CHAPTER

1

Introduction to Bioenergy

Samir Kumar Khanal and Yebo Li

> **What is included in this chapter?**
>
> This chapter provides an introduction to non-renewable and renewable energy resources. Different forms of non-renewable and renewable energy and their current demand/consumption are discussed. An overview of bioenergy, its merits and demerits, and current status are also presented.

1.1 Energy

Our modern society depends on energy for nearly everything, including our basic needs that we often take for granted (e.g., to supply drinking water, produce food, and even provide air in some cases). Whether we admit it or not, we are addicted to energy in order to power appliances, light our homes, streets, and offices, and, perhaps more importantly, power the advanced technological gadgets we keep in our pockets. Many of the things we commonly overlook, like our vast transportation networks, are heavily reliant on an abundant and consistent supply of energy. Yet energy, in the form of electricity and fuel, is not as ubiquitous worldwide as it is in the USA and Western Europe. In many rural areas of developing countries, energy is derived from burning wood and local biomass resources, and the ability to secure energy consistently has significant socio-economic implications affecting the quality of life for local communities. In all cases, in both developing and developed nations, energy is essential for the growth, prosperity, and well-being of society.

Sustainability (i.e., meeting the needs of present generations without compromising the needs of those in the future) is another key issue of great concern caused by the rapidly growing global population and the corresponding increase in energy demand. As of October 2011, the world population reached 7.0 billion, and the United Nations projects that the population will continue to grow to 10.1 billion by the end of the twenty-first century (UNFPA, 2011). Standards of living are also on the rise, particularly in developing countries, a fact that is expected to contribute significantly to

Bioenergy: Principles and Applications, First Edition. Edited by Yebo Li and Samir Kumar Khanal.

Companion website: www.wiley.com/go/Li/Bioenergy

increased energy consumption and the stress already being placed on our diminishing non-renewable resources (i.e., fossil fuels), which currently meet over 85% of primary energy demands.

Discussions of energy are often associated with countries' gross domestic product (GDP), and per capita energy consumption is frequently viewed as an index of development. For example, developing countries have very low per capita energy consumption, typically less than 1.0 metric ton of oil equivalent per year (toe/year) compared to over 4.0 toe/year for developed countries (IEA, 2010a). For example, developing countries such as Nepal, India, Kenya, and Ghana have per capita total primary energy supply (TPES; inclusive of total energy consumed for exports, imports, etc.) of just 0.34, 0.54, 0.47, and 0.41 toe/year, respectively. In comparison, the world's average per capita TPES is 1.83 toe/year (IEA, 2010a). GDP growth and increases in electricity demands are linearly correlated with a coefficient of approximately 1 (i.e., every 1% increase in GDP is associated with a 1% increase in electricity demand; IEA, 2010b).

In 2010, global energy consumption was around 524 quadrillion Btu (QBtu – 13,205 million metric tons of oil equivalent or Mtoe). This value is projected to increase by 56% to 820 QBtu (20,664 Mtoe) by 2040 based on the International Energy Outlook 2013 (EIA, 2013). Currently, over 85% of total energy consumption is met through the use of non-renewable sources such as petroleum, coal, natural gas, and nuclear energy. China recently overtook the USA with total primary energy consumption of 2,550 Mtoe (101.2 QBtu; EIA, 2013).

According to the International Energy Outlook 2013 (EIA, 2013), the dynamics of energy consumption are changing dramatically. Non-OECD (Organization for Economic Cooperation and Development) countries, which account for 90% of global population growth and 70% of economic outputs, are expected to have over 85% growth in energy consumption from 2010 to 2040. Energy consumption in non-OECD developing Asian countries, especially China and India, will increase by 112% from 2010 to 2040. The rest of the non-OECD countries are also projected to show a strong growth in energy consumption during the projected period: for example, by 76% in the Middle East, by 85% in Africa, and by 62% in Central and South America. It is projected that China's energy consumption will grow by as much as twice that of the USA between 2010 and 2040. Because of its large population, however, on a per capita basis, China's energy use will still be half that of the USA. Another country of interest is India, which currently ranks as the third largest consumer (615 Mtoe or 24.4 QBtu) of energy. Despite the unprecedented rapid development of China seen over the last decade, the growth rate and energy consumption of other countries, such as India, Brazil, Indonesia, and the Middle Eastern nations, are expected to be even higher.

Many developing countries continue to struggle to provide sufficient energy to address the basic needs of all citizens. In India, nearly 840 million people lack proper access to modern energy services. Based on a 2009 estimate, over 1.3 billion people in sub-Saharan Africa and developing Asian countries do not have access to electricity, and nearly 2.7 billion people in these countries, 40% of the world's population, still rely on traditional biomass for cooking. Perhaps not surprisingly, 84% of people without electricity live in remote rural areas of these countries (IEA, 2011b). In these situations, bioenergy, especially biogas (which is covered in Chapters 17 and 18), may be a viable and attractive option for supplying cheap and consistent energy to rural populations.

Throughout this chapter, there is a fundamental, resounding question: What major energy resources can be implemented to meet the rising energy demands of rapidly growing populations? The answer is not easy for many reasons, including the uncertainty of various factors such as the availability of non-renewable resources; threats to the environment, such as climate change; geopolitics and energy security; changing governmental policies and regulations in light of emission and safety concerns, especially for nuclear power plants; and the unpredictable cost of fossil fuels. One thing, however, is certain: our future energy portfolio will be extremely diverse and an increasing

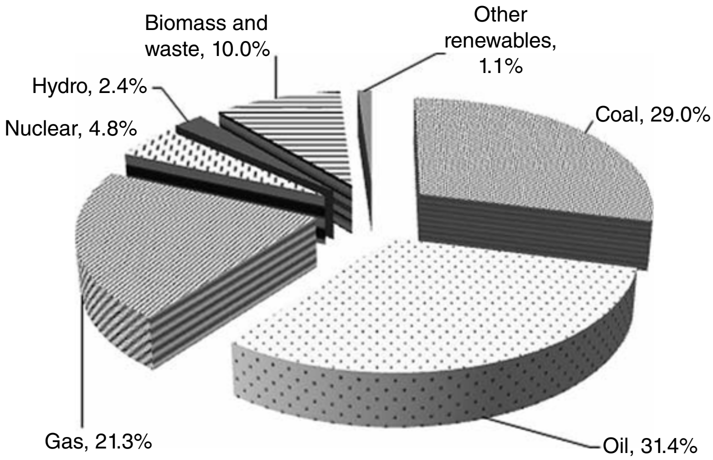


FIG. 1.1 World total primary energy supply by fuel type in 2012. Source: Data from IEA, 2014.

share of our energy will come from renewable sources, which have the highest annual growth rate of 2.5% among all energy resources (EIA, 2013).

1.2 Non-renewable Energy

Non-renewable energy is derived from materials or resources that cannot be replaced during a human lifetime and that, by definition, are available only in limited (finite) reserves. The world TPES by fuel type in 2012 is shown in Figure 1.1. Petroleum, natural gas, coal, and nuclear energy, which are considered to be conventional non-renewable energy resources, are discussed in detail in the rest of this section.

Petroleum, the primary source of *transportation fuel*, is a *fossil fuel* that accounts for nearly 31% of the world's TPES based on 2012 data. Table 1.1 shows the major crude oil consumption by nations and regions in 2011. The total world liquid fuel consumption in 2011 was 87.3 million barrels (bbl) per day, with the USA accounting for nearly 22% of total demand (EIA, 2012). It is interesting to note that the USA imported nearly 45% of the petroleum (crude oil and petroleum products) that it consumed in 2011 (EIA, 2012).

Coal is estimated to be the world's most abundant fossil fuel. Globally, it is the second most heavily used resource after petroleum, and accounted for nearly 29% of the TPES in 2012. Coal plays a critical role in electricity generation, comprising over 40% of the global electricity output in 2010 (IEA, 2011b). China is the largest consumer of coal, with a demand of 2,653 million metric tons coal equivalent (Mtce) or 73.5 QBtu in 2010, over 48% of the total global demand. The USA and India are the second and third largest consumers of coal, respectively. Table 1.2 compares the major coal-consuming regions of the world.

Coal is considered to be one of the highest polluting energy sources in terms of greenhouse gas (GHG) emissions. Carbon dioxide (CO_2) released from coal-fired power plants is a major concern, and significant attention is required to improve the efficiency of these plants and develop technologies for carbon capture and storage (CCS). In China and India, where coal is abundant and

Table 1.1 Major petroleum oil consumers in the world in 2011

Countries/regions	Petroleum oil consumption (million barrels per day)
USA	18.34
Europe	15.08
China	8.92
Japan	4.48
Africa	3.51
India	3.43
Saudi Arabia	2.99
Brazil	2.79
Russia	2.73
Germany	2.42
Canada	2.24
South Korea	2.23
Iran	2.03
France	1.82

Source: Data from http://www.eia.gov/

Table 1.2 Annual coal consumption by major economies in the world in 2010

Countries/regions	Coal consumption, Mtce (QBtu)
China	2648 (73.5)
USA	750 (20.8)
Europe	465 (12.9)
India	453 (12.6)
Japan	174 (4.8)
Russia	171 (4.7)
Africa	157 (4.4)
South Korea	107 (3.0)

Source: Data from http://www.eia.gov/

electricity supply is limited, coal consumption is expected to grow by as much as 70% and 190%, respectively, by 2035 (IEA, 2011b). The 450 Scenario in the World Energy Outlook 2011 aims to limit atmospheric CO_2 equivalent (CO_2eq) to around 450 parts per million (ppm), and will require the share of coal used for electricity generation to decline from 40% in 2009 to 15% in 2035. To meet this goal, power generation will need to originate from alternative resources such as renewables, nuclear, and natural gas, which emit significantly less CO_2.

Natural gas is another important component of the world's current energy portfolio, accounting for almost 21% of the TPES in 2014. Based on the New Policies Scenario (World Energy Outlook 2011), global gas demands in 2009 were 3,076 billion m^3 and are projected to increase to 4,750 billion m^3 by 2035, nearly a 54% increase. Table 1.3 shows the major consumers of natural gas in 2010. The USA is the largest with a total annual demand of 673 billion m^3. The second largest consumer is Russia, where natural gas comprises over 50% of total primary energy use (IEA, 2011b). Ranked third is Iran, followed by China. China is believed to play a key role in the future growth of natural gas demand due to its rapid economic growth, new energy policies (favoring natural gas as a less polluting resource), and access to new resources via pipelines from Russia.

Table 1.3 Natural gas consumption by major economies in the world in 2010

Countries/regions	Natural gas consumption billion m^3 (ft^3)
USA	673 (23,775)
Europe	584 (20,638)
Russia	424 (14,961)
Iran	145 (5,106)
China	107 (3,768)
Japan	105 (3,718)
India	64 (2,277)
South Korea	43 (1,515)
Africa	101 (3,554)

Source: Data from http://www.eia.gov/

Natural gas is primarily used for power generation and currently comprises nearly 21% of global electricity production (IEA, 2011b). The second largest consumption of natural gas is in buildings, typically for space and water heating, and accounted for nearly 24% of the total natural gas consumed in 2009. In industry, 17% of the total gas consumed is used to produce steam and heat for the production of goods and commodities. In addition, there is a growing market in the transportation sector for use as fuel; that is, *compressed natural gas (CNG)* or *liquefied natural gas (LNG)*. Presently, 70% of the world's natural gas–powered vehicles are concentrated in five countries: Pakistan, Argentina, Iran, Brazil, and India.

The overall growth in natural gas demands is due to policy intervention in favor of natural gas over other fossil fuels that require stricter emission regulations to protect the environment. Natural gas–fired power plants emit the lowest level of CO_2 compared to all fossil-fuel plants, and produce almost half that of coal-fired plants. Moreover, there are fewer safety concerns related to natural gas. Limitations in nuclear power production due to safety concerns are likely to lead to additional growth in the demand for natural gas for power generation.

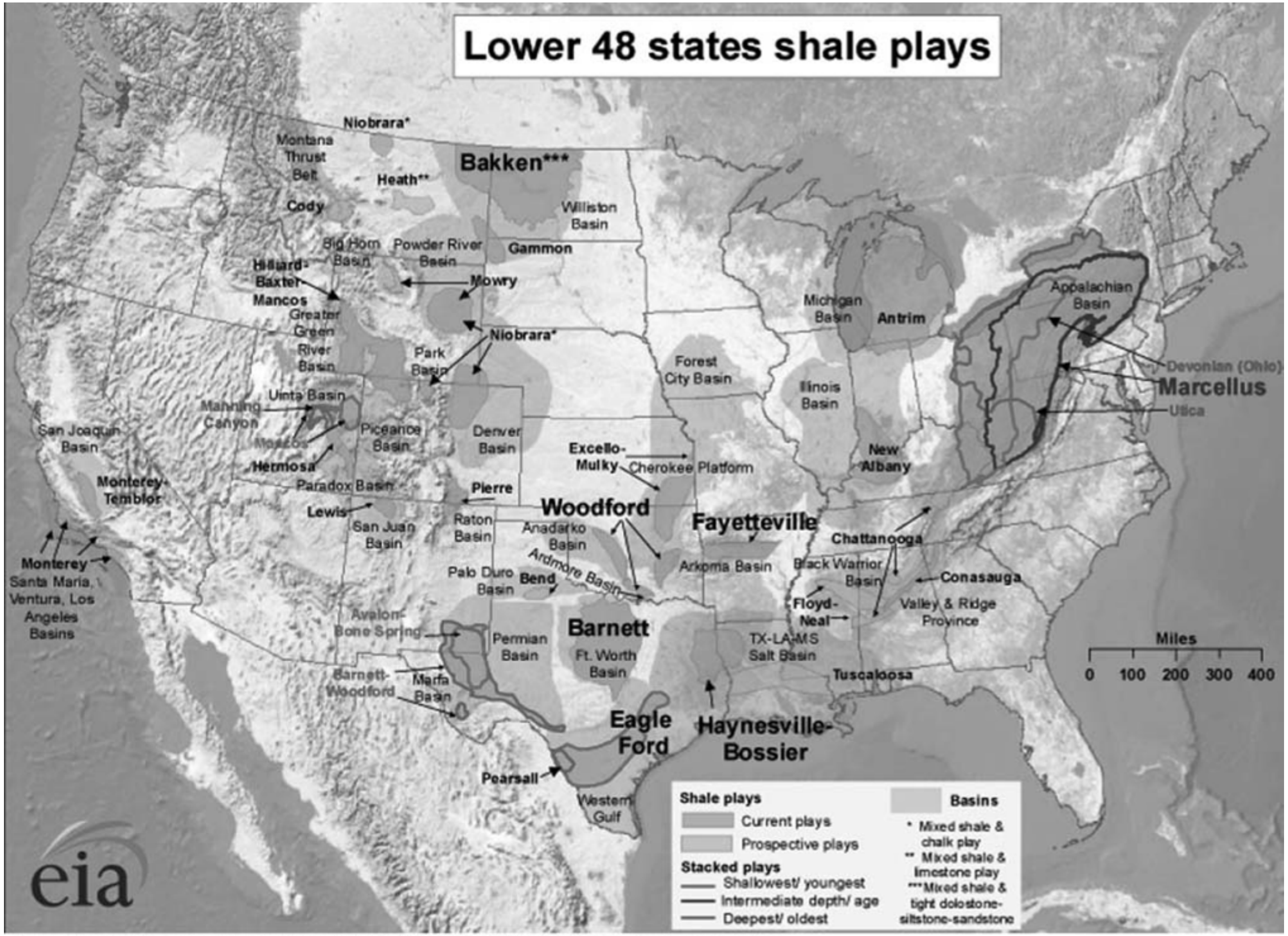
Nuclear energy is primarily used for power generation and supplied 2,461 terawatt-hours (TWh) of electricity (about 4.8% of the total global primary energy supply) in 2014. In France, nearly 75% of the total power produced domestically originates from nuclear facilities, followed by Ukraine (48%), South Korea (31%), and Japan (27%). In terms of total nuclear-based electricity generation, the USA leads the world with 790.2 billion kilowatt-hours (kWh), followed by France (421.1 billion kWh), Russia (161.7 billion kWh), Japan (156.2 billion kWh), and South Korea (147.7 billion kWh; http://www.nei.org/). In 2011, there were 441 nuclear plants operating in 30 countries with a gross installed capacity of 393 gigawatts (GW; 374 GW net), and nearly 83% could be found in OECD countries. Non-OECD countries, however, are leading recent efforts to build new nuclear plants, representing 55 of the planned 67 new facilities under construction. China reportedly had 28 new nuclear power plants under construction in 2010 (IEA, 2011b). Two important considerations that favor nuclear power generation are its ability to provide electricity at a relatively low price; and its potential to curb GHG emissions. Thus, if climate change becomes a serious tangible threat and renewables are unable to meet energy demands, nuclear energy will likely become the primary option for immediate deployment.

The safety of nuclear power plants has been a longstanding issue after two major nuclear power plant accidents, at Three Mile Island in the USA (1979) and Chernobyl in Ukraine (1986). More recently, following the March 11, 2011 tsunami in Japan, significant damage to the Fukushima Daiichi nuclear plant resulted in the release of radioactive materials into the environment. The incident resulted in significant policy debates in many countries over the risk and safety of nuclear power plants, whose long-term role in supplying energy to the world is in question. The Fukushima incident has caused significant public concern about the safety of nuclear power and, as a result, Germany has decided to phase out its nuclear power facilities before the end of their economic life. Similarly, Switzerland has decided to phase out nuclear power generation by 2034 and France, a major nuclear power producer, plans to invest in more renewable sources of energy. Significant delays in obtaining permits and rising costs of construction to meet additional safety measures, coupled with public concerns, are expected to be major hurdles to developing nuclear energy in the future. In spite of this, non-OECD countries such as China, India, and Russia plan to continue the expansion of their nuclear power capacity by 109 GW, 41 GW, and 28 GW, respectively, from 2010 to 2035 (EIA, 2013).

Unconventional non-renewable resources include oil shale and natural gas hydrates in marine sediments, as well as natural gas from coal beds (coal bed methane), low-permeability reservoirs (tight gas), and shale formations (shale gas, discussed further shortly). Unconventional proven reserves account for a significant share of the total reserves in the USA and Canada. Oil shale is a sedimentary rock that contains solid bituminous materials known as kerogen, which release petroleum-like liquids during pyrolysis, a process in which rock is heated under limited oxygen conditions.

While extending throughout the continental USA, shale, a fine-grained sedimentary rock composed of clay, is considered to be an "unconventional reservoir," as it has not been historically exploited for energy (see Figure 1.2). **Shale gas** (a gaseous resource in contrast to shale oil) had been virtually untapped and ignored until the 1973 energy crisis, when new recovery technologies were developed by the US Department of Energy and commercially tested by Mitchell Energy and Development Corporation in the 1980s and 1990s. The recent boom in shale gas production is a result of two main technologies developed during this period: horizontal wells and hydraulic fracturing. Compared to conventional vertical wells, horizontal wells offer the ability to replace four or more vertical wells due to greater reservoir exposure and to reduce surface disturbance from construction. To overcome the low permeability of the shale and to make gas production economically viable, horizontal drilling is used in conjunction with hydraulic fracturing. Hydraulic fracturing involves the use of an aqueous fracturing fluid at high pressure to create fissures and interconnected cracks, which increase the permeability of the shale and allow greater flow rates of gas into the well.

As the fluid injected during the hydraulic fracturing treatment needs to be recovered and disposed of before the gas can flow out of the shale, treatment of the hydraulic fracturing fluid poses a substantial challenge. The aqueous fluid that returns to the surface after pressure is relieved is called "flowback" and constitutes 10–40% of the total fracturing fluid. The flowback period depends on the geology of the formation and may last several weeks. The created brine solution may be composed of salts, metals, oils, greases, soluble organic compounds, and radioactivity from radioactive underground sources (Gregory *et al.*, 2011). The most common method of disposal is by injecting the wastewater underground. The wastewater is normally confined to a designated Class II–type well that is regulated under the Underground Injection Control program to minimize possible pollution and contamination. The disposal well is placed thousands of feet underground in porous rock that is separated from groundwater by an encasement of impermeable rock. The nature of the well's geological requirements limits the use of this disposal method to only particular shale wells. If a Class II well is not available locally, the wastewater may be transported or piped to a suitable location, thus increasing the costs. Other treatment options for shale gas wastewater include freeze–thaw/evaporation, ion exchange, capacitive desalination, electrodialysis reversal, and artificial wetlands. These treatment options, however, suffer from limitations, including restriction to colder climates, high costs, reliance on additional chemical treatments, and the limited salinity tolerance of plant species.



Source U.S. Energy Information Administration based on data from various published studies.
Upeate: May 9, 2011

Fig. 1.2 US shale plays. Source: Data from US Energy Information Administration.

1.3 Renewable Energy

Renewable energy is derived from resources that are available on a renewable basis and inexhaustible in the foreseeable future. Examples of these types of resources are wind, solar, geothermal, ocean (tidal), hydro, and biomass. Although only about 10% (1,452 Mtoe or 57.6 QBtu) of total energy use was met by renewables in 2010, the share of renewables is anticipated to reach 15% (i.e., 3,098 Mtoe or 123 QBtu) by 2040 (EIA, 2013). The growth in electricity generation from renewables is expected to originate from four primary resources: wind, hydro, biomass, and solar photovoltaics. The European Union (EU) is likely to lead this growth. Renewable resources have significant and growing potential, particularly since the technology for harnessing renewable energy is developing rapidly and production costs have been decreasing. Some of the major renewable energies are discussed in this section.

Globally, **hydroelectricity** is currently the largest source of renewable electricity generation. In 2009, net global hydroelectricity generation was 3,145 billion kWh (3,145 TWh), which accounted for almost 84% of the renewable electricity generated, and 17% of the total electricity generated (from all sources). There is significant potential for growth in hydroelectricity generation in non-OECD countries where the water resources are relatively underutilized. However, it is important to note that there is also significant natural fluctuation in energy output depending on rainfall, glacier melt, and other weather-related conditions. Table 1.4 presents the major hydroelectricity-generating countries as of 2010. China is the largest, followed by Brazil and Canada.

The major issues facing hydroelectric projects are environmental concerns created by damming rivers and the large capital investment required. Smaller hydroelectric projects, referred to as micro- and pico-projects, are more viable in developing countries as they have lower installation costs and can be privately owned by co-operatives. Micro- and pico-projects can also provide electricity in remote rural areas that are not connected to the national power grid.

Wind energy, another important resource, uses wind turbines to convert the kinetic energy of air flow into electricity. Both onshore and offshore wind energy sources are being aggressively explored by many countries. The net wind energy electricity generation was 328 billion kWh in 2009, which accounted for 7% of the total renewable net electricity generated. The USA produces the largest amount of electricity from wind, followed by Spain, Germany, China, and India. Denmark, however, has the largest penetration of wind-derived energy into its national grid (nearly 20% of its electricity generation; IEA, 2011a).

The **solar** energy system converts sunlight into energy that can be used to heat water or to generate electricity directly using photovoltaic (PV) technology. Currently, total solar PV electricity generation is about 20 billion kWh worldwide, and is expected to reach 740 billion kWh in 2035 (IEA, 2011b), corresponding to an average growth rate of 15% per year. Significant growth in PV

Table 1.4 Major hydroelectricity-producing nations in 2010

Country	Net hydroelectricity generation (billion kWh)
China	715
Brazil	400
Canada	350
USA	260
Russia	165
Norway	115
India	110

Source: Data from http://www.eia.gov/

electricity is anticipated to occur in the EU due to strong governmental support. Countries such as the USA, China, and India are also likely to have strong growth and may meet and exceed the EU in total electricity generation from PV.

Natural heat located close to the Earth's surface created by geological hot spots is referred to as a **geothermal** resource. This geothermal heat can be converted into electricity. Net global geothermal electricity generation in 2010 was 64 billion kWh. The USA is presently the largest producer of geothermal electricity (16 billion kWh), followed by the Philippines (9 billion kWh), Indonesia (8.5 billion kWh), and New Zealand (6.6 billion kWh). In Iceland, nearly 26% of net electricity generation originates from geothermal resources (EIA, 2012).

The lunar- and solar-induced tidal motions of oceans can be captured using wave energy converters (WECs) for producing electricity. For example, Canada and Norway have several small tide mills underwater for electricity generation. The first large-scale **tidal energy**–based power plant was built on the Rance river in Brittany, France. The Rance tidal power plant has an installed capacity of 240 megawatts (MW) and has been in operation since 1966. Presently, the world's largest tidal power plant is the Shihwa Lake tidal power plant in South Korea, with a generating capacity of 254 MW. This plant has been in operation since 2011.

Bioenergy is generated from feedstocks of biological origin, also known as biorenewable resources. Examples of bio-based feedstocks are crops rich in starch (corn, cassava, sorghum) and sugar (sugarcane, sugarbeet, sweet sorghum); oil-rich seeds (soybean, rapeseed, canola, palm fruits); lignocellulosic biomass (agricultural residues, forest residues, dedicated energy crops); and organic wastes (animal manure, industrial waste, agri-waste, food waste, sewage sludge). These feedstocks can be used to produce energy/energy carriers in three forms: liquid (e.g., ethanol, butanol, and biodiesel); gas (e.g., hydrogen and methane); and solid (e.g., fuel wood and biobriquettes).

Technologies for producing ethanol from sugar and starch-rich crops, biodiesel from seed oil and waste (cooking) oil, and methane from biomass are already available commercially in many developed countries. In 2012, total global bioethanol and biodiesel production was about 64 million gallons/day (242 million liters/day) and 14 million gallons/day (53 million liters/day), respectively (EIA, 2012). The USA is the leading biofuel-producing nation with a total capacity of 37 million gallons/day (140 million liters/day), followed by Brazil with 22 million gallons/day (84 million liters/day). Europe, on the other hand, is paving the way for anaerobic biotechnology in the form of biogas production. Biogas technology is currently being implemented for the production of electricity and heat using combined heat and power (CHP) units, upgraded to natural gas quality for injection into gas pipelines, and compressed for use in CNG engines for transportation. Europe alone produced 3,000 MW of electricity from biogas in 2007 and nearly half of that came from Germany, a global leader in biogas technology.

1.4 Why Renewable Energy?

There are several factors driving the rapid growth in renewable energy. Some of the motivation for this is discussed here. Renewable energy development policies in the USA emphasize the importance of energy independence, whereas in Europe the aim is in relation to climate change.

1.4.1 Energy Insecurity

The OPEC (Organization of the Petroleum Exporting Countries) oil embargo of 1973 against the USA significantly affected the US economy because of soaring petroleum prices. For the first time in

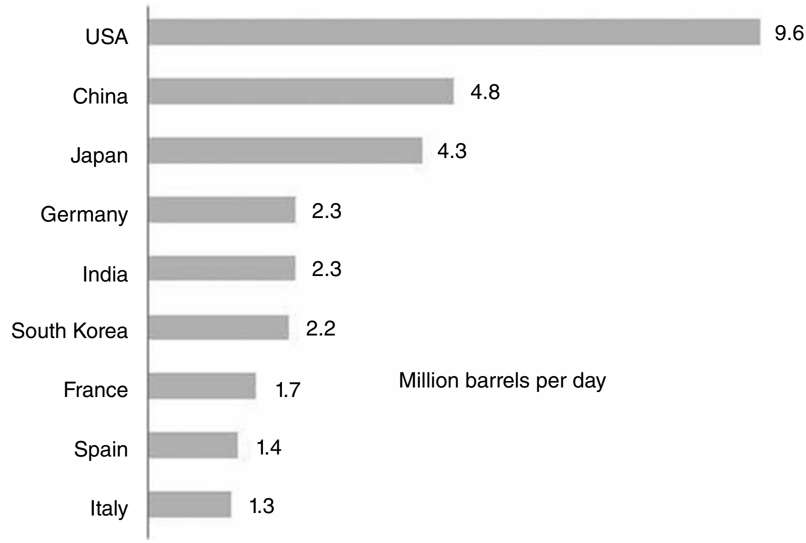


FIG. 1.3 Top 10 oil-importing nations. Source: Data from EIA, 2011.

its history, the USA realized its vulnerability caused by an insatiable dependence on petroleum imports. The economies of many other developed countries also strongly rely on the continual availability of energy at an affordable price. Many nations currently meet their energy demands through imports from geo-politically unstable countries. For example, in 2011 the USA imported nearly 45% of its liquid fuels (net imports of 8.4 million barrels/day) to meet its transportation needs, and Japan imported nearly 84% of its total energy needs. China also depends heavily on imported oil and brought in nearly 52% of its consumption from overseas in 2010. Figure 1.3 shows the top 10 oil-importing nations. It is evident that the development of renewable energy could significantly reduce the world's reliance on imports and the risk of energy insecurity.

1.4.2 Depletion of Energy Resources Reserves

The economies of the OECD countries have primarily been built on energy. These countries account for about 43% of total global energy demand, but contain less than 20% of the world's population. Moreover, there is a growing demand for energy in non-OECD countries, particularly emerging economies such as China, India, Brazil, Russia, and Indonesia, where people have only recently begun to enjoy the comforts of their rising affluence. The International Energy Outlook 2013 projects that the energy demand in non-OECD countries will increase by nearly 85% of current levels by 2040 (EIA, 2013). Most (>85%) of our energy needs today are met through the exploitation of non-renewable energy resources, the reserves of which are known to be limited. Table 1.5 illustrates proven reserves of non-renewable energy resources correlated with current consumption rates. It is apparent from the table that known energy reserves may be exhausted within one to two generations. In addition, as reserves begin to empty, oil becomes increasingly difficult to extract until market prices rise enough to make extraction economically viable. The result is higher consumer fuel prices. Thus, renewable energy resources are and will become critical to buffer increasing global energy demands and associated cost increases.

Table 1.5 Global proven reserves of non-renewable energy resources

Energy resources	Years proven reserves to last
Petroleum oil	48
Coal	150
Natural gas	48
Uranium	90

Source: Data from IEA, 2011b; OECD NEA, 2010.

1.4.3 Concern about Climate Change

The use of fossil-derived energy is a major source of GHG emissions, especially CO_2. Energy-derived CO_2 emissions are considered to be a significant contributor to global climate change. Among the various types of fossil fuels, coal releases the most CO_2 per unit of energy, followed by petroleum. Natural gas (also derived from fossil fuel) is considered to be the cleanest form of non-renewable energy in terms of emissions of CO_2 and other pollutants. Globally, China is the largest emitter of energy-related CO_2 with estimated emissions of 7.5 giga metric tons (Gt) in 2010, followed by the USA (5.4 Gt) and India (1.6 Gt). Coal is the biggest contributor to total emissions due to its extensive use in China and India. Energy-related CO_2 emissions worldwide were estimated at 30.5 Gt in 2010, and the World Energy Outlook 2011 projects that emissions could be as high as 36.4 Gt by 2035, leading to a long-term increase in the Earth's temperature by more than 3.5 °C. The effects of global warming are likely to be devastating, such as rising sea levels that cause the large-scale dislocation of human settlements, along with erratic rainfall patterns, drought, flood, and heat waves (IEA, 2011b). Some researchers believe that we may already be witnessing the beginning of some of these severe and unpredictable weather events.

The 450 Scenario (World Economic Outlook 2011) aims at reducing the release of energy-related CO_2 to 21.6 Gt by 2035 through strong policy interventions. The goal of the 450 Scenario is to limit the long-term atmospheric CO_2 concentration to 450 CO_2eq. This change is expected to cap the global average temperature increase to 2 °C. The projected CO_2 emissions reduction will likely shift the share of fossil energy in the total global energy mix from 81% in 2009 to 62% in 2035. Renewable energy resources are anticipated to play a significant role in supplying carbon-neutral energy and tackling global climate change.

1.5 Bioenergy

Bioenergy also has the potential to contribute a portion of future energy needs; however, there are many challenges that need to be overcome. This section discusses the current status, benefits, and limitations of bioenergy. It is important to note here that presently there is no formal definition of bioenergy and biofuel, but for convenience and clarity, the following definitions of bioenergy and biofuel are used in this book.

- **Bioenergy** is a generic term that includes solid, liquid, and gaseous fuels of biological origin. The energy, which is in the form of heat and power (i.e., electricity) for stationary applications or as a liquid biofuel for transportation, can be collectively termed bioenergy.

- **Biofuel** is a more specific term that refers to any liquid fuel derived from biological materials with sufficient energy density and combustion characteristics to make it a suitable transportation fuel. Common examples of biofuels are ethanol, biodiesel, and biomass-derived Fischer–Tropsch fuels. Methane and hydrogen are gaseous fuels that can be compressed for use in jet propulsion and may also be considered biofuels.

1.5.1 Current Status of Bioenergy Production

The technologies for sugar and starch-derived ethanol, and seed oil and waste oil–derived biodiesel are commercially available. Feedstocks that produce these types of fuels are known as first-generation feedstocks as a result of early research into these renewable resources. Current commercial facilities and processing are expected to continue to dominate biofuel production in the foreseeable future. Currently, the USA and Brazil are the major biofuel-producing countries.

The *second- and third-generation feedstocks*, which consist of non-food feedstocks such as *lignocellulosic biomass*, *Jatropha*, and *microalgae*, can also be used to produce bioenergy, but are not currently economically viable for commercial-scale production. Considerable research and technology development efforts are underway to produce advanced *drop-in fuels*, such as *butanol* and jet fuel at prices comparable to petroleum oil. Several commercial-scale *cellulosic ethanol* plants have been built in the USA (Iowa and Kansas) and China in recent years that use corn stover/cobs as the major feedstock. Dilute acid and steam explosion are pretreatment technologies adopted in these commercial cellulosic ethanol plants, while enzymes for enzymatic hydrolysis are provided by biotechnology companies—Novozyme or DuPont.

Algal biomass for biofuels, specifically biodiesel and biobased hydrocarbons production, has received significant attention in recent years. Algal technology, however, faces many engineering challenges, including efficient reactor design for light penetration and CO_2 transfer, contamination of open pond systems, algal cell recovery/harvesting, dewatering, and lipids extraction. Among the major bottlenecks for scale-up is the low biological productivity of lipids, the precursor for biodiesel and other hydrocarbons.

Anaerobic digestion is arguably the oldest form of renewable energy production and has been widely applied commercially to produce bioenergy, namely biogas, from food-processing wastes, animal manure, high-strength industrial wastewaters, and even agri-residues and energy crops. The biogas produced is used to generate electricity and heat via combined CHP units. Biogas can also be upgraded to natural gas quality for injection into gas pipelines or implemented as CNG for use as transportation fuel. In addition, anaerobic biotechnology has been employed for ethanol, butanol, and hydrogen production from fermentable sugars and synthesis gas ($CO + H_2$) also known as syngas. The organic acids produced during anaerobic fermentation also have the potential to be converted into gasoline, jet fuel, and diesel through various microbial pathways currently under investigation. In rural areas of developing countries, household anaerobic digesters play an important role and have been providing the energy necessary for cooking and lighting for decades. Anaerobic biotechnology may be an important avenue in providing energy globally.

Somewhat related to anaerobic digestion is the development of microbial fuel cells (MFCs), which exploit the biological electricity-generation capabilities of naturally occurring microbes. However, MFCs face significant challenges as a means for sustainable electricity generation due to the complexity associated with growing and maintaining microbiological cultures, in addition to technological challenges such as low electricity production and maintaining the required pH (potential hydrogen) gradients across membranes.

Combustion, *pyrolysis*, and *gasification* (the major thermal conversion technologies) have been widely studied in recent decades. Biomass combustion and co-firing of biomass with coal for energy (steam and electricity) production have been commercialized. *Pyrolysis* of biomass at a high temperature and pressure under a low oxygen environment produces a liquid fuel called bio-oil and a solid residue called *biochar*. Bio-oil can be refined to produce liquid hydrocarbons and chemicals. Gasification of biomass at high temperature under a controlled environment produces syngas, which can be further converted to electricity or biofuels such as ethanol and liquid hydrocarbons. Coal gasification is commercially available for large-scale production, while most of the biomass gasification units have only been demonstrated at a smaller scale.

1.5.2 Merits of Bioenergy

Bioenergy is considered to be a low carbon footprint and an environmentally friendly energy resource. Its potential merits include providing energy security, benefiting local and national economies by contributing to agricultural sectors, and improving local and global ecology. Some of the merits of bioenergy are highlighted here.

Reducing the Nation's Dependence on Imported Energy Resources

As discussed previously, many countries around the world are heavily reliant on imported petroleum to meet their energy demands. Most often, this non-renewable resource originates from unstable nations, posing a threat to national security and the quality of life. Biorefineries, premised on the fractionation of biomass feedstocks into bioenergy and biochemicals, can reduce our dependence on imported energy resources and mitigate the issue of national security.

Environmental Merits of Bioenergy

The Clean Air Act Amendments of 1990, which mandated the use of oxygenated gasoline in areas with unhealthy levels of air pollution, were the turning point in the boom of biofuel industries in the USA. Since 1992, *methyl tertiary-butyl ether* (MTBE), a fuel oxygenate octane enhancer, has been used at higher concentrations in some gasoline mixes to fulfill the oxygenation requirements. Oxygenated fuel promotes gasoline to burn more completely and cleanly, thereby reducing harmful tailpipe emissions from motor vehicles. In the past, MTBE was chosen over other oxygenates, primarily due to its excellent blending characteristics and low cost. However, groundwater contamination due to the poor biodegradability of MTBE prompted some states, including California, to phase out MTBE use by the end of 2002. This prompted the use of ethanol as an oxygenate to replace MTBE and resulted in a boom in ethanol industries across the USA. Ethanol is an alcohol that contains 35% oxygen and improves fuel combustion when blended with gasoline, resulting in low tailpipe emissions of carbon monoxide, unburned hydrocarbons, and nitrogen oxide (NOx). With favorable properties, such as a higher octane number (108), broader flammability limits, higher flame speeds, and higher heat of vaporization, ethanol has become a valued replacement for MTBE. A lifecycle assessment looking at ethanol produced from renewable resources indicated that compared to gasoline, sugarcane-based ethanol reduces GHG emissions by 84% (on a volume basis), corn ethanol by 30%, sugar beet ethanol by 40%, and cellulosic ethanol by 85%. Consequently, ethanol has been considered to have significant implications as a fuel in addition to being an oxygenate.

In developing countries, biogas has played a critical role in curtailing indoor air pollution by replacing highly polluting firewood and cow dung as a cooking fuel, in addition to providing much-needed energy resources for cooking. Additionally, bioenergy has also provided an opportunity for improving health and sanitation by effective stabilization of biowastes, especially during anaerobic digestion. Anaerobic digestion technology, including methane capture, at landfills also helps reduce GHG emissions from those sites. Methane is an important GHG that has a global warming potential (GWP) of 20 times higher than that of CO_2 on a 100-year timescale (Forster *et al.*, 2007).

Socio-Economic Benefits of Bioenergy

The successful creation of a biobased economy has the potential to create local jobs and improve rural economies. Various entities likely to benefit from the deployment of biorefineries are rural farmers and farm co-operatives; industries involved in agricultural equipment, facility design, and fabrication; construction companies; and biotechnology industries. State and federal governments are also likely to benefit from additional tax revenues. In developing countries, improved access to local energy sources will have significant social merits, such as increased time for women and children to pursue education and other activities rather than collecting fuel biomass.

1.5.3 Demerits of Bioenergy

Although real and/or perceived environmental benefits are important drivers for the greater use of bioenergy, no fuel system is free of environmental ramifications. Multi-dimensional conflicts exist in the use of land, water, energy, and other environmental resources for food, feed, and bioenergy production. Biofuels derived from starch, sugar, and oil-seed crops, and even lignocellulosic biomass, face several challenges. Some of these issues are outlined here.

Potential Impact on Food/Feed Supplies and their Prices

The utilization of first-generation feedstocks for biofuel production has intensified the competition globally for resource utilization (including land) for food, feed, and biofuels. This, among other factors, has contributed to a rise in prices of essential staples in recent years, as starch and sugar-rich cereal grains make up nearly 80% of the world's food supply.

Impact on Biodiversity

The rising demand for bioenergy feedstocks also has led to the increased clearing of forestlands for growing more grains and oilseeds for biofuels, thereby having impacts on biodiversity and ecological balance. This reduction in biodiversity could also be an issue with second-generation biofuel crops such as energy crops. In addition, it is not certain whether the clearing of land for bioenergy feedstocks is advantageous or detrimental to reducing global GHG emissions.

Impact on Water Quantity

Significant amounts of water are needed for both biomass feedstock production and processing. The requirement for fresh, clean, and consistent water supplies is a major issue for emerging biofuel industries.

Impact on Water Quality

The water quality in streams/lakes is likely to deteriorate due to the transport of eroded soils from newly established cropland to various water bodies. In addition, leaching of chemicals from fertilizers, insecticides, and pesticides to surface water and groundwater may also affect water quality. Nutrients in water bodies are responsible for eutrophication (algal growth) and subsequent hypoxia. Water pollution from wastewater disposal from biofuel facilities is another challenge facing the biofuel industries. For example, vinasse, which is produced as waste stream after ethanol recovery from sugarcane-to-ethanol plants, is posing a significant challenge to sugarcane-to-ethanol producers in Brazil.

Degradation of Soil Quality/Soil Erosion

There is potential for the deterioration of topsoil quality with second-generation biofuels, because agricultural residues such as corn stover, wheat, and rice straw provide organic carbon and nutrients when left in the field. Removal also reduces the mulching effect of these biomass feedstocks, which protects the nutrient-rich topsoil against erosion. Adoption of a no-till farming method, although limited in certain areas, may be required in order to reduce the impact of residue removal on soil quality.

References

EIA (2011). *Short-Term Energy Outlook*. Washington, DC: U.S. Energy Information Administration. http://www.eia.gov/forecasts/steo/, accessed April 2016.

EIA (2012). *International Energy Statistics*. Washington, DC: U.S. Energy Information Administration. http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=44&pid=44&aid=2&cid=regions,&syid=2005&eyid=2009&unit=QBTU, accessed April 2016.

EIA (2013). *International Energy Outlook 2013*. Washington, DC: U.S. Energy Information Administration. http://www.eia.gov/forecasts/ieo/pdf/0484(2013).pdf, accessed April 2016.

Forster, P., Ramaswamy, V., Artaxo, P., *et al.* (2007). Changes in atmospheric constituents and in radioactive forcing. In: S. Solomon, D. Qin, M. Manning, *et al.* (eds.), *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, pp. 114–43.

Gregory, K.B., Vidic, R.D., and Dzombak, D.A. (2011). Water management challenges associated with the production of shale gas by hydraulic fracturing. *Elements* 7: 181–6.

IEA (2010a). *Key World Energy Statistics 2010*. Paris: International Energy Association. doi: 10.1787/9789264095243-en.

IEA (2010b). *World Energy Outlook 2010, Executive Summary*. Paris: IEA. http://www.iea.org/Textbase/npsum/weo2010sum.pdf, accessed April 2016.

IEA (2011a). *Key World Energy Statistics 2011*. Paris: International Energy Agency. doi: 10.1787/key_energ_stat-2011-en.

IEA (2011b). *World Energy Outlook, Executive Summary*. Paris: IEA. http://www.worldenergyoutlook.org/publications/weo-2011/, accessed April 2016.

IEA (2014). *Key World Energy Statistics 2014*. Paris: International Energy Agency. doi: 10.1787/key_energ_stat-2014-en.

OECD NEA (2010). *Uranium 2009: Resources, Production and Demand*. Publication 6891. Paris: OECD Nuclear Energy Agency/International Atomic Energy Agency. https://www.oecd-nea.org/ndd/pubs/2010/6891-uranium-2009.pdf, accessed April 2016.

PEIS Information Center (2012). *About Oil Shale*. Lakewood, CO: Oil Shale & Tar Sands Programmatic EIS. http://ostseis.anl.gov/guide/oilshale/index.cfm, accessed April 2016.

UNFPA (2011). *State of World Population 2011*. New York: United Nations Population Fund. http://foweb.unfpa.org/SWP2011/reports/EN-SWOP2011-FINAL.pdf, accessed April 2016.

Exercise Problems

1.1. Why is energy so important for the socio-economic development of a nation?
1.2. Briefly discuss the current global energy situation.
1.3. Define renewable and non-renewable energy resources, with examples.
1.4. If climate change is associated with energy-derived CO_2, what would be the short- and long-term goals of curtailing CO_2 emissions?
1.5. Briefly discuss shale gas and shale oil and the impacts they are having on the development of renewable energy resources.
1.6. Explain the major motivations for moving toward renewable energy.
1.7. What are the major reasons for the slow development and implementation of renewable energy technologies?
1.8. Differentiate between bioenergy and biofuel, with examples.
1.9. What are some of the potential advantages and disadvantages of bioenergy?
1.10. What are the various feedstocks for producing first- and second-generation bioenergy?