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ENERGY RESOURCES, GREENHOUSE GASES, AND MATERIALS

1.1 ENERGY SUPPLY AND CONSUMPTION

Energy has always played an important and inseparable role in human survival and civilization. In the nebulous stage of the early life, men learned to use fire from volcanoes, lightening, and other sources. With the ability to acquire, preserve, and care for fire, men started staying in secured shelters and eating cooked food. Fast forward, starting from the first century AD, steam engines were conceived, advanced, and remained the dominant source of power well into the twentieth century. They are the moving force behind the Industrial Revolution and enjoyed widespread commercial use driving machinery in factories, mills, and mines. By now, different energy sources have been put to our use: coal, nuclear, hydro, solar, etc. We relish in our abilities to make things bigger, faster, more comfortable, and cheaper. Today, with the fast economic growth in highly populated countries such as China and India and our desire to live and work wherever we please (we give it a catchy name "globalization"), suddenly our thirst for energy seems to generate some problems that have not been envisioned.

While the majority of us agree that energy is becoming a top priority in our standard of living, prosperity, and even national security, opinions still differ on the scope, severity, and urgency of the issue. Some extreme examples are as follows. In *Out of Gas* (2004), David Goodstein describes an impending energy crisis brought on by The End of the Age of Oil: the crisis will bite, not when the last drop of oil is extracted, but when oil extraction cannot meet demand—perhaps as soon as 2015 or 2025 [1]. "The survival of the United States of America as we know it is at risk," Former Vice President Al Gore said in July 2008. In *The Skeptical Environmentalist*

Materials in Energy Conversion, Harvesting, and Storage, First Edition. Kathy Lu.

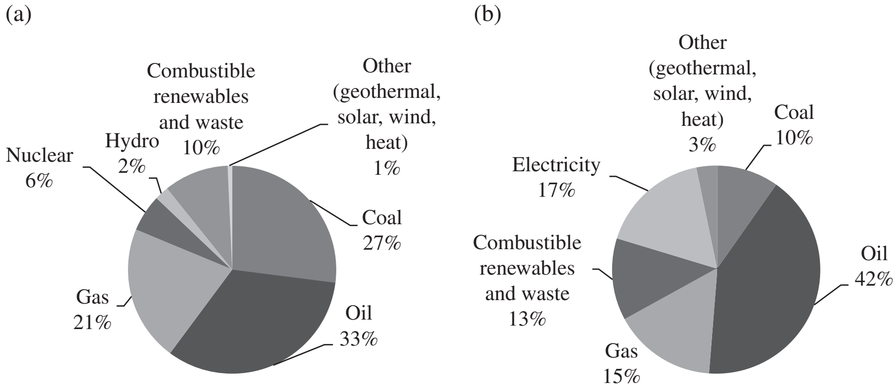

FIGURE 1.1 Worldwide energy supply (a) and consumption distributions (b) in 2008. Data from Ref. 2.

(2001), Bjørn Lomborg, however, claimed that declining energy resources, deforestation, species loss, certain aspects of global warming, and an assortment of other global environmental issues are unsupported by analysis of the relevant data [1]. In light of this, first we need to have a look at why we are debating energy sources and supplies and why we should examine these issues in an urgent sense.

The best starting point to understand the world energy problems is to look at where we acquire all our energy and where we expend them. Figure 1.1 shows the world total energy supply and consumption by source (2008) [2]. Because the energy consumption landscape is changing quickly, the data here may be slightly different from the numbers in the subsequent chapters for individual energy sources. Nonetheless, all sets of data show that fossil fuels are the primary energy source and take a huge majority in the overall energy consumption (Fig. 1.1a). In the total supply pie chart, coal, oil, and natural gases are the three major components of fossil fuels. They take up 27, 33, and 21%, respectively, with a whopping total of 81%. The second energy source comes from combustible renewables and wastes at 10%. This is mainly extracted from local biomass resources such as crop residuals, trees, and animal wastes. The main users of these resources reside in developing or underdeveloped countries as necessities for living. Nuclear energy, even with all the debate raging in the society, only takes about 6%. Hydropower takes only about 2% of the world energy supply; geothermal, solar, wind, and heat sources all together take only about 1%. Overall, we are either digging up the ground or drilling through it to obtain the energy needed to maintain and improve our living standards. The sources present on the Earth surface have been largely untapped or remain inaccessible to us.

From a different angle, global energy consumption offers a similar picture and includes 10% coal, 42% oil, and 15% gas, at a total of 67% (Fig. 1.1b). In addition, we consume 17% of energy in the form of electricity, which is mostly generated from coal. Overall, our vast majority of energy use is derived from fossil fuels. The rest of the energy consumption distribution mirrors that of the supply. In brief, we consume what we procure. The two sides of the energy coin (supply and consumption) tell the same story.

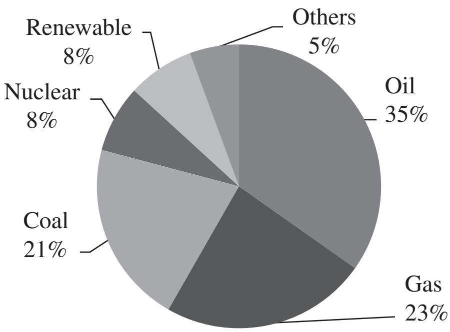

FIGURE 1.2 Energy usage in the United States. Data from Ref. 2.

As to the energy usage in the United States, the data from the U.S. Energy Information Administration [3] presents a very similar picture to the world energy supply (Fig. 1.2) and needs no further discussion here.

1.2 ENERGY PROBLEMS AND CHALLENGES

Part of the energy demand increase is fueled by the world population increase; part of it is fueled by the desire to improve living standards and expand economic growth. As of today, it is estimated that the world population is 7.096 billion [4]. When the entire population demands to be fed and clothed at a better quality, it is not surprising that energy demand dramatically increases. As of now, the world's primary energy consumption has increased to 14 TW-years year^{-1}, almost 50 times the preindustrial level of about 0.3 TW-years year^{-1}. Since 1971, global energy use has risen nearly 70% and is poised to continue its steady increase over the next several decades [5, 6]. To state this in a different manner, demand has risen at over 2% year^{-1} for the past 25 years and will continue to climb at about the same rate over the next 15 years if current energy use patterns persist, according to the International Energy Agency.

The first problem related to the rising energy demand is the uneven distribution of energy sources (Fig. 1.3). Since coal energy conversion has various environmental complications, different countries lean more toward oil consumption. As a result, the energy markets have been shaken by the instability of Middle East oil. Moreover, developing countries like China are becoming bigger energy consumers, while energy producers like Russia see the opportunity to widen their influence. In this changing landscape, the energy dependency (especially from countries without many reserves) places developed and high energy consumption countries in a highly vulnerable position, both economically and politically. What is thought of as energy geopolitics today has come to encompass much more than physical control over resources to advance state interests. It also refers to the ability to influence or even set world prices for fuels and technologies, and to leverage energy power to achieve a larger political end or ward off interference from other states and nongovernmental bodies. Energy geopolitics can also mean expanding one state's power and security at the expense of another's in a zero-sum game.

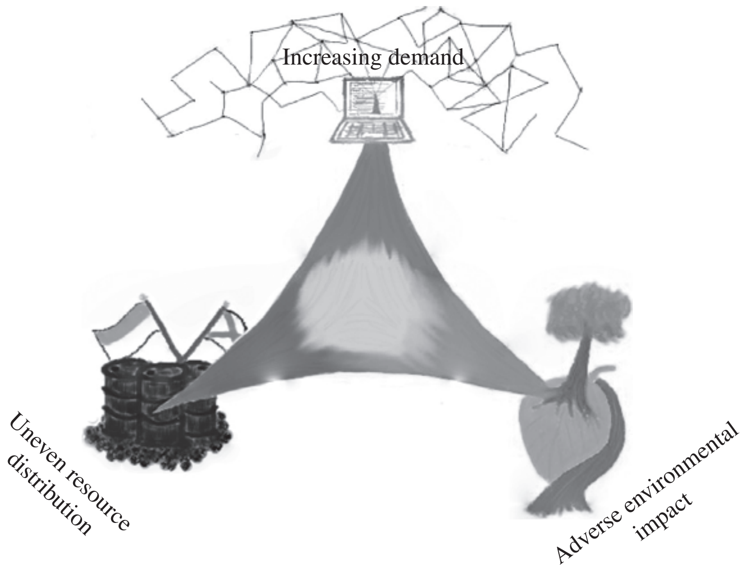

FIGURE 1.3 Opposing issues related to energy use. (*See insert for color representation of the figure.*)

Another major issue related to rising energy demand is the increasingly adverse, nonrepairable impact on the environment (Fig. 1.3). If we examine the energy deposits today (such as coal), running out of resources does not emerge as the major worry, if they can be redistributed as demanded. Yet there is another worry, greenhouse gas emission, which is becoming more insidious and urgent. Along with rising energy demand and use comes a concomitant increase in greenhouse gas emissions from fossil fuels. As shown in Figure 1.1a, fossil fuels supply >80% of the world's energy; energy-related emissions account for >80% of the CO_2 released into the atmosphere each year. In 2008, the CO_2 emission worldwide was 29.4 billion tons with the contribution distribution shown in Figure 1.4. The International Energy Agency estimates that global energy consumption and annual CO_2 emissions rise by almost 50% from 1993 levels. The average CO_2 emissions from different energy sources are as follows: coal at 1000 g kWh^{-1}, oil at 800 g kWh^{-1}, natural gas at 400–500 g kWh^{-1}, solar at 13–730 g kWh^{-1}, wind at 7–124 g kWh^{-1}, and nuclear at 2–60 g kWh^{-1} [7]. Again, the math is clear. Heavy reliance on coal, oil, and natural gas comes with a heavy price. CO_2 enters the atmosphere mainly through burning of fossil fuels (oil, natural gas, and coal), solid wastes, and trees and wood products. When an overwhelming amount of CO_2 is released into the atmosphere, even though a small portion of it can be absorbed by plants as part of the photosynthesis cycle, the rest will stay and accumulate as greenhouse gases.

Greenhouse gases absorb infrared radiation (heat) heading out from the Earth and re-emits it in a random direction; this random redirection of the atmospheric heat traffic impedes the flow of heat from the planet, just like a quilt. As a result, excessive CO_2 emission has a warming effect on the climate and is termed "global warming." There have been numerous publications and debates about global warming. We will

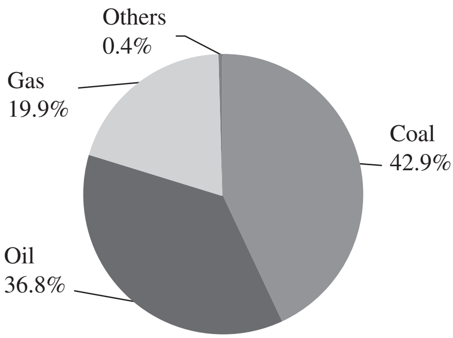

FIGURE 1.4 Worldwide CO_2 contribution from different sources. Data from Ref. 2.

not spend more efforts on that. It should only be noted that there is now more acceptance in the society that global warming is real; the climate change problem is principally an energy problem.

1.3 CURRENT STATE OF IMPROVING ENERGY EFFICIENCY

So what needs to be done to solve the world's increasingly urgent energy problems? The first thing is to stop arguing whether there is an energy problem. Fortunately, there seems to be less of a debate about this nowadays, and a general consensus is in place about the needed efforts to face energy issues. Either from geopolitical point of view or carbon emission point of view, we generally agree that energy needs to be conserved and strategically consumed.

With this admission in place, the next question is how we can more effectively address the energy issues. Different strategies need to be examined and implemented simultaneously, which can be done in three ways: (i) by reducing our population, (ii) by changing our lifestyle, and (iii) by reducing energy intensity through "efficiency" and "technology." Apparently, the first one is not an easy solution with the huge population the world already has, let alone different historical, cultural, political, and economical factors. The second can be done, but it would require difficult, if not painful, choices among our daily conveniences. The third one might enable us to enjoy what we already have in a sustainable way. This means more investment in energy innovation and technology, as well as continuous and long-term energy investment through generations.

Before discussing the strategies to address energy problems, energy sources and uses should be grouped and viewed carefully. There are seven major energy forms as alluded to earlier, namely, fossil, nuclear, solar, biomass, geothermal, hydro, and wind. Comparison of different energy sources can be made as follows [8].

Let's first look at fossil fuels. The main features for coal are that the sources are finite and its use is rapidly expanding on a global basis. Even though coal is cheap, burning fossil fuels produces dust, smoke, and oxide impurities, which may lead to environmental pollution. Burning fossil fuels also produces CO_2, which contributes to the "greenhouse effect," warming the Earth. In addition, burning coals produces photochemical pollution from nitrous oxides and acid rain from SO_2. As to the reserves, we currently have plenty of coal supplies, with 860 billion tonnes recoverable and available in >70 countries worldwide. As to oil, the total reserve has a different picture. Oil has a finite source, and there are several different categories of oil, each having different costs, characteristics, and, above all, depletion profiles. In terms of global consumption, crude oil remains the most important primary fuel, accounting for 36.4% of the world's primary energy consumption. However, 47% of the total reserves of conventional oil discovered so far have been consumed. For the cumulative crude oil production until the end of 2005 (143 billion tonnes), half of it was produced within the last 23 years. If the crude oil consumption pace continues as it has been, we only have a few decades of oil left unless new technologies are developed for oil extraction.

Nuclear power is mainly generated using uranium through nuclear fission. The desirable features of nuclear energy are that there is no smoke or CO_2 production, and huge amounts of energy can be generated from small amounts of fuel with small amounts of waste. However, waste produced is highly dangerous and must be sealed up and buried for thousands of years to allow the radioactivity to die away. A lot of investment is needed on nuclear reactor safe operation and waste disposal. If anything does go wrong, a nuclear accident can be a major disaster. Even though it is not currently an urgent issue, fuels for nuclear power are not renewable; once all the Earth's nuclear fuel is dug up and used, there will not be any more nuclear fuel resources.

Solar energy from the Sun is the most abundant source of energy. The annual solar radiation reaching the Earth is over 7500 times the world's annual primary energy consumption of 450 exajoules. However, currently the energy conversion efficiency for solar radiation is low, ~10%. Large investment is needed for photovoltaic conversion efficiency increase and collector cost reduction.

In its most primitive form, biomass is widely used throughout the world by burning up plant residuals for heating and cooking. Bioethanol extraction from corn and sugar is a mature technology as a fuel. Recently, biomass production through cellulosic decomposition and algae harvesting has generated renewed interests. It is widely believed that bioenergy reduces CO_2 emission and is a renewable energy source. However, the competing use of arable land and the potential impact on the environment need to be addressed.

Winds are generated by complex mechanisms involving the rotation of the Earth, heat energy from the Sun, the cooling effects of the oceans and polar ice caps, temperature gradients between land and sea, and the physical effects of mountains and other obstacles. The world's wind resources are vast. It has been estimated that if only 1% of the land area on the Earth were utilized, and allowance made for wind's relatively low capacity factor, wind power potential would roughly equate to the current level of worldwide energy-generating capacity. Some of the windiest regions are to be found in the coastal regions of the Americas, Europe, Asia, and Australia. However, large investment cost is required for windmills, and energy storage capability has to be drastically developed for wind energy usage.

Geothermal energy utilizes the natural heat of the Earth's crust. There are no major perceivable drawbacks from geothermal use. However, it is not a perpetual source of energy as solar, wind, and hydro energies are.

Hydro energy is currently the largest of all perpetual or so-called renewable energy resources. Total world hydro capacity is ~778 GW.

Based on the earlier understanding of different energy forms, energy can be utilized in three responsible ways: (i) We can invest in "clean coal" technology; (ii) We can invest in other energy sources that can satisfy our appetite for energy, such as nuclear fission; (iii) We can harness different renewable energies. Any of these energy generation strategies will require new and improved knowledge and facilities to happen. We either have to solve existing environmental issues, address new ones, or develop more efficient energy conversion processes.

Up to now, the criteria for energy choice have been based on their availability, accessibility, and affordability. To this list, we must now add three other imperatives: the sources must be sustainable, they should emit a minimum amount of CO_2, and they should not pose dangers to global security. In addition, the "no CO_2" resources have to be made efficient, economical, and available. Unfortunately, primary energy sources are not always of a form that is suitable for the end use. Instead, the sources have to be converted, and this involves wastage of energy and adverse environmental impact.

For the "converted" (or "secondary") energy sources, the most important, versatile, and controllable one is electricity. However, we only have limited ability in electricity storage. Even if we convert the primary energy sources into electricity, there is still an issue of how to store and release it as demand fluctuates.

To increase energy conversion efficiency, harness energy sources in a more responsible way, and open new, sustainable energy sources, many new technologies need to be developed. For example, CO_2 capture techniques for coal-fired plants are being explored. For sustainable energy source use, solar energy, wind, and hydropower are active research topics. Different countries have provided varying degrees of subsidiaries to encourage the commercial use of renewable energy sources. There is also active research about more efficient energy storage systems. Such activities add up to efficient energy use efforts.

With this understanding in mind, this book is intended to take a closer look at the available energy conversion systems, examine current state and future development trends of more efficient energy systems, and discuss how renewable and sustainable energy sources can be more effectively utilized. New energy harvesting technology and energy storage options will be presented. The core is to discuss different material functions, usages, and challenges in improving energy conversion, harvesting, and storage performance.

1.4 INSEPARABLE LINKS BETWEEN ENERGY AND MATERIALS

Energy and materials have a continual and mutually enriching relationship (Fig. 1.5). In the complex web of energy resource, production, storage, use, and efficiency, materials play a critical role as diverse and far-reaching as energy itself. Materials enable the production of energy or the transformation of primary energy into useful forms. Energy, in turn, has made possible the production of a broad range of materials for the society: from liquid-state fluids, to solid-state devices, and to high-temperature components.

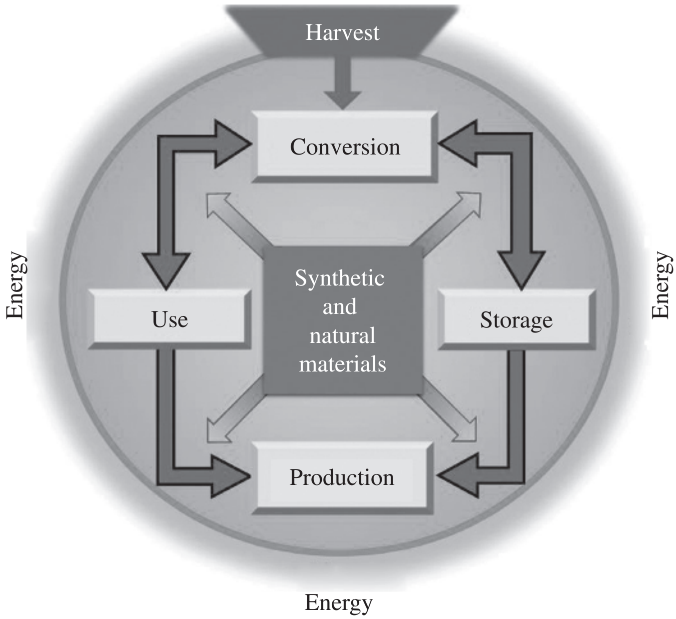

FIGURE 1.5 The intertwining relationship between energy and materials. (*See insert for color representation of the figure.*)

Materials for energy come in a near continuum: naturally occurring materials releasing energy through chemical or nuclear reactions, refractory metals and ceramics used in energy conversion systems, and functional (sometimes nanoscale) materials for energy storage and use. Increasing demand for energy, diminishing stocks of fossil fuels, and the public's desire to enhance environmental quality, particularly by reducing greenhouse gas emissions, all point to the need for improved materials. For example, generating electricity from the most abundant fossil fuel, coal, efficiently and with no environmental damage, presents notable challenges to developing higher-performance materials in harsh environments. New materials that increase the efficiency of the energy conversion and lower its cost would provide valuable flexibility in material use. Producing electricity with no CO_2 emissions is a major frontier for materials research in combustion and gas separation. New nuclear fuels and cladding materials would realize a new generation of safer, more efficient nuclear reactors. Photovoltaic materials convert solar energy into electrical power. Wind turbine blades transform wind energy into mechanical or electrical power. Engineered thermoelectric and mechanoelectric materials can tap otherwise wasted energy and transform it into useful forms. Materials also store and deliver energy in the forms of batteries, supercapacitors, and biofuels. High-performance materials for storing hydrogen would enable more energy efficient vehicles and off-grid operation. It is these fascinating material behaviors and properties that give us the high hope of tackling the challenging energy problems.

1.5 TERMS RELATED TO ENERGY AND POWER

Before proceeding to different energy systems, it would be helpful to examine some common technical terms related to energy measurement, use, and conversion.

1. Energy is the capacity to do work; power is the rate at which work is done. Energy is the power used or generated within a given time period and can be defined as

$$\text{Energy} = \text{power} \times \text{time} \tag{1.1}$$

   Energy is conserved and measured in kWh or MJ. Energy density is simply the amount of energy per unit weight (gravimetric energy density, expressed in Wh kg^{-1}) or per unit volume (volumetric energy density, expressed in Wh L^{-1}). We cannot actually produce, create, or consume energy; we can merely convert it from one form to another. However, we loosely use the term "energy creation," "energy production," and "energy consumption" when we talk about a certain form of energy.
2. Power is the rate at which work is done and is measured by W (watts), kW (kilowatts), MW (megawatts), GW (gigawatts), or TW (terawatts). One joule per second is called 1 W. One 40 W light bulb, kept switched on all the time, uses $0.96\,\text{kWh}\cdot\text{day}^{-1}$. Rate capability is expressed as gravimetric power density (in $\text{W}\cdot\text{kg}^{-1}$) and volumetric power density (in $\text{W}\cdot\text{L}^{-1}$).
3. Energy density is the amount of energy stored in a given system or region of space per unit volume. It determines how much energy a given system can accommodate and often times the ability to run certain devices for an expected duration. Power density is defined as power per unit volume or per unit mass. Power density often determines how fast energy can be supplied to a specific demand, which is critical for the operation of a given device.
4. Capacitance is the ability of a body to store electrical charge. Any object that can be electrically charged exhibits capacitance. Capacitance is directly proportional to the surface area of the conductor plates and inversely proportional to the separation distance between the plates. If the charges on the plates are $+q$ and $-q$, and V gives the voltage between the plates, then the capacitance C is given by

$$C = \frac{q}{V} \tag{1.2}$$

5. Specific charge (in $\text{Ah}\cdot\text{kg}^{-1}$) is the ratio of stored charge to its mass, and charge density (in $\text{Ah}\cdot\text{L}^{-1}$) is a measure of electric charge per unit volume of space, in one, two, or three dimensions.

1.6 OUTLINE OF THIS BOOK

The outline of this book can be presented as follows. This chapter outlines the energy resources, environmental impacts of rising energy demands, and relations between energy and materials. Chapter 2 will focus on material uses and demands in fossil energy conversion systems. Chapter 3 will address nuclear energy generation and nuclear materials. Chapter 4 will explain solar energy and solar cell material requirements. Chapter 5 will cover different forms of biomass and biofuels and related material issues. Chapter 6 will discuss wind energy and related materials. Chapter 7 deals with materials in hydrothermal, geothermal, and ocean energy conversion. Chapter 8 is focused on different types of fuel cells and material needs. Chapter 9 is related to mechanoelectric energy harvesting. Chapter 10 discusses materials in thermoelectric energy conversion. Chapter 11 examines materials from a different perspective: energy storage. Chapter 12 specifically focuses on hydrogen storage.

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