not relying on our finite fossil fuel deposits and are thus called renewable fuels. In addition, they do not emit traditional pollutants responsible for poor air quality, nor carbon dioxide responsible for global warming. The concept of **sustainability** was born. As the human society continues to grow in complexity, population, and economic output, more and more attention is needed to ensure that such development considers and preserves the natural resources: fuels, but also our and our descendants' rights to clean air, water, and soil.

In the early years of the twenty-first century, world's energy landscape is once again undergoing profound changes. Centers of energy consumption and pollution are shifting from the developed to the developing countries, who are trying to avoid the costly mistakes made by the now-developed countries during their industrialization one or two centuries ago. Fuel mixture is changing too: once-dominant coal has been dethroned by the cleaner

Figure 1.5 Smog, shown here in Hong Kong, is one of the many undesirable effects of our massive energy use. Fossil fuels are especially problematic, but even renewable sources of energy can have questionable environmental consequences when deployed on a huge scale. Source: Andrea Piacquadio, via Pexels.

Figure 1.6 Our century is seeing an accelerating shift from using the fuels buried deep within Earth's interior to producing energy from sources that replenish themselves day after day – such as wind, solar, and biomass. Source: Yves Bernardi from Pixabay.

natural gas as the main fuel for electricity generation in the United States. Renewable energy sources (Figure 1.6) are coming down in price and increasing in their market share. And many of these changes are driven by the fear of accelerating climate change, caused by the unrestrained emissions of carbon dioxide into the atmosphere by fossil fuel combustion.

This book will delve deep into the incredibly diverse fields of energy and sustainability. In the first half of it, we will offer the reader a broad perspective of the ways we produce and consume energy today. We will talk about fossil fuels, nuclear energy, and hydroelectric power and will analyze energy consumption patterns in the fields of electricity generation, transport, industry, agriculture, as well as in the residential sector. The second part of the book will discuss the technologies that will become more relevant in the future energy production and consumption patterns. Between the two, we will build a case for the transition between the fuels of the present and the future.

Before all this, we need to learn how to describe, quantify, and measure energy, sustainability, and the related physical quantities.

1.1 Discussion Questions

1.1. Imagine how our energy consumption patterns would look today if there was no oil. What if there was no natural gas? Repeat this analysis, excluding, one by one, all the fuel sources we currently use.

1.2. Find the earliest examples of global efforts that aimed to tackle a problem associated with pollution. Which have succeeded and which have failed?

1.3. Find examples, both old and new, of popular books, songs, or works of art that touch upon energy issues. Are any of them intended for children, or are they only for adults?

1.4. Poll your friends and relatives with some simple energy-related questions. Where does electricity come from? How is it produced? How much carbon dioxide does their car generate? What is carbon dioxide and what does it do to you? Do their answers surprise you?

1.5. Research the closest power plant to the place where you live. Which fuel does it use and what is its generating capacity?

Further Reading

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2

Defining and Quantifying Energy

What do we mean when we say the word "energy"? The word itself is certainly used (and maybe overused) in everyday conversation. We speak of "not having enough energy," "good energy," "feeling energized," but also about "energy crisis," "alternative energy," or "clean energy." Modern physical definition of energy is **the capacity to do work**. This is in fact quite close to our intuitive understanding of the concept of energy and brings about the important equivalency between energy and work. Work is simply the energy that is expressed in a visible, useful, **mechanical** form: work is making something move. A gallon of gasoline contains energy, but until we burn it and use it to move a car, we are not directly aware of it.

Energy is a physical quantity which can be measured and quantified. Energy is also a commodity of extreme importance to our society; being able to quantify it allows its trade, taxation, and regulation. Section 2.1 will show how to define and measure energy, as well as how to connect it to other physical quantities.

2.1 International System of Units

Measurement of physical quantities is almost as old as the human civilization. First, sophisticated systems of measurement were developed approximately 4000 years BCE in societies in ancient Egypt, Mesopotamia, and the Indus valley. Today, we measure a large set of physical quantities; our ancestors focused on just a handful of them which were relevant to agriculture and trade. **Time** was measured by relating it to the motions of the Sun, the Moon, and the significant stars, while the **length** of objects was most commonly measured by relating it to the human body (e.g. a forearm, finger, foot) or our ability to travel (e.g. a day of walking). **Weight** and **volume** measurements were frequently related to gourds, seeds, or stones. Some of the units of measurement from this ancient age still persist: *carat* – the unit of weight used to measure jewels – comes from the carob seed, which was once a unit of volume.

Because of the regional variations in plants, seeds, and human stature, these ancient measurement systems produced a bewildering array of units to describe these four quantities. Most of these units are today forgotten, but by reading a classic novel, you will learn of Russian *verstas* (1.0668 km), Turkish *arşins* (69 cm), Scandinavian *alens* (60 cm), Spanish *canas* (1.57 m), American *furlongs* (201 m), and French *lignes* (2.2558 mm). All of these and

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numerous others were units of length alone! Each of these regional units was highly important to the local transactions, but their importance would diminish with distance. As an example, the German town of Speyer had its own unit of measurement – called the Shoe of Speyer and equaling 28.899 cm – until the nineteenth century. Such was the importance of this unit, that the Old Gate of the town had an iron bar attached to it with the exact length of the Shoe of Speyer, which local merchants could use for calibration (Figure 2.1).

The development and globalization of science, engineering, and international trade created a need to standardize units of measurement for easy comparisons across countries. The final outcome of these efforts was the **International System of Units**, abbreviated SI from French *Le Système International d'Unités*. Fully completed in 1960, the SI system grew out of the older **metric system**, which itself was adopted during the French Revolution. The two terms are in fact used somewhat synonymously even today.

The SI system is used universally, with one important exception: the United States still largely uses the customary system of British imperial units, even though the US Congress decided in favor of metrification in 1975. In addition to the United States, Liberia and

Figure 2.1 The calibration standard for the Shoe of Speyer – a now abandoned unit of length – is attached to the old Town Gate in the German town of Speyer. Source: Ognjen Miljanić.

Myanmar are the only two countries not using the metric system, while the United Kingdom, Canada, and India still retain some remnants of the old British imperial measuring system. In many other countries, the metric system is the law of the land, but some ancient units are occasionally used in informal transactions. In this book, we will use the SI system of measures, with the US units (if different) following them in parentheses.

International System of Units standardizes units for all commonly used physical quantities. It is based on seven basic units, from which all others are derived. The seven basic units are:

Meter (m), which is a unit of **length (*L*)**. In the United States, a meter is not used in everyday life; instead a **foot** (abbreviated ft; 1 ft = 0.3048 m) and a **yard** (abbreviated yd; 1 yd = 0.9144 m) are more common units. For measuring longer distances, **miles** are commonly used in the United States; 1 mile has 1609 m.

How big is a meter? Rigorous scientific definition of a meter is: *the length of the path traveled by light in a vacuum in a small fraction of a second:* $0.769\,353\,594\,7 \times 10^{-9}$ *seconds*. This definition, although very precise, is far from intuitive. Therefore, we will not use it. Instead, we will describe the meter and all other units that follow, in a less precise but more approachable fashion that relates them to everyday objects. A standard kitchen counter is about 1 m high; a very tall person would be 2 m tall. Note here that in writing, all designators for quantities are italicized (see "*L*" above), while those for units (such as "m" above) are not.

Length is the basis of two other derived physical quantities: area and volume. **Area** describes the size of a two-dimensional object and its units are meters squared (m^2), while **volume** does the same for a three-dimensional object and is expressed in cubic meters (m^3) or liters (L). One liter (1 L) is 0.001 m^3.

Kilogram (kg), which is a unit of **mass** (***m*** – note how the italicized "*m*" stands for mass, while regular "m" stands for meter). This unit is also not common in the United States, instead being replaced by a **pound** (lb; 1 lb = 0.454 kg). Four large apples weigh approximately 1 kg. One thousand kilograms (1000 kg) is 1 **tonne**, also known as the **metric ton**. The United States also uses **ton** as the unit of mass equaling 2000 lb or 907 kg. One ton is therefore slightly lighter than 1 tonne; since the two words are pronounced the same, their spelling is quite important here!

Second (s) – a unit of **time (*t*)**, which is used universally. Second was originally defined as 1/86 400th of a day, and that definition will serve our purposes well because it is quite intuitive. Time is an exception among other physical quantities, since it is measured in units not based on the decimal system: one **minute** is 60 seconds, and one **hour** is 60 minutes – or 3600 seconds. Larger units of time, such as **day** (equaling 24 hours) or **year** (equaling 365 days), are also not based on the decimal system.

Kelvin (K), a unit of **temperature (*T*)**. As a unit, Kelvin is used only in science. In Europe and most of the world, the standard everyday unit of temperature is a **degree Celsius (°C)**. This temperature scale is tied to the physical properties of water: 0 °C is defined as the freezing point of water, while its boiling point is 100 °C. One hundredth of that span is defined as one degree Celsius. One degree Celsius (1 °C) is equal in size to 1 K, but their zero points are different: a temperature of 0 K is known as the **absolute zero** and is very cold indeed, equal to −273.16 °C. Absolute zero is the coldest theoretically possible temperature in the Universe and is defined as the temperature at which all atomic and molecular motion stops. While we can get very close to absolute zero, achieving that temperature is physically impossible. How close did scientists get to absolute zero? The lowest ever recorded temperature is only 0.000 000 000 1 K above the absolute zero.

In the United States, a third unit is used in everyday measurements of temperature: **degree Fahrenheit (°F)**. One degree Fahrenheit (1 °F) represents a smaller quantity that 1 K or 1 °C; the three are related as 1 °F = 5/9 K = 5/9 °C (Figure 2.2). On the Fahrenheit scale, water freezes at 32 °F (=0 °C = 273.16 K) and boils at 212 °F (=100 °C = 373.16 K). To convert a temperature in K into its equivalent in °F, the following equation is used:

$$T_{^\circ\mathrm{F}} = \frac{9}{5} T_{\mathrm{K}} - 459.67$$

The fourth, **Rankine temperature scale**, is used less commonly than the three we discussed. Mostly limited to some engineering fields, it is the hybrid between the Fahrenheit and Kelvin scales: its zero point is at 0 K, but a degree Rankine is the same size as a degree Fahrenheit.

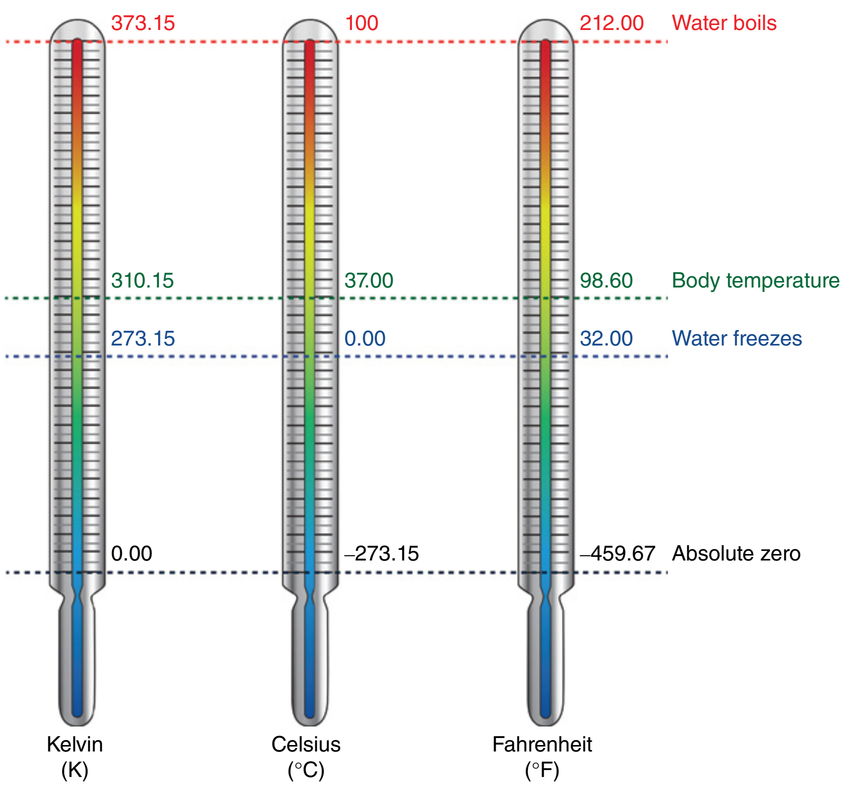

Figure 2.2 Comparison between the three most used temperature scales. Source: Stephanie Romero.

Ampere (A) is a unit of **electrical current (*I*)** and is also accepted globally. Often abbreviated as **amp**, you may have seen this unit on the back of various electrical appliances. Electrical current corresponds to the amount of electrical charge passing through a point in a conductor within a unit of time. For example, an incandescent tungsten lightbulb operating at a standard US household voltage would draw a current of slightly more than half an ampere. We will talk a lot more about Amperes and other units and quantities related to electricity when we discuss the production and transportation of electricity in Chapter 13.

Candela (cd) is a unit of **light intensity**. Coming from the Latin word for a candle, 1 cd is in fact quite accurately describing the intensity of light produced by a standard wax candle. We will speak more about the candelas and related units describing light in the discussion of energy use in lighting in Section 16.3.

Mole (mol) is the unit for the **amount of substance (*n*)** and is most commonly used in chemistry. This quantity is intimately connected to the molecular structure of matter. When two chemicals react, they most commonly do so in a one-to-one ratio of their molecules: every molecule of chemical A will react with one molecule of chemical B. However, since molecules of different substances have different masses, this one-on-one reaction of molecules does not mean that we will have a one-to-one reaction ratio of masses as well. To bring the amounts of the two reactants to the common comparison point, we use the concept of a mole: namely, 1 mol of any substance contains 6.02×10^{23} atoms or molecules of that substance. For carbon, this number of atoms is found in 12 g. For carbon dioxide, 1 mol – containing the same number of molecules – corresponds to 44 g. Mole is defined only for chemically pure substances: thus, we can talk about a mole of aluminum or mole of sugar (the scientific name for which is sucrose), but not about a mole of clay or mole of rice. For us, mole will be important when we talk about combustion (Section 6.2) and photosynthesis (Section 20.1), since various chemical reactants engage with each other in precisely defined mole ratios.

Names of Units: A Globalization Story

Units of measurement that are abbreviated with an uppercase letter were named after a real person. Many of these people were prominent scientists and inventors and are being honored by having such frequently used units named after them. **Lord William Thomson Kelvin** (1824–1907) was a Scottish physicist and engineer responsible for the formulation of first and second laws of thermodynamics in the mid-nineteenth century. **Anders Celsius** (1701–1744) was a Swedish astronomer who developed a universal temperature scale in the first half of the eighteenth century, and a contemporary of **Daniel Gabriel Fahrenheit** (1686–1736) who developed a competing temperature scale in the Netherlands and also invented the mercury thermometer. Ampere is named after French mathematician and physicist **AndréMarie Ampère** (1775–1836), while the unit of force bears the name of **Sir Isaac Newton** (1642–1726), who made numerous discoveries that established modern calculus and mechanics. Units of energy and power were respectively named after **James Joule** (1818–1889), an English physicist who studied heat, and **James Watt** (1736–1819), the Scottish inventor of steam engine.

Together, these names tell a story of science as an international endeavor, but one that was dominated by European – and particularly British – male scientists in the eighteenth and nineteenth centuries.

The relationship between the number of moles of a given substance and the corresponding mass of that substance is

$$m = n \times M$$

where M stands for the **molar mass** of a compound. Molar mass has the units of grams per mol ($\mathrm{g\,mol^{-1}}$). To calculate a molar mass of a chemical compound, we need to know its chemical formula. For example, ethanol has a formula C_2H_6O, meaning that its molecule is composed from two carbon, six hydrogen, and one oxygen atom. Looking up the molar masses of these atoms in the Periodic Table of the Elements (found in Appendix A), we find 12 for carbon, 1 for hydrogen, and 16 for oxygen. Multiplying these masses by the number of corresponding atoms and then adding it all together give us a total molar mass of $46\,\mathrm{g\,mol^{-1}}$ for ethanol.

Quite often, the standard units we just introduced are either too big or too small to be practical for describing a given object or phenomenon. For example, a meter is too small to describe the size of a country, while at the same time too large to describe the dimensions of bacteria. A kilogram may be too large to describe the masses of insects and too small to describe the masses of planets. Conveniently, each unit of measurement can be combined with standardized prefixes that make it ten, hundred, thousand, million, etc., times larger or smaller. These prefixes are given in Table 2.1, and we will use them to establish **orders of magnitude** – rough comparisons of the sizes of numbers by classifying them into orders, each one of which is approximately 10 times larger than the previous one. As an example, a roughly 100-fold increase from 5 to 650 is an increase of 2 orders of magnitude (two powers of 10).

Table 2.1 Prefixes used to make units larger (left two columns) and smaller (right two columns).

Prefix (abbreviation)	Meaning	Prefix (abbreviation)	Meaning
deca- (da-)	10 (10^1)	deci- (d-)	0.1 (10^{-1})
hecto- (ha-)	100 (10^2)	centi- (c-)	0.01 (10^{-2})
kilo- (k-)	1000 (10^3)	milli- (m-)	0.001 (10^{-3})
mega- (M-)	10^6	micro- (μ-)	10^{-6}
giga- (G-)	10^9	nano- (n-)	10^{-9}
tera- (T-)	10^{12}	pico- (p-)	10^{-12}
peta- (P-)	10^{15}	femto- (f-)	10^{-15}
exa- (E-)	10^{18}	atto- (a-)	10^{-18}
zeta- (Z-)	10^{21}	zepto- (z-)	10^{-21}
yotta- (Y-)	10^{24}	yocto- (y-)	10^{-24}

Let us look at some exemplary usage of these prefixes. The prefix **deca** (meaning 10) is not used too frequently, but the unit of decagrams (=10 g) is occasionally seen in older European cookbooks when expressing quantities of baking ingredients. **Hecto**liters (=100 L) are a common unit to express volumes of beer in wholesale transactions. **Kilo**grams (=1000 g) and **kilo**meters (=1000 m) are very common units of measurement in the metric system, used to discuss, e.g. a mass of bought produce or a distance between cities, respectively. **Mega**hertz (=1 000 000 Hz) is a unit of frequency used to describe FM radio stations. **Giga**watt (=1 000 000 000 W) is a unit of power convenient for measuring the outputs of large power plants. **Tera**byte (=10^{12} B) is often used as a unit of hard drive capacity; however, its strict definition uses the binary system in which $1\,\mathrm{TB} = 2^{24}\,\mathrm{B} = 1.099 \times 10^{12}\,\mathrm{B}$, so a slightly larger number than 10^{12}. **Peta**watts (=10^{15} W) are the power delivered by the world's most potent lasers, while **exa**joules (=10^{18} J) present a convenient unit to describe the amount of energy released in earthquakes or consumed by a country in a year. Other, even larger, prefixes are used less commonly.

How about the smaller side of things? A **deci**liter (=0.1 L) is often used to describe the volume of drinks in European and Asian restaurants. **Centi**meters (=0.01 m) are a common unit for taking measurements of clothes, while **milli**seconds (=0.001 s) can make a difference between winning and losing a bobsleigh race. **Micro**meters (=0.000 001 m) are commonly used to describe sizes of biological cells, while large biomolecules have dimensions in the **nano**meter (=10^{-9} m) range. The growing field of **nanotechnology** deals with the unique phenomena that are observed at the nanometer length scale. Atoms have the sizes best expressed in **pico**meters (=10^{-12} m). The fastest chemical reactions take several **femto**seconds (=10^{-15} s) to complete. An **atto**gram (=10^{-18} g) is approximately the mass of a single ribosome – the cellular unit responsible for protein synthesis, while a **zepto**joule (=10^{-21} J) is approximately the energy of a single photon of microwave light.

All the physical quantities we have introduced above will have their relationship to energy, and we will discover those relationships later in this book. For now, the mechanical derivation of energy can be based on just the first three of these quantities: length, mass, and time.

2.2 Definition of Force, Energy, and Power

Our intuitive understanding of energy is based on an ability to cause motion. Thus, our first derivation of energy will be mechanical, that is, relating to objects in motion. But before we reach the definition of energy, we need to introduce a handful of other derived mechanical quantities. For any moving object, we can define its **speed** (***v***) as the length it passes in a unit of time:

$$v = \frac{\Delta L}{\Delta t}$$

In the equation above, Greek letter delta (Δ) denotes a change in some quantity – in this case, length and time. Accordingly, the unit of speed is defined as meters per second (m/s or $\mathrm{m\,s^{-1}}$). This is a general rule: if some physical quantity A is defined as B divided by C, then the units of that quantity A will also be defined as the units of quantity B divided by the units of quantity C. In everyday life, we often talk about speed of driving, and meters per second are not commonly used in that context. Instead, in the United States, we express the speed in miles per hour (mph), while in Europe kilometers per hour (kph or $\mathrm{km\,h^{-1}}$) is a more common unit. Note that both units are still formed by dividing a unit of length (kilometer or mile) by a unit of time (hour). In the Insert on this page, we show how to convert between these three units of speed.

Converting Between the Units of Speed

Let us see how to convert the speed in miles per hour (mph) or kilometers per hour (kmph) into $\mathrm{m\,s^{-1}}$. In any unit conversion, you should first check whether the units are used to describe the same physical quantity. In our case, all three units pass that test: all divide a unit of length (mile, kilometer, or meter) with a unit of time (hour or second). Then, you can proceed. For mph, convert the mile into its equivalent in meters (1609 m to a mile) and then do the same for an hour (3600 seconds to an hour):

$$1\,\mathrm{mph} = \frac{1\,\mathrm{mile}}{1\,\mathrm{hour}} = \frac{1609\,\mathrm{m}}{3600\,\mathrm{s}} = 0.447\frac{\mathrm{m}}{\mathrm{s}}$$

Repeating the same process for kmph gives

$$1\,\mathrm{kmph} = \frac{1\,\mathrm{km}}{1\,\mathrm{hour}} = \frac{1000\,\mathrm{m}}{3600\,\mathrm{s}} = 0.278\frac{\mathrm{m}}{\mathrm{s}}$$

Speed alone tells us simply that an object is moving, but not about the trend of that movement. For example, a car driving at a speed of $60\,\mathrm{km\,h^{-1}}$ may be accelerating from $0\,\mathrm{km\,h^{-1}}$ (which would require an input of energy) or decelerating from $100\,\mathrm{km\,h^{-1}}$ (which would be dissipating some of its energy). To get some idea about the process that was involved in getting it to move, another physical quantity is needed: **acceleration (*a*)**, which is a measure of how quickly the speed of an object changes. Acceleration is defined as the change in the speed that occurs during an interval of time:

$$a = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{t_2 - t_1}$$

What are the units of acceleration? The unit of speed is $\mathrm{m\,s^{-1}}$, and the unit of time is s. Divide these two, and you get $\mathrm{m/s^2}$ or $\mathrm{m\,s^{-2}}$. We do not talk about acceleration as often in daily life as we do about speed, but you may hear it mentioned in advertisements for fast cars, which go from 0 to 60 mph (change in speed) in just a couple of seconds (change in time). Practice converting this way of expressing acceleration into $\mathrm{m\,s^{-2}}$.

So, we clearly need an input of energy to accelerate an object. How large of an input? That will depend not only on the acceleration we want to achieve, but also on the mass of the object: the heavier the object, the higher the amount of energy needed to accelerate it. A notion of **force (*F*)** captures this relationship:

$$F = m \times a$$

The unit of force is $\mathrm{kg\,m\,s^{-2}}$. Since this accumulation of basic units becomes cumbersome, and since force is a very common physical quantity, a special new unit is introduced: one **Newton (N)**, which is equal to $\mathrm{kg\,m\,s^{-2}}$. The unit of Newton is named after Sir Isaac Newton (1642–1726), the famed English physicist and mathematician.

Force is a measure of an instant: how forcefully you have to "push" a car of a certain mass to give it a certain acceleration. Implied in the definition of energy, or work, is the length of the application of that force. This physical **work (*W*)** is defined as force multiplied by length:

$$W = F \times l$$

Unit of work is accordingly Newton meter (N m), or another new unit: **Joule (J)**, named after an English physicist James Prescott Joule (1818–1889).

Energy and work are equivalent, and their units are the same: work is just the energy that has received its mechanical manifestation. Work can therefore be defined as the change in the energy content because of an action, or:

$$W = \Delta E = E_1 - E_2$$

Energy can be defined in several other ways that will be relevant to our future discussion. One is the definition of **kinetic energy**, which is the energy of an object with a mass m moving at velocity v (Figure 2.3). In that case, its energy is

$$E_\mathrm{k} = \frac{mv^2}{2}$$

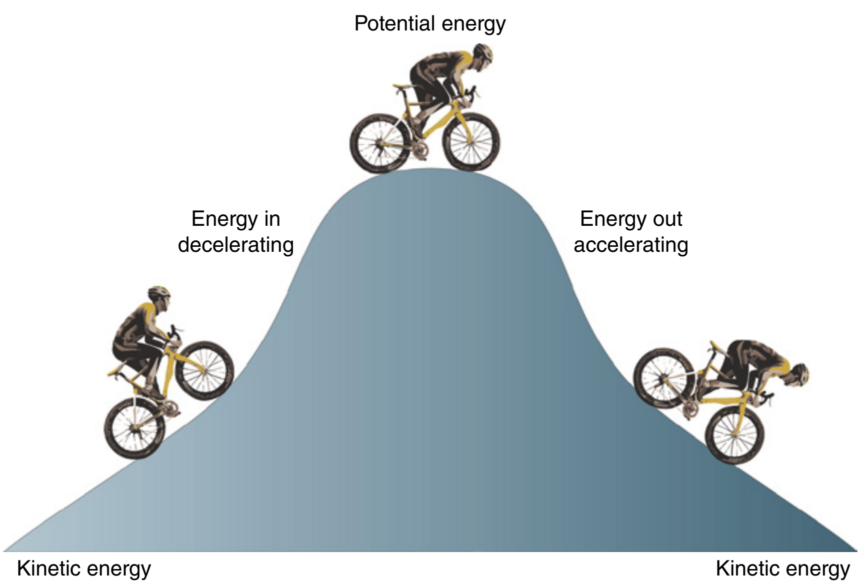

Figure 2.3 The difference between kinetic and gravitational potential energy illustrated by a biker climbing a hill and descending from it. Source: Stephanie Romero.

A stationary object with a mass m at an elevation h will also have an energy content associated with it – as it had to be elevated against the force of Earth's gravity. This **gravitational potential energy** is defined as:

$$E_p = m \times g \times h$$

Here, g is the acceleration of Earth's gravity, experienced by all objects that fall. The value of g at sea level is $9.81\,\mathrm{m\,s^{-2}}$, often rounded to $10\,\mathrm{m\,s^{-2}}$. The value of g changes slightly (less than 1%) with altitude and latitude.

Finally, **heat** is a form of energy defined as the sum of kinetic energies of all molecules of a given object. As these molecules move in random directions, their individual velocities cannot be measured, but their average can be related to absolute temperature. The most likely energy of a single molecule at temperature T is

$$E = \frac{3}{2}kT$$

where k stands for the Boltzmann constant: $1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$.

One last physical quantity that we will introduce is **power (*P*)**, defined as the rate of consumption of energy:

$$P = \frac{\Delta E}{\Delta t}$$

Power is a frequently used quantity – for example, all household appliances must have a power rating which describes how much energy they draw from the electrical grid per unit of time. Because of its importance, power also has its own named unit: **Watt (W)**, defined as $\mathrm{J\,s^{-1}}$, and named after James Watt. Capacities of power plants are also expressed in megawatts (MW) or gigawatts (GW), meaning that they produce millions or billions of Joules of energy per second. The key here is "per second": any power plant can produce a vast amount of energy, but a big one can do so quickly.

2.3 Units of Energy and Their Interconversion

So, the international unit of energy is a Joule, derived as we have seen above. Everyone in the world uses this unit when discussing energy, right? Not quite! In fact, there are several different units of energy in continuous use around the world. Unlike the metric system, whose use (or lack thereof) is typically defined by geographic boundaries, various units of energy are being used by different professional groups: physicists, engineers, chemists, regulators, oil companies, electricity consumers, etc. This section will therefore serve as a dictionary of sorts, translating between these different terms for the same thing. Here are some of the most used units of energy:

Joule (J) is the standard SI unit, used commonly in scientific and engineering circles. One Joule is a relatively small quantity of energy. If you think about its definition in terms of gravitational potential energy ($E_p = mgh$), it would be the energy needed to lift an object weighing 0.1 kg (perhaps an apple) to a height of 1 m, against the force of Earth's gravity (approximately $10\,\mathrm{m\,s^{-2}}$). This is an easy action to do – meaning that not much energy is expended.

Kilowatt-hour (kWh) is another very common energy unit. You will see it on your electricity bill: it is simply the sum of power ratings of your appliances (expressed in W or kW), multiplied by the time in hours they were used. This is the reason why this unit is so popular: it can relate power to the electricity consumption very directly. One kilowatt-hour (1 kWh) is quite a large unit compared to 1 J. Joule is defined as $1\,\mathrm{W} \times 1\,\mathrm{s}$; 1 kWh is $1000\,\mathrm{W} \times 3600\,\mathrm{s}$ (number of seconds in one hour) = 3 600 000 J, or 3.6 MJ. This is an amount of energy consumed by e.g. a laptop (a 100 W consumer) running for 10 hours. You should also remember that while Watt is a unit of power, kWh is a unit of energy as it multiplies power with time – confusing the two is a common mistake.

Calorie (cal) is also a unit you might have encountered, especially if you pay attention to your exercise or nutrition. It is often said that we are "burning calories," that is, expending energy through exercise. This is a unit commonly used in biology, chemistry, and nutrition science. One calorie is the amount of energy needed to heat up 1 g of water by 1 K, and it equals 4.184 J; therefore, it is also a rather small amount of energy. You should be careful about a very common confusion, often encountered when using "calories" in the context of nutrition science: 1 cal then signifies 1 kcal according to the above definition. Thus, standard energy input of a healthy adult – typically quoted as 2000 cal – is in fact 2000 kcal by the above definition. In the Insert on this page, we show how to calculate the power rating of a human using this piece of information.

Power Rating of a Human

What is the power rating of a human? While this may sound like an odd question, it is a relatively straightforward one to answer. A common nutritional recommendation is to consume 2000 kcal in food per day. Kilocalories are a unit of energy, while one day represents a unit of time, and dividing the two should give us the power rating of a human. First, let us convert the kilocalories into Joules:

$$2\,000\,000\ \mathrm{cal} \times 4.184\ \mathrm{J\,cal^{-1}} = 8\,638\,000$$

and one day into seconds:

$$24\,\mathrm{h\,day^{-1}} \times 3600\ \mathrm{s\,h^{-1}} = 86\,400\ \mathrm{s}$$

and then divide the two to get the power:

$$8\,638\,000\ \mathrm{J} / 86\,400\ \mathrm{s} = \mathbf{96.85\,W}$$

Thus, an average adult consumes as much energy as a laptop, or as an old-fashioned incandescent 100-W lightbulb.

This short exercise is important in designing air-conditioning systems for large venues. They are supposed to compensate not only for the ambient heat, but also for the body heat radiated by the people inside of it – approximately 100 W for each person. This is why large lecture halls should always feel cold when you are the first one to enter them in the morning: they are supposed to feel comfortable only when their air-conditioning is offset by the heat radiated by hundreds of students!

British thermal unit (btu) is a unit of energy commonly used in steam generation, air-conditioning, and heating industries. One British thermal unit equals the amount of energy needed to heat 1 lb (454 g) of water by 1 °F. Note that the definition of the btu is very analogous to that for the calorie, but with different base units used in the derivation. One British thermal unit (1 btu) is approximately 1054 J.

Quad (Q) is a unit of energy equivalent to 10^{15} (quadrillion) btu, or 1.054×10^{18} J (1.054 EJ) in SI units. Clearly, a quad is a very large unit: it is commonly used to measure annual energy consumption of entire countries. For example: in 2019, the United States consumed 100.2 Q, while France used 10.7 Q. One Quad (1 Q) is equivalent to the energy content of approximately 8 billion gal of gasoline, 36 million tons of coal, or 13.3 tons of uranium-235.

Electron-volt (eV) is in contrast a very small unit, used typically in particle physics. It is the amount of energy needed to move one electron (carrying a very small amount of charge) across a potential difference of 1 V, approximately hundred times lower than the standard US electricity voltage. One electron-volt (1 eV) equals 1.602×10^{-19} J.

Barrel of oil equivalent (boe) is, as its name implies, an amount of energy contained in a standardized barrel (42 gal, 159 L) of crude oil. Its approximate value is 6.12×10^{9} J and is a unit used mostly by oil and gas companies to describe the energy content of these two fuels or to compare it to other fuels. For example, we can speak of how much energy – in barrel of oil equivalents – is found in a ton of coal. A related unit is also:

> **Tonne of oil equivalent (toe)** is defined as the amount of energy released by burning 1 tonne (or metric ton) of crude oil. As toe is related to weight and boe to volume of crude oil, their conversion depends on the exact density of oil in question, so toe is typically defined by an IEA/OECD[1] convention as 41.868 GJ or 11.63 MWh.

Table 2.2 gives quick conversion factors between these eight units. For example, to find how many eV are in 1 Q, choose the column title “Q into” and follow down until you reach the row labeled “eV.”

We should also mention some alternative and commonly used units of power. Apart from Watts, which are widely utilized, you have probably heard of:

> **Horsepower (hp)**, which in its original meaning had many different values but is now standardized at 746 W. Curiously, this was a unit introduced by James Watt himself as he was starting to market his steam engines as the competition for horses that were used to pull water and coal out of mines. Watt appears to have overestimated the horses (or was intentionally under-advertising his steam engines and then ended up over-delivering), as few horses can produce a sustained power of 746 W over a long period of time. An average human can deliver a power of 1.2 hp for a short period of time, but only 0.1 hp sustained for longer stretches; trained athletes can do about twice better.

Horsepower is a unit commonly used by car manufacturers: for example, a 2020 Volkswagen Passat is advertised as having 174 hp, meaning a power rating of 130 kW! This power is impressive but is in fact rarely used, only during the moments of quick acceleration. Most of the energy consumption of the car goes toward moving the car itself rather than its passengers and cargo.

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1 **IEA** stands for **International Energy Agency**, while the **OECD** stands for **Organisation for Economic Co-operation and Development** – a club of 35, mostly wealthy, countries.

Table 2.2 Conversion factors between the most common units of energy.

	J into	kWh into	cal into	Btu into	Q into	eV into	boe into	toe into
J	1	3.6×10^{6}	4.2	10^{3}	10^{18}	1.6×10^{-19}	6×10^{9}	42×10^{9}
kWh	2.8×10^{-7}	1	1.2×10^{-6}	1.2×10^{-4}	2.8×10^{11}	4.4×10^{-26}	1.67×10^{3}	11.7×10^{3}
cal	0.24	8.6×10^{5}	1	252	2.3×10^{17}	3.8×10^{-20}	1.4×10^{9}	10^{10}
btu	10^{-3}	3.6×10^{3}	0.004	1	10^{15}	1.6×10^{-22}	6×10^{6}	42×10^{6}
Q	10^{-18}	3.6×10^{-12}	4.2×10^{-18}	10^{-15}	1	1.6×10^{-37}	6×10^{-9}	42×10^{-9}
eV	6.25×10^{18}	2.25×10^{25}	2.6×10^{19}	6.25×10^{21}	6.25×10^{36}	1	3.75×10^{28}	26×10^{28}
boe	1.7×10^{-10}	0.6×10^{-3}	7.1×10^{-10}	1.6×10^{-7}	1.7×10^{8}	2.6×10^{-29}	1	7
toe	2.4×10^{-11}	8.6×10^{-5}	10^{-10}	2.4×10^{-8}	2.4×10^{7}	3.8×10^{-30}	0.14	1

Btu per hour (**btu h^{-1}** or frequently – but incorrectly – **btuh**) is a unit commonly used to rate performance of air-conditioning and heating systems, especially in the United States. It is defined as 1 btu (1054 J) consumed per one hour (3600 seconds), so it is equal to 1054 J/3600 seconds = 0.29 W.

2.4 Heat Capacity

In Section 2.3, you may have noticed that two units of energy (calorie and British thermal unit) were defined by an amount of energy needed to slightly heat up a certain mass of water. The choice of water in these cases was one of convenience, as it is readily available. But would the same amount of energy be needed to warm up some different liquid – e.g. gasoline or oil, or a gas or a solid? The answer is no. Different materials differ in how easily they can be warmed up or cooled down. This difference is captured in a physical property known as **heat capacity**: the amount of energy needed to increase the temperature of the sample by 1 K. Heat capacity scales with the mass of the sample, and its units are J K^{-1}. A property independent of the mass is the **specific heat capacity** (abbreviated ***c***): the amount of energy associated with a 1-K increase or decrease in the temperature of a 1 kg of the sample. Specific heat capacities are expressed in J K^{-1} kg^{-1}, and values for some materials and fuels are given in Table 2.3. Specific heat capacities allow us to determine the energy changes that accompany the changes in temperature using a simple equation:

$$Q = m \times c \times \Delta T$$

in which Q stands for heat needed (or released), m for the mass of the material, c for specific heat capacity, and ΔT for temperature change.

Among the commonly used materials, water has the highest specific heat capacity. This feature of water has profound effects on many phenomena related to biology, energy, and climate. Oceans are harder to warm up or cool down than the neighboring coastal areas. They therefore have a tempering effect on the climates of coastal regions: cooling them

Table 2.3 Specific heat capacities of some common materials and fuels.

Substance	Specific heat capacity ($J\,K^{-1}\,kg^{-1}$)
Air (dry)	1005
Aluminum	897
Asphalt	920
Brick	840
Coke	840
Concrete	880
Copper	385
Ethanol	2440
Gasoline (octane)	2220
Methane (at 2 °C)	2191
Steel	466
Steam (at 100 °C)	2080
Water (at 25 °C)	4181

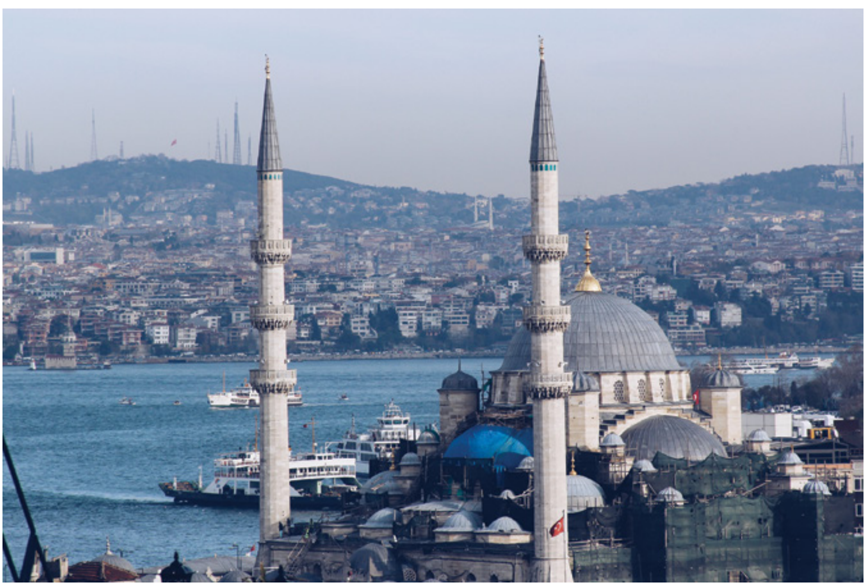

Figure 2.4 Climate of large coastal cities, such as Istanbul, is tempered by the large bodies of water that surround them. Water's high heat capacity means that it will capture much of summer's heat and store it for the winter. Source: Michael Parulava on Unsplash.

down in the summer and warming them up in the winter (Figure 2.4). Ocean breezes are caused by this almost constant difference in temperature between air above the ocean and that above the land. The use of water as a heat transfer or cooling fluid is justified not only by its low cost and nonflammable character – but also by the fact that a small amount of water can carry away a large amount of waste heat. In fact, you can easily observe high-specific heat capacity of water in your kitchen. Heating up water to boil takes a long time; heating up frying oil takes significantly less – even though the temperature it reaches is higher than 100 °C. Notice also that liquid water and gaseous steam have quite different specific heat capacities.

The choice of materials with high heat capacity is important in building design. In cold climates, intelligent building design captures the maximum amount of solar heat by trapping it in a material with high heat capacity. Water is obviously not a suitable construction material, but concrete is – and its low costs, superb mechanical properties, and relatively high heat capacity means that it slowly warms up during the day, but then also slowly radiates that heat back into the dwelling at night.

2.5 Phase Changes

In Section 2.4, we have seen that as we heat water, its temperature steadily increases. What happens as we approach the boiling point of water at 100 °C (212 °F)? Does heating water from 97 to 99 °C require the same amount of energy as converting water at 99 °C to steam at 101 °C? The answer is "no" – we need a significantly higher amount of energy for the second transformation compared to the first one. This additional energy is expended on the conversion of water from its liquid form to its gaseous state – a **phase change** known as **evaporation**.

There are three main states (or phases) of matter: solid, liquid, and gaseous. The main difference between the three is the amount of energy that molecules have available for their random motions. In the solid state, molecules essentially do not move; they just minimally oscillate around relatively well-defined positions. In the liquid, molecules have significantly more freedom and they can move around. They do not move around independently, but instead in smaller or larger clusters that contain multiple molecules loosely held together. Finally, in the gaseous state of matter, individual molecules can move without any correlation with other molecules and have the highest kinetic energy and the highest freedom of movement. Phase changes convert substances from one form of matter into another, in turn rapidly increasing or decreasing the available energy for the motion of molecules. **Evaporation** converts liquids into gases, increasing the freedom of molecules to move; **condensation** does the opposite. **Melting** converts solids into liquids (also increasing freedom of movement), while **freezing** (or crystallization) does the opposite. Finally, a rare phase change known as **sublimation** directly converts solids into gases. Each of these transformations is associated with a **specific** or **latent heat of transformation** which is the energy released or consumed per unit of mass in transforming matter from one phase to another. For example, the specific heat of vaporization (evaporation) of water is $2257\,\mathrm{kJ\,kg^{-1}}$, while its heat of fusion (melting) is $334\,\mathrm{kJ\,kg^{-1}}$. Specific heats of vaporization and fusion for other materials are given in Table 2.4.

What does all this mean in practice? As we add heat to a solid, e.g. ice (Figure 2.5), we initially monotonously increase its temperature at a rate determined by its specific heat capacity. Once we reach the melting point of that solid, further addition of heat no longer increases its temperature. Instead, it is consumed as heat of fusion, supplying the heat

Table 2.4 Specific heats of vaporization (left two columns) and fusion (right two columns).

Substance	Specific heat of vaporization (kJ kg^{-1})	Substance	Specific heat of fusion (kJ kg^{-1})
Water	2 257	Water	334
Aluminum	10 500	Aluminum	398
Ethanol	841	Ethanol	108
Iron	6 090	Iron	272
Methane	481	Paraffin wax	200–220
Gasoline	250–450	Mercury	11.6
Diesel	~230	Sodium acetate	264–289
Propane	356	Lead	23

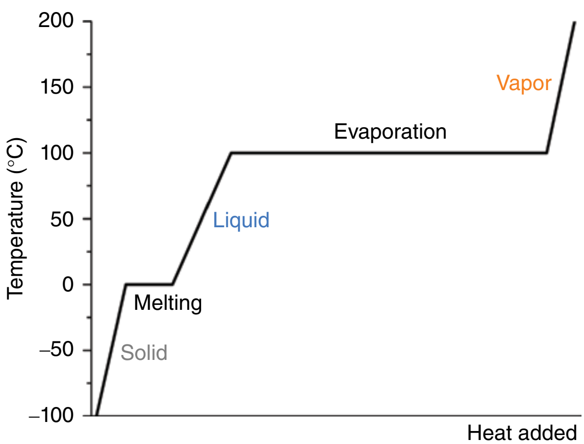

Figure 2.5 Temperature changes that occur as the heat is added to solid ice (gray). Temperature increases until the melting point, then stays constant during melting, and then increases again – but at a different rate – while liquid water (blue) is being heated. During boiling, temperature stays constant. Further added heat converts water into vapor (orange) and then continues increasing its temperature monotonously.

needed for the molecules to go into the higher-energy liquid phase. **During the phase change, the temperature stays constant**: the temperature of a mixture of ice and water is 0 °C and it will stay so until all the ice melts. Only then will the additional applied heat continue increasing the temperature of the water, at a rate proportional to water's specific heat capacity (which is higher than that of solid ice). This additional energy that is contained in the liquid water simply because it is a liquid is referred to as **latent heat**. Similarly, once the boiling point of water is reached, further added heat is consumed in supplying the specific heat of evaporation needed to convert the water into steam. The temperature of boiling water will stay at 100 °C until all the water evaporates.

How do we use the heats of vaporization and fusion? They are needed when we are considering energy costs associated with temperature changes that include the phase transition temperatures. For example, to calculate the energy needed to convert water from a room temperature to steam at 200 °C, we need to consider three separate processes. First, we need to heat the water up from 20 to 100 °C, and the amount of required energy is guided by the specific heat of water. Then, that water needs to evaporate, the energy cost of which can be calculated using the mass of water and its specific heat of vaporization. Finally, the resulting steam now needs to be heated from 100 to 200 °C, and guiding us again is the specific heat – but now of steam, which is lower than that of liquid water. Add those three energies together and we get the total energy cost of this process. Figure 2.5 shows that the largest contributor to the total needed heat is found in the specific heat of evaporation of water.

Heat of fusion is becoming increasingly important in the thermal energy storage systems, which store energy as heat. One of the ways to store large amounts of heat is by utilizing it to melt a salt when the heat is readily available. When the heat becomes needed, the salt is induced to crystallize, and during its crystallization it releases back the heat of fusion used to melt it. To be practical in energy storage systems, salts used for this purpose need to be inexpensive, be nontoxic, have a low melting but high boiling point, and have a reasonably high heat of fusion so that a relatively small amount of salt could store a large amount of heat. Sodium acetate (Table 2.4) satisfies all these requirements and is in fact used to store and release heat in large pools of molten salt.

2.6 Energy Content of Fuels

The unit conversions introduced above can now be used, as they will allow us to compare energy content of various fuels per unit of mass or volume. These are listed in Table 2.5. Note that the energy content and the specific heat are very different concepts – even though we can speak of both quantities for the same fuel. Energy content is the amount of energy

Table 2.5 Energy content of various fuels per unit of mass.

Fuel	Energy content ($MJ\,kg^{-1}$)	Notes
Coal	24–31	Depending on coal quality
Crude oil	42	Or 40 $kWh\,gal^{-1}$
Diesel fuel	45	
Gasoline	46	
Natural gas	47–55	Or 1000 $btu\,ft^{-3}$
Wood	17	
Hydrogen	142	
Natural uranium	520 000	
Uranium-235	82 000 000	
Deuterium	330 000 000	When used as a fuel in nuclear fusion
Water	12 000	When used as a fuel in nuclear fusion

released when a certain mass of a fuel is combusted or used in a nuclear reactor. Specific heat capacities and heats of evaporation and fusion relate to the amount of energy needed to warm up a fuel; the fuel itself is not consumed. Both are important in engine design, but in different contexts. Warming up the fuel to the engine's operational temperature will require an input of heat, which is generally compensated many times over by the much larger amount of heat released by the combustion of that fuel.

Note that all these numbers are quoted in megajoules (i.e. millions of joules) per kilogram. For example, 1 kg of coal releases approximately 25 million joules upon combustion. Using the conversion factors in Table 2.2, these 25 MJ translate into approximately 7 kWh of energy. If all this energy could be converted into electricity – and this is a big "if," which we will discuss at length in Chapters 3 and 5 – then it would be sufficient to power a 100-W laptop for 70 hours continuously. This number is impressively large and impressively small at the same time. If you consider that a mere handful of coal powers a sophisticated instrument for almost three days, then you realize how dense of an energy source coal is. Consider at the same time how many of those laptops and other appliances are running in your city and you will recognize that even a midsized coal-fired power plant must consume vast amounts of coal: between 1 and 2 million tons each year!

From Table 2.4, you will also notice that crude oil and its derivatives, as well as natural gas, have progressively higher energy contents than coal. One way to think about this difference is to consider the liquid and gaseous fuels as more "refined" by Nature. On the other hand, biomass (wood) has a lower energy content than coal, because the "refining" process has still not begun – and because even dry wood still has a considerable amount of moisture in it. These relative differences are important in mitigating carbon dioxide emissions from energy generation. Producing the same amount of electricity using energy-dense natural gas will result in fewer emissions than producing that energy from coal – since the mass of carbon emissions scales with the mass of the fuel consumed.

Continue reading through Table 2.4 and you will get to uranium, with an energy density of more than 20 000 times greater than coal! What causes such a big difference? Coal, oil, and natural gas are collectively known as **fossil fuels**. They, together with biomass and hydrogen, all produce energy through the process of **combustion**, during which their constituent atoms combine with oxygen. In contrast, the energy from uranium is extracted through a very different process: **nuclear fission**. In this transformation, the uranium atom's nucleus breaks down into two smaller nuclei, releasing in turn vast amounts of energy. Another way to think about this: combustion of coal – which is mostly composed of pure carbon – produces carbon dioxide, which still contains carbon, just chemically rearranged and bound to oxygen. In contrast, nuclear fission of uranium destroys uranium, and after the fission two different chemical elements are obtained. This vastly larger energy density of uranium means that nuclear power plants need refueling much less frequently that coal-fired ones: while the former need a truckload of uranium fuel once a year, the latter typically consume a large train worth of coal in just a week. But such large concentration of energy in nuclear power plants also poses risks in the terms of security that are brought to the forefront by nuclear accidents and concerns about nuclear material falling into terrorist hands. There are different forms (or isotopes, defined in Section 11.1) of uranium, and the most active one in fission is uranium-235, which therefore represents the most energy-rich form of uranium.

An even more dense energy source is present in the Sun: pure hydrogen. Under the extremes of pressure and temperature found in the Sun, two nuclei of hydrogen will fuse into a larger nucleus of helium and release immense amounts of energy – about 10 million times more than carbon per unit of mass. This process is called **nuclear fusion**. At present, nuclear fusion cannot be replicated on Earth under controlled conditions, mostly because there are no materials that can withstand the extremely high temperatures needed to start and sustain the fusion process. If proven viable, controlled nuclear fusion could essentially provide limitless energy, as vast amounts of energy could be obtained from hydrogen that is itself derived from water (and its pure fusion-active form, deuterium). Such promise of an infinite energy source remains futuristic at this point.

Missing from Table 2.4. are some of the energy sources which are gaining more importance in today's energy makeup: solar, wind, or hydroelectric energy. This is the case because those kinds of energy do not come in the form of a discrete fuel; instead, they are energy flows that we can tap into and extract a portion of their energy from. There is no physical "stuff" to consume in a solar panel or a wind turbine – just energy transferred from one source to another. Because of this distinction, speaking of an energy content per unit of mass is not useful or even possible, because mass cannot be directly assigned to an energy source in the case of solar energy, or the energy content of a certain mass of, e.g. air or water varies (with the speed of wind motion or the drop of the river reservoir).

All the sources of energy shown in Table 2.4 release their energy content in the form of heat. Sometimes it is just heating that we want from a fuel: for example, most of natural gas is used to heat our dwellings and offices, or to heat water which we in turn use for cooking, washing, and bathing. But quite often, we would like to convert that heat into work. Such work can be used to power transportation of goods and people across land, sea, or air. Work could also be used to spin turbines in power plants and produce electricity – which is a much more versatile form of energy that allows us to run a great variety of different appliances. Interconversions of energy from one form to another and especially from heat to work lie at the heart of many energy technologies. Such interconversions are guided by rules that are commonly known as the **laws of thermodynamics**. We will come back to them in depth in Chapter 5.

2.7 Practice Problems

2.1 Define the physical quantities of energy and work.

2.2 A very sparsely furnished room has one lightbulb (60 W), one small fridge (300 W), and a TV (100 W). If the fridge works 12 hours each day, TV 4 hours, and lightbulb 8 hours, calculate the total daily energy consumption of this room in kilowatt-hours and joules.

2.3 Find the examples of objects whose dimensions are most conveniently expressed in kilometers, micrometers, and nanometers.

2.4 US annual energy consumption is approximately 100 Q. What is the average American's rate of energy consumption in W?

2.5 Using the energy content of the first six fuels given in Table 2.4, calculate how long an appliance of your choice would be able to run on 1 kg of each fuel. For example:

"One kg of coal would allow us to run a 300 W refrigerator for x hours." Choose a different appliance for each fuel. Look up the actual power ratings of chosen appliances either online or on the back of the appliance in your home.

2.6 An idle large horse consumes about 9000 kcal worth of food per day, while a draft horse can consume as much as 30 000 kcal. What are their respective power ratings in W and hp?

2.7 Find the official EPA (Environmental Protection Agency) fuel efficiency for your car – or the car you wish you were driving. Estimate your yearly mileage and determine the amount of fuel you would save (or lose) if you switched to a 40-mpg Ford Fiesta. Use the local price of gasoline to translate these potential fuel savings/losses into dollars.

2.8 Other physical quantities also have different units in the imperial and metric systems. An example is volume, which is expressed in gallons in the United States and liters in the rest of the world, with 1 gal equaling 3.78 L. This conversion is important in evaluating fuel efficiencies of vehicles, which in the United States are expressed in miles per gallon (mpg, where a higher value means a more efficient car) and in Europe in liters per 100 km (L/100 km, wherein a lower value is better). What is the mpg rating of your car, for both city and highway driving? Convert those values into L/100 km.

2.9 In 2015, US coal production was 450 million tonnes of oil equivalent but dropping at an annualized rate (over 2005–2015) of 2.5%. On the other hand, India produced 280 million tonnes of oil equivalent, but with its production rising by 4.0% (on average) annually. In which year will India overtake the United States in terms of coal production, assuming these trends hold?

2.10 What is the molecular mass of cetane – one of the main components of diesel, with molecular formula $C_{16}H_{34}$?

2.11 While it is not common, we can in fact assign energy content per kilogram of moving air or water – allowing comparisons of renewable energy sources with fossil fuel and nuclear ones. How much energy is contained in 1 kg of water in a 100-m tall reservoir? How does this amount compare to the energy content of firewood found in Table 2.5?

2.8 Solutions to Practice Problems

2.1 Energy is the capacity to do work. For example, the calories liberated after consuming nutritious food. Work is the energy that is expressed. For example, lifting something off the ground, which uses the calories stored in the body from eating.

2.2 Since the power ratings of appliances are already expressed in Watts and their running time in hours, it is easier to solve this problem first in kWh. The total consumption of this room in one day is equal to the sum of individual appliances' consumption, which in turn are equal to the products of their power rating and the number of hours of operation. Thus, the total consumption is 60 W (lightbulb) $\times$ 8 h + 300 W (fridge) $\times$ 12 h + 100 W (TV) $\times$ 4 h = 4480 Wh, or 4.48 kWh. Since 1 kWh = 3 600 000 J, this daily consumption in Joules is 4.48 kWh $\times$ 3 600 000 J kWh^{-1} = 16 128 000 J.

2.3 Dimensions of cities – or distances between the cities – are commonly expressed in kilometers. For instance, the distance between Boston and New York is about 350 km. Thickness of human hair is approximately 50 μm, and most biological cells are of similar dimensions. Finally, nanometers are a convenient unit for describing the sizes of large molecules: an insulin molecule has a radius of 1.34 nm.

2.4 One Quad (1 Q) is equal to 1.054×10^{18} J, so 100 Q will be 1.054×10^{20} J. Population of the United States is approximately 326 million, so annual energy consumption per capita equals 1.054×10^{20} J/326 million = 3.23×10^{11} J. Number of seconds in one year is 365 days year^{-1} $\times$ 24 h day^{-1} $\times$ 3600 s h^{-1} = 3.15×10^{7} s, so an average American's energy consumption rate is 3.23×10^{11} J/3.15×10^{7} s = 10 250 W. Contrast this number with the power rating of a human, which is just ~100 W. An average American consumes energy at a 100 times faster rate than their metabolism.

2.5 For each of the fuels, energy content is expressed in MJ kg^{-1}. Since our appliances have their power rating in Watts, it is more convenient to first devise a conversion factor that will take us from MJ kg^{-1} to kWh kg^{-1}. Since 1 kWh = 3.6 MJ, this means that 1 MJ kg^{-1} = 0.278 kWh kg^{-1} or 278 Wh kg^{-1}.

For coal, let us choose an average heat content of 28 MJ kg^{-1} = 7785 Wh kg^{-1}. A 35-W fan could run for 7785 Wh/35 W = 222.4 h on 1 kg of coal.

For crude oil, heat content is 42 MJ kg^{-1} = 11 676 Wh kg^{-1}. A 90-W inkjet printer could run for 11 676 Wh/90 W = 129.7 h on 1 kg of crude oil.

For diesel, heat content is 45 MJ kg^{-1} = 12 510 Wh kg^{-1}. A 500-W washing machine could run for 12 510 Wh/500 W = 25.02 hours on 1 kg of diesel.

For gasoline, heat content is 46 MJ kg^{-1} = 12 788 Wh kg^{-1}. A 80-W 42-in. LED TV could run for 12 788 Wh/80 W = 159.85 hours on 1 kg of gasoline.

For natural gas, let us choose an average heat content of 51 MJ kg^{-1} = 14 178 Wh kg^{-1}. A 300-W fridge could run for 14 178 Wh/300 W = 47.26 hours on 1 kg of natural gas.

For wood, heat content is 17 MJ kg^{-1} = 4726 Wh kg^{-1}. A 100-W laptop could run for 4726 Wh/100 W = 47.26 hours on 1 kg of wood.

All these calculations assume 100% efficiency in the conversion of a fuel's energy content into electricity powering an appliance. The actual efficiencies are much lower, as we will see in Chapter 5.

2.6 We have seen that human power rating is 96.85 W, equivalent to consuming 2000 kcal of food per 24 hours. An idle horse consumes 9000 kcal, or 4.5 times more than a human. Thus, its power rating is 4.5×96.85 W = 387.4 W. The working horse consumes 30 000 kcal, or 15 times more than a human; its power rating is 15×96.85 W = 1452.8 W. Converted into hp, these values are 387.4 W/746 hp W^{-1} = 0.52 hp (idle horse) and 1452.8 W/746 hp W^{-1} = 1.95 hp (working horse).

2.7 At the time of this writing, one of the authors was driving a 2016 Mazda 6, with an estimated fuel consumption of 28 mpg. With an annual 12 000 miles driven, its consumption per year was 12 000 miles/28 mpg = 428.6 gal of gasoline. For Ford Fiesta, this annual consumption was 12 000 miles/40 mpg = 300 gal of gasoline. The savings were thus 428.6 gal − 300 gal = 128.6 gal of gasoline. At July 2018 gasoline prices in Houston of US\$2.40 per gal, these savings corresponded to 128.6 gal $\times$ US\$2.40 per gal = US\$308.6 in savings per year.

2.8 The 2016 Mazda 6 had rated gas mileage of 26 mpg city and 38 mpg highway. This means that 26 miles $\times$ 1.609 km mile^{-1} = 41.834 km in the city and 38 miles $\times$ 1.609 km mile^{-1} = 61.142 km on the highway could be traveled using 1 gal (3.78 l) of fuel. To travel 100 km in the city, one would use 100 km/41.834 km = 2.39 times more fuel, or 2.39 $\times$ 3.78 l = 9.03 l. To travel 100 km on the highway, one would need 100 km/61.142 km = 1.64 times more fuel, or 1.64 $\times$ 3.78 l = 6.20 l. Thus the "European" gas mileages for the 2016 Mazda 6 are approximately 9.0 l/100 km in the city, and 6.2 l/100 km on the highway.

2.9 This problem can be solved analytically by deriving the corresponding equations, but it is also simple and quite instructive to construct a table of estimated coal production numbers for the two countries, based on the presented trends:

Year	US production (million toe)	India production (million toe)
2015	450	280.00
2016	438.75	291.20
2017	427.78	302.85
2018	417.09	314.96
2019	406.66	327.56
2020	396.49	340.66
2021	386.58	354.29
2022	376.92	368.46
2023	367.49	383.20
2024	358.31	398.53

The production of coal in India is projected to surpass that of the United States in 2023, if the presented trends hold.

2.10 Molecular mass of cetane is equal to the sum of masses of 16 carbon atoms and 34 hydrogen atoms: $16 \times 12\,\mathrm{g\,mol^{-1}} + 34 \times 1\,\mathrm{g\,mol^{-1}} = 226\,\mathrm{g\,mol^{-1}}$.

2.11 Water in a high reservoir has the potential energy which is defined as the product of the reservoir height (100 m), the acceleration of Earth's gravity (9.81 m s^{-2}), and the mass of water. Per unit of mass, it is simply the product of height and the acceleration of Earth's gravity, or 981 J kg^{-1}. Compared to the combustion of firewood, which releases 17 000 000 J kg^{-1}, this is a miniscule energy density – which is why hydroelectric power plants must be huge installations dealing with very large flows of water. In fact, as we will see in Chapters 5 and 12, we are able to extract energy almost three times more efficiently from moving water than from burning firewood, which makes the comparison a bit more favorable for the water in the reservoir.

2.9 Discussion Questions

2.1 Research the ancient units of measurement that have been used in your region. How do they compare to the modern ones?

2.2 For most units of measurement that have been named after a person, the namesake was a European man. Are there any units of measurement named after women and/or non-Europeans?

2.3 Why does the United States continue to use English imperial units, even though the US Congress decided to use the metric system in 1975?

2.4 The establishment of the SI system of units seems like a clear evidence – and perhaps one of the causes – of globalization. But globalization also has negative consequences. Can any of them be attributed to the standardization of units of measurement? Provide and research possible examples.

2.5 In this book, we will often use the OECD (Organisation for Economic Co-operation and Development) as a shorthand for the developed world. Look up the members of this organization and discuss if there are any notably developed countries missing – or if there are developing countries which have been included in it.

2.6 Look up the latest edition of the BP Statistical Review of World Energy and analyze the units used to describe energy and power. Comment on the choices the authors of the review made.

2.7 First calendars were developed in the Mesopotamian times. The smaller units of time were introduced later, with seconds being introduced only in the Middle Ages. What is your hypothesis on why these time units were not developed simultaneously?

2.8 Research why the division of units of time – minutes into seconds and hours into minutes – is not based on the decimal system.

Further Reading

Books

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3

Flows and Conversions of Energy and Matter

Ancient Greek philosopher Heraclitus (c. 535 BCE to c. 475 BCE) famously said:

> *Ever-newer waters flow on those who step into the same rivers.*

This statement is often summarized as *panta rhei*: everything flows, and it describes the constant change and impermanence of all things. It also applies very literally to the concepts of energy and to the energy-fueled flows of matter which we will discuss in this chapter.

Energy and matter are continuously being transformed from one form to another and moved from one location to another. These transfers occur both on the planetary scale and within our society. While the details of these transfers may differ, they all involve communications between **reservoirs** and **flows**. The former are locations on the Earth where matter or energy are stored in large quantities. Examples include fossil or nuclear fuels – which are reservoirs of energy or oceans – which are reservoirs of water as well as carbon. The energy and material flows are the process that move energy or matter from one reservoir to another. An example would be the processes of photosynthesis that moves carbon from the atmosphere into the biosphere, or that of rain, which takes water from the atmosphere and returns it to the ground. In fact, the transfers of energy and matter are closely connected to each other, especially when it comes to the transformations of energy, air, water, and carbon-based matter. This chapter explores these interconversions and aims to quantify them. We will begin by looking at the different forms of energy.

3.1 Forms of Energy

In defining energy, we have already encountered three distinct forms of it: the **kinetic energy** of an object in motion, the **gravitational potential energy** of an object elevated against Earth's gravity, and the **thermal energy** or **heat**, which is effectively the sum of kinetic energies of numerous molecules moving randomly about. In this section, we will look at the other forms of energy. All these kinds of energy can be interconverted and share physical equivalency: they can be expressed in the same units.

Introduction to Energy and Sustainability, First Edition. Ognjen Š. Miljanić and Joseph A. Pratt.

While our intuitive understanding of energy as the ability to do work is quite close to its rigorous physical definition, the language that we use to describe energy can occasionally be imprecise or misleading. Among the most significant examples of such imprecision are our notions of **production** and **consumption of energy**. In a strict scientific sense, energy in a closed system can never be destroyed or created from nothing – it can only be **converted** from one form to another. This notion is known as the **law of conservation of energy** and is one of the universal laws of nature. In the context of energy, the terms "production" and "consumption" therefore have a meaning slightly different from their literal definitions. "Production of energy" implies conversion of energy from a form that humanity views as less useful into a form that it values more. An example of such a production would be the conversion of chemical energy contained in coal – for which we have almost no direct use, into the electricity that can power a myriad of different appliances found in our homes or heat that can be used to melt steel. Conversely, energy consumption would be the conversion of such useful electricity into diffuse heat (e.g. our TV will warm up after being on for a few hours), for which we no longer have a use. As this book aims to talk about humanity's relationship with energy, we will subscribe to these slight misnomers and use them with the caveats just outlined. So, what different kinds of energy can we talk about?

In our discussion of the relationship of energy with the base SI quantities, we have relied on the **mechanical** description of energy. The kinetic energy is the energy of an object in motion and is related to the mass of an object and its velocity. Analyzing kinetic energy will be relevant when we discuss the energy of an, e.g. moving car or of air that powers a wind turbine. The gravitational potential energy is also defined in a mechanical context, as the energy of a stationary object raised to a certain elevation against Earth's gravity. This form of energy is seen in the elevated reservoirs of hydroelectric power plants, which hold water whose potential energy eventually gets converted into electricity.

Fossil fuels embody **chemical energy**. They have relatively unstable chemical bonds between carbon atoms or between carbon and hydrogen atoms. When burned, these bonds break and form new, more stable, bonds with oxygen. Such combustion converts chemical energy into **thermal energy** or **heat** and at the same times converts hydrocarbon fuels into combustion products: carbon dioxide (CO_2) and water (H_2O). Conversion of chemical energy into heat is the basis of all combustion energy technologies, whether they use coal, petroleum, natural gas, hydrogen, or biomass as the fuel.

Nuclear energy is found within the atom itself rather than in its bonds with other atoms. Breaking up the atomic nucleus of some isotopes of uranium (chemical symbol U), thorium (Th), or plutonium (Pu) atoms creates two lighter atomic nuclei. This is not only much harder to accomplish than simple combustion but also releases dramatically larger amounts of energy. Nuclear energy is also the energy source that powers the Sun and all stars, but in this scenario, very light atomic nuclei of hydrogen and helium are fused into bigger ones. In short, chemical energy is liberated by breaking up and reforming bonds between atoms and nucleus by breaking up or fusing atoms themselves.

Solar radiation that reaches the Earth is an example of **electromagnetic energy**, which is often called **radiation** or simply **light**. Electromagnetic energy is transmitted in small "packages" known as **quanta** (singular is quantum), which contain only a well-defined amount of energy:

$$E = h\nu$$

In the equation above, h is the Planck's constant (6.63×10^{-34} m^2 $kg\,s^{-1}$) and ν is the **frequency of light**, expressed in the units called **Hertz** (abbreviated **Hz**, $1\,Hz = 1\,s^{-1}$). The higher the frequency, the more energy such a "package of light" carries. The energy of a quantum of light can also be related to the **wavelength** of that light (abbreviated λ; wavelength has the units of length) as:

$$E = h\frac{c}{\lambda}$$

In this equation, c stands for the speed of light in vacuum: approximately $3 \times 10^8\,m\,s^{-1}$.

The most energetic form of radiation are the γ rays; they have the highest frequency and the shortest wavelength. This highly destructive form of light is followed by X-rays, which have slightly lower energy per quantum. Moving to lower energies, we reach ultraviolet, visible, and infrared light. These three forms of radiation constitute the bulk of energy that arrives on Earth from the Sun; solar radiation is roughly one-third ultraviolet, one-third visible, and one-third infrared. Finally, microwaves and radio waves are the low energy forms of light. Together, these forms of radiation form the **electromagnetic spectrum** (Figure 3.1), which spans numerous orders of magnitude in terms of wavelength, frequency, and energy.

Electric energy is the final form of energy, which can be (simplistically) viewed as the kinetic energy of charged particles – typically electrons – moving in an electric field. We will talk about it more in Chapter 13 when we discuss electricity.

Interconversions between various forms of energy constitute the basis of all our energy production and consumption technologies that we will explore thoroughly throughout the book. Now, let us look at the interconversion and transfers of matter from one reservoir to another. We will begin with water.

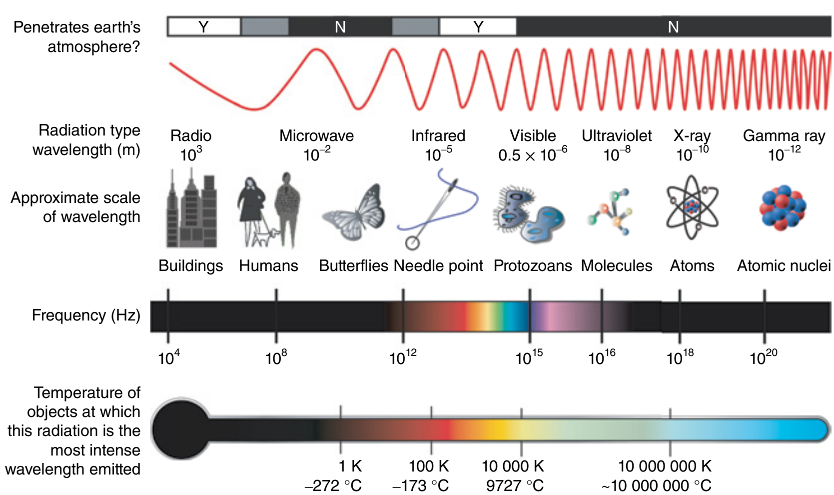

Figure 3.1 Forms of electromagnetic radiation, along with their typical frequencies, wavelengths, and information on atmospheric penetration. Source: Stephanie Romero.

3.2 Earth's Water Cycle

Water (chemical formula H_2O) covers 72% of Earth's surface and is continuously being circulated between four large reservoirs: (i) oceans, (ii) lakes and rivers, (iii) snowcaps and glaciers, and (iv) atmosphere. The four reservoirs store very different amounts of water: oceans contain approximately 96.5% of all water on earth, with lakes/rivers and snowcaps contributing about 1.7% each. The atmosphere stores just 0.001% of all water on Earth, but nevertheless plays a crucial role in its circulation.

Sun's heat and Earth's gravity power the **water cycle** (Figure 3.2): the movement of water from one reservoir to another. In tropical and temperate climates, evaporation from lakes, rivers, and oceans is powered by the Sun and this evaporation transfers water vapor into the atmosphere. As it is raised upward by the warm air, water vapor cools down and then **condenses** into clouds and eventually comes to the surface of the Earth as **precipitation** (Figure 3.3). Depending on the season, location, and climate, this precipitation will return to the Earth's surface as either rain, hail, sleet, or snow – the latter is being stored in snowcaps and released as snowmelt in the spring. Global climate changes threaten to alter the balance of snowfall and rainfall, leading to potentially dramatic issues in water supply for agriculture and human consumption. While snow essentially presents a "slow release water" that is brought back from the mountaintops over several months of spring melting,

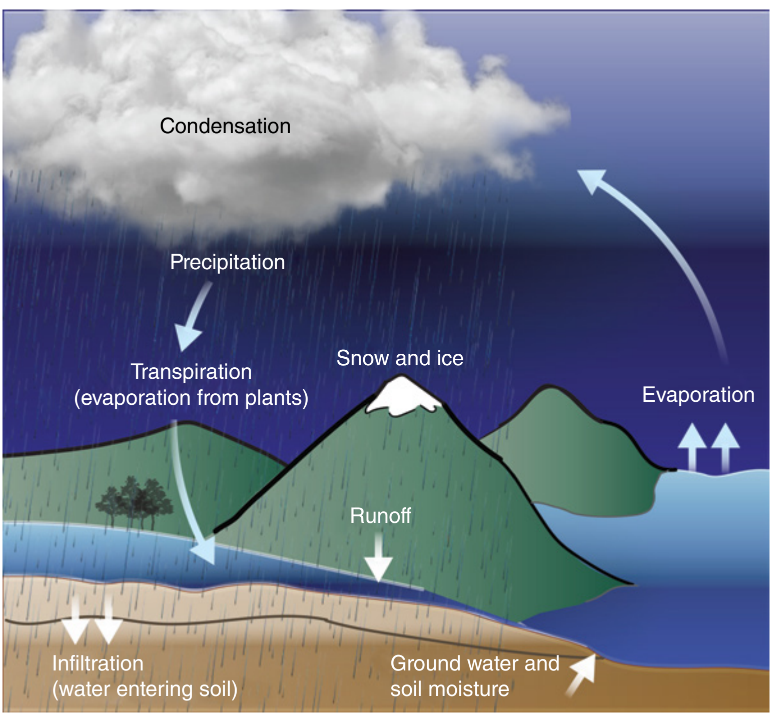

Figure 3.2 Earth's water cycle involves its continuous circulation between reservoirs. Source: Stephanie Romero.

Figure 3.3 Rain is one of the flows in the Earth's water cycle with importance in water supply and agriculture, but also in the transfer of airborne water-soluble pollutants. Changes in the balance of rain and snow fall are among the predicted effects of climate change. Source: Wolfgang Claussen from Pixabay.

rain quickly seeps underground in the process of **infiltration** or reaches the oceans through rivers. Rainfall thus cannot be stored from one season to the next, except for the rainfall that is collected in lakes and artificial reservoirs. This change will have important consequences for year-round water supply, thus affecting water sources for human consumption, agriculture, and irrigation.

The Earth's water cycle is a huge and important mass transfer, but its importance to our energy picture is somewhat limited. Only a small fraction of the water cycle powers the hydroelectric power plants. Where available, hydroelectric power has been a long-established source of clean, emission-free electricity. Perhaps more important is the role of the water cycle in agriculture, climate, and freshwater supply. We will touch upon these points when discussing the sustainable use of water resources in Chapter 4.

Water cycle, however, does play an important role in the movement of pollutants produced by energy technologies. Oxides of nitrogen and sulfur, which are released into the atmosphere by the combustion of fossil fuels (mostly coal and diesel), can be dissolved by the atmospheric water. The rain that forms is then acidic and such acid rains contribute to the acidification of lakes and corrosion of man-made structures. We will talk more about acid rain in Chapter 6. Similarly, ocean waters dissolve very large amounts of carbon dioxide as a part of the Earth's cycling of carbon, which we will cover in Section 3.3. This phenomenon helps with keeping the atmospheric carbon dioxide concentrations rising slower than they would have in the absence of oceans. At the same time, the dissolved carbon dioxide is converted to carbonic acid, which leads to the slow acidification of the oceans and is endangering certain fragile marine species. Many other pollutants are transferred from one location to another through the water cycle.