

PART I

Background and Outline

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Bioenergy Systems: An Overview

The use of fossil fuels that are currently our major energy sources leads to undesired effects such as global warming, environmental pollution, and health damage. Moreover, an increased consumption of fossil energy results in a fast depletion. Therefore, it is desired that renewable energy sources, such as biomass, solar, and geothermal, should replace fossil fuels. Biomass was the first fuel used by people that had dominated the global energy supply until the nineteenth century and is still used mainly in rural areas of developing countries for cooking and heating. However, biomass can be converted into all major energy carriers such as electricity, heat, and transport fuels as well as a wide diversity of chemicals and materials that are presently produced from fossil fuels. Biomass as a sustainable energy source can significantly contribute to the future world energy supply. This chapter presents a brief introduction to biomass and bioenergy systems. We start this chapter with a discussion of current energy and environmental problems in Section 1.1. Section 1.2 is an introduction to bioenergy systems, including historical development, biomass resources, and their characteristics as well as environmental impact and economics. Biomass conversion processes, including pretreatment, thermochemical, biochemical, and chemical conversion, are reviewed in Section 1.3. Finally, Section 1.4 is devoted to the utilization of biomass for transport fuels, power generation, heating, and chemicals.

1.1 ENERGY AND THE ENVIRONMENT

1.1.1 Global Energy Consumption

Energy is commonly considered as one of the most essential elements in the development of human civilization. We need energy for almost all activities, such as food, clothing, shelter, materials, transportation, and communication. The demand for energy has continuously increased since the beginning of human civilization. In the hunter-gatherer society, man used food as the main energy source. After the fire discovery, energy was also used for heat and light as well as cooking and roasting. About 10,000 years ago, the agricultural technology started

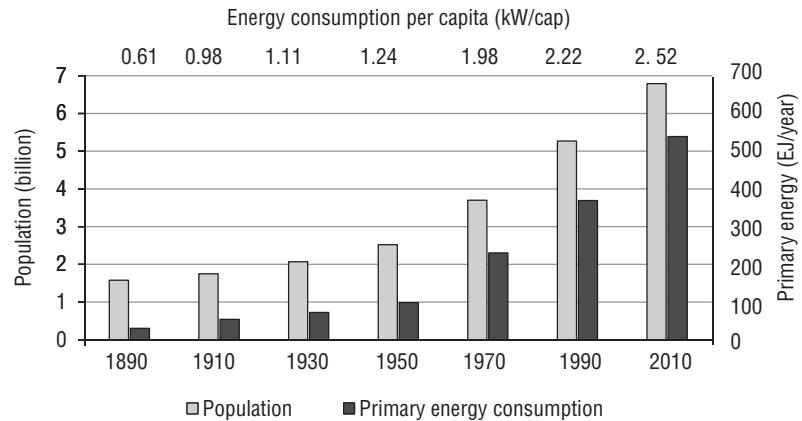


FIGURE 1.1
World population and primary energy consumption, 1890–2010 (sources: Klass, 1998; UN, 1999; IEA, 2013).

that increased energy demand for field irrigation, soil cultivation and crops production, and nonagricultural purposes, such as tools made from wood and iron. Since the industrial revolution in the nineteenth century, large amounts of energy have been required for new applications, such as steam and internal combustion engines and various electrical equipment.

Figure 1.1 illustrates the change of world population and primary energy consumption from 1890 to 2010. In this period, the world population has increased by a factor of more than 4, from 1.6 to 6.8 billion people. On the other hand, the global primary energy consumption has increased by a factor of more than 17, from 31 to 539 EJ/year. Between 1890 and 2010, the per capita consumption of primary energy (expressed as power expenditure) has quadrupled from 0.61 to 2.52 kW/capita. This amount significantly exceeds the energy of the Western food consumption of about 0.2 kW/capita, which is sufficient for the human existence.

However, the regional distribution of energy use is very diverse. Table 1.1 summarizes the 2010 population, total primary energy consumption, and primary energy consumption per capita (expressed as power expenditure) of several countries selected from all continents, including developed and less developed countries. The world's highest energy consumption per capita relates to the developed countries in North America, such as Canada (12.9) and the United States (10.6), Europe, such as France (5.7), Germany (5.7), and the United Kingdom (4.8), and Asia, such as Japan (5.7 kW/cap). On the other hand, major parts of the world population consume much less energy per capita, particularly in the developing countries such as India (0.63), Bangladesh (0.21), and in Africa, such as Ethiopia (0.053 kW/cap).

The highest energy consumers are China and the United States that use 19.8 and 19.3% of the world's primary energy, respectively. To the world's 10 highest primary energy consumers also belong Russia (5.7), India (4.3), Japan (4.3), Germany (2.7), Canada (2.5), Brazil (2.2), France (2.2), and the United Kingdom (1.7%). The top 10 countries consume more than one-third of the world's total primary energy.

Table 1.1 also presents the energy intensity of economic output that is expressed as a ratio between the primary energy use and the gross domestic product (GDP) (in US\$₂₀₀₅). Generally, more developed countries show lower energy intensity of their economy that is mainly due to the higher efficiency of energy conversion. Some countries, such as Russia, China, and less developed countries consume more primary energy per GDP, which is largely due to a less efficient economic system. However, differences in the energy intensity are also caused by other factors, such as country size, climate, composition of primary energy supply, and differences in an industrial structure (Smil, 2000).

TABLE 1.1 Energy Characteristics for Several Countries, 2010

Country	Population (million)	Primary Energy Consumption (EJ/year)	Primary Energy Consumption Per Capita (kW/cap) ^a	Energy Intensity (MJ/US\$ ₂₀₀₅)	Carbon Dioxide Emissions (Mton/year)
The United States	309.3	103.4	10.6	7.92	5,637
Canada	33.8	13.7	12.9	11.4	547
Mexico	112.5	7.69	2.17	8.33	432
Germany	81.6	14.7	5.68	5.01	793
France	64.9	11.6	5.71	5.28	389
The United Kingdom	62.3	9.41	4.78	4.04	529
Russia	142.5	30.9	6.88	34.2	1,642
Brazil	195.8	11.9	1.93	10.9	451
Argentina	41.3	3.53	2.71	13.9	174
China	1,330.1	106.4	2.54	27.7	7,997
India	1,173.1	23.1	0.625	18.5	1,601
Japan	127.6	23.0	5.71	5.01	1,180
Bangladesh	156.1	1.04	0.212	13.4	57.0
Saudi Arabia	25.7	8.28	10.2	23.0	469
South Africa	49.1	5.90	3.81	20.5	473
Egypt	80.5	3.49	1.38	27.8	191
Ethiopia	86.0	0.144	0.053	7.16	6.45
World	6,863.2	538.7	2.49	10.5	31,502

Source: EIA (2013a).

^aExpressed by power expenditure.

It is expected that energy consumption will significantly increase in the future. This is mostly due to two effects, namely, the expected population growth in the future and the increase of energy use per capita in less developed countries. According to the Shell energy scenarios, the global primary energy consumption in 2050 can range between 770 and 880 EJ/year, depending on the future pattern of energy consumption (Shell, 2008). The United Nations Development Program foresees in 2050 the primary energy consumption in the range of 600–1040 EJ/year and in 2100 in the range of 880–1860, depending on the population and economic growth (UNDP, 2000).

Historical energy use shows a very large change not only in the amount of consumed energy, as described above, but also in the pattern of energy sources. Human civilization has used biomass (mainly wood fuel) as a primary energy source for a long time until the beginning of the industrial revolution. The fossil fuels era began at the end of the nineteenth century when coal started to replace wood as the primary fuel. Later, other fossil fuels, such as oil and natural gas, were available in large amounts and low cost. Figure 1.2 illustrates the historical primary energy consumption pattern for the United States for the years 1850, 1930, and 2010. In 1850, wood was the dominant fuel contributing more than 90% to the primary energy consumption in the United States. Eighty years later in 1930, biomass was replaced by coal as the main fuel that contributed 58% to the primary energy consumption. The same year the remaining fossil fuels were oil (25%) and natural gas (8%), whereas the share of biomass was reduced to 6% only. Eighty years later, in 2010, fossil fuels contributed 83% to the primary energy consumption, whereas the remaining primary energy was supplied as nuclear electric (8.6%), biomass (4.4%), and other renewables (3.9%). Figure 1.2 also illustrates that over the period

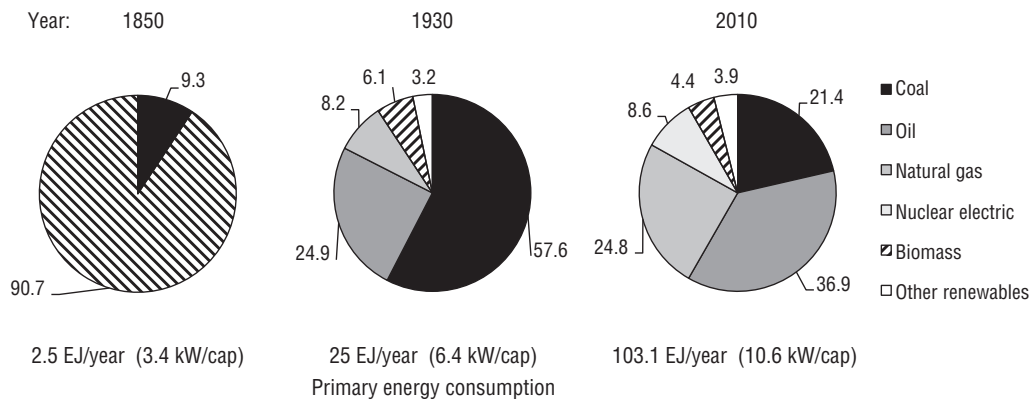


FIGURE 1.2 Historical primary energy consumption patterns (%) for the United States (source: EIA, 2011).

1850–2010, the primary energy consumption in the United States has dramatically increased from 2.5 to 103.1 EJ/year, which is due to the availability of fossil fuels. Over the same period, the primary energy consumption per person has increased from 3.4 to 10.6 kW/capita.

Figure 1.3 illustrates the share of various energy sources in the global primary energy consumption for the years 1973 and 2011. For both years, the global energy pattern was dominated by fossil fuels that contributed 86.6 and 81.8%, respectively, to the global primary energy consumption. In 1973, oil (46%) was the main fossil fuel, whereas in 2011 its share was reduced to 32%. Over the period 1973–2011, the share of coal increased from 25 to 29% and that of natural gas from 16 to 21%. On the other hand, the contribution of bioenergy remained almost constant, 10.6% in 1973 and 10.0% in 2011. Other energy sources in 2011 were nuclear electric (5.1%) and various renewable energy forms (3.3%), such as hydro, geothermal, solar, and wind.

It should be noticed that currently biomass is the fourth fuel in the world that has an average share of 10% in the global primary energy consumption. However, the distribution of biomass consumption is very unequally spread between developed and developing countries. The major part of biomass (about 80% of the world biomass) is consumed in Africa, Asia, and Latin America where it is used mainly for cooking and heating. The largest share of biomass in total primary energy consumption corresponds to Africa (47%), followed by Asia (25%) and Latin America (19%). In some of the least developed countries in these regions, biomass is the dominant fuel whose share is up to 80% of a country primary energy consumption (FAO, 2010).

On the other hand, in the developed countries, biomass is mainly consumed for production of power, fuels, and chemicals, which is the main subject of this book.

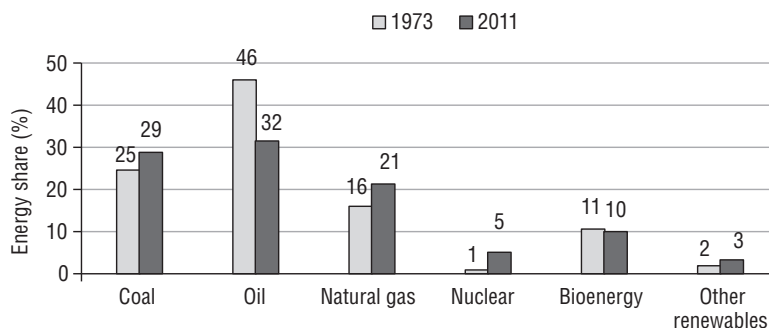


FIGURE 1.3 Share of energy sources in the global primary energy supply (source: IEA, 2013).

1.1.2 Conversion and Utilization of Energy

Primary energy is not suitable for a direct use by consumers and is usually converted using an energy system into various secondary energy forms that can be either stored or transported to end users. An energy system is arranged as a chain that comprises a number of stages, as illustrated in Figure 1.4. The energy chain begins with a supply of the primary energy and ends with the final energy users. Primary energy can be supplied from the environment in various forms, such as fossil fuels (coal, oil, and natural gas), nuclear fuels (uranium), and renewable energy, such as biomass, hydropower, wind, solar, and geothermal. Currently, the primary energy is mainly supplied from fossil fuels (81.6% in 2011) (see Fig. 1.3), as mentioned in Section 1.1.1.

Conversion of the primary to the secondary energy (also called energy carriers) takes place in various plants and devices, such as power and combustion plants, petro- and biorefineries, and fuel plants. The most common energy carriers are electricity, heat, cold, and various fuels, such as hydrocarbons [gasoline, diesel, or liquefied petroleum gas (LPG)], alcohols, and hydrogen.

The share of electricity as an energy carrier has substantially increased over the years, which is due to its easy transmission and use flexibility. Currently, about 40% of fossil fuels is converted into electricity compared to less than 2% in 1900 (Smil, 2000). In 2011, the amount of produced electricity was equal to 79.7 EJ, which was mainly generated in fossil fuel power plants (68.0%), followed by hydroelectric plants (15.8%), nuclear power plants (11.7%), and renewable sources (4.5%) (IEA, 2013).

Hydrocarbon fuels are other important energy carriers that are produced in oil refineries. In 2011, the amount of 3896 Mton of hydrocarbon fuels were produced, namely, middle distillates (34.7%), motor gasoline (23.1%), fuel oil (13.2%), LPG/ethane/naphtha (9.5%), aviation fuels (6.4%), and other products (13.1%) (IEA, 2013). The advantage of hydrocarbon fuels is that they can be easily transported and stored, whereas electricity can be easily transmitted but is very difficult to store.

In the last stage of the energy chain, energy carriers are consumed by the end users that can be classified into several sectors, as shown in Figure 1.5. This figure illustrates the proportions of the primary energy use in 2010 in four major energy end-use sectors. Notice that Figure 1.5 refers to the primary energy and comprises not only the direct use of energy carriers but also the primary energy consumption required for the production of energy carriers and their transmission and distribution, including appropriate energy losses, for example, electricity losses.

The highest share of the primary energy consumption (51.0%) corresponds to the industrial sector, mainly for the production of bulk materials, such as chemicals,

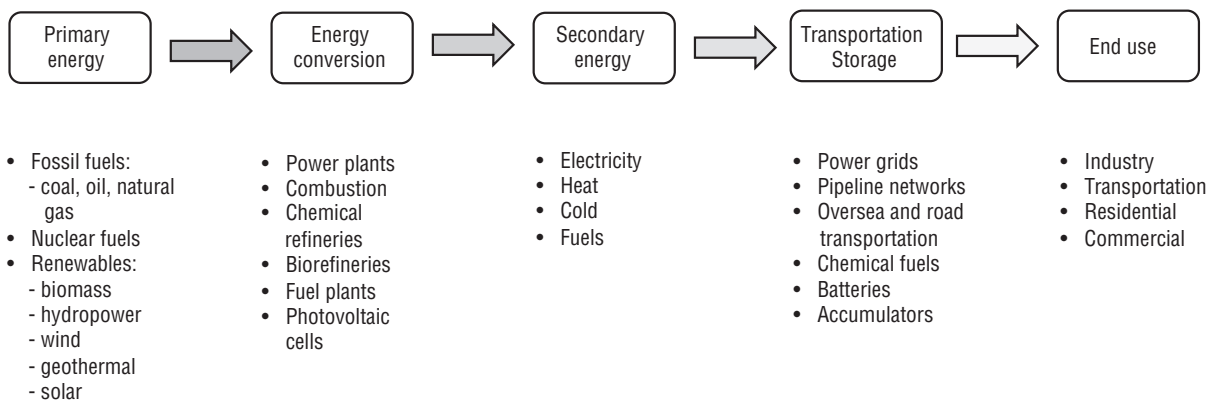
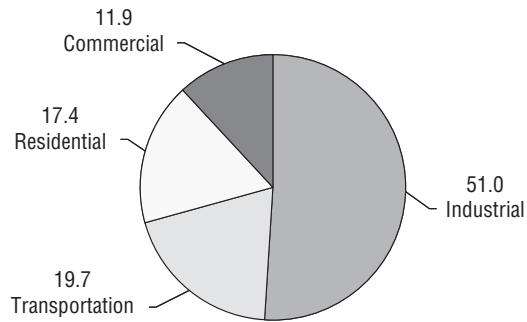


FIGURE 1.4 Schematic of major stages of an energy chain.

FIGURE 1.5
Proportions (%) of primary energy use in 2010 in various world economy sectors (source: EIA, 2013b).



iron and steel, aluminum, pulp and paper, and cement. Transportation sector consumes 19.7% of the primary energy, which almost exclusively (95%) is supplied from oil-based fuels (GEA, 2012). Road transport is responsible for almost 70% of the primary energy consumption in the transportation sector.

The remaining amounts of the global primary energy are consumed by the residential (17.4%) and commercial sectors (11.9%). The largest amounts of primary energy in the residential sector are used for space heating (28%) and cooling (15%), water heating (13%), lighting (10%), and electronic devices (8%) (GEA, 2012). In the commercial sector, the largest primary energy share corresponds to lighting (20%), space heating (16%) and cooling (14%), ventilation (9%), and refrigeration (7%).

1.1.3 Fossil Fuel Resources

Fossil fuels (coal, petroleum, and natural gas) are at present the major source of energy as they supply more than 80% of the global primary energy. Two serious global problems relate to fossil fuels, namely, the fast depletion due to the increased use and the environmental damage due to atmospheric pollution and global warming. Among fossil fuels, oil (petroleum) has the largest share (32%) in global primary energy supply exceeding that of coal (29%) and natural gas (21%), as indicated in Figure 1.3.

Petroleum is a liquid mixture of hydrocarbons and other organic compounds with various molecular weights. Crude oil is found in geological reservoirs under the ground or seabed, mainly in Middle East, North America, Russia, North and West Africa, and South and Central America. Crude oil is refined in refineries into various hydrocarbon fractions that are used either for manufacturing of motor fuels (kerosene, gasoline, diesel, motor oils) or chemicals, mainly plastics. Liquid hydrocarbons can also be recovered from the unconventional resources, such as oil shales and tar sands.

Coal was historically the first fossil fuel that began to replace wood at the end of the nineteenth century. The main combustible substance in coal is carbon whose content varies from about 60% (lignite or brown coal) to more than 90% (anthracite). The remaining constituents are mineral ashes, moisture, and sulfur. Similar to crude oil, coal is found in various parts of the world, mainly in the United States, Russia, China, Australia, Germany, Poland, and South Africa. The principal application of coal is for generation of electricity and heat. Some amounts of coal are liquefied into hydrocarbon fuels or gasified into synthesis gas (syngas) that is used to produce chemicals, such as Fischer-Tropsch (F-T) fuels and methanol.

Natural gas primarily contains methane and small amounts of higher alkanes as combustible substances in addition to carbon dioxide, nitrogen, and hydrogen sulfide. Natural gas is found in reservoirs under the ground and in seabed, very often in proximity to crude oil. Unconventional natural gas reservoirs also exist as

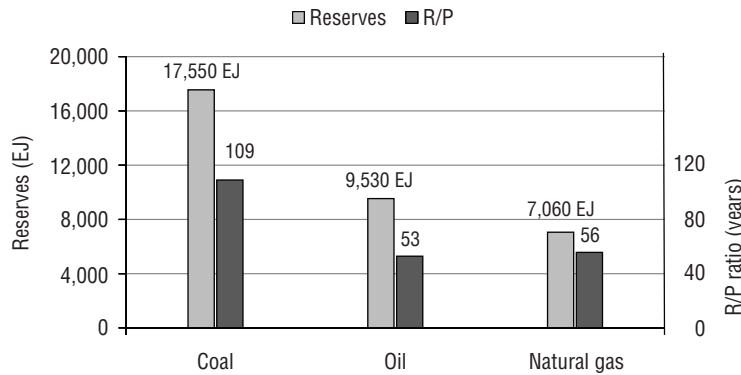


FIGURE 1.6
Global proven fossil fuel reserves and reserves-to-production ratio (R/P) in 2012 (source: BP, 2013).

gas trapped in shale rocks and sandstones as well as at the bottoms of oceans as methane hydrates. In the last years, natural gas became the preferred fossil fuel, mainly due to easy and clean combustion and very high calorific value. The main application of natural gas is generation of electricity in power plants and heat for domestic and residential purposes. Large amounts of natural gas are also used as a chemical feedstock for manufacturing of hydrogen, which is applied to produce ammonia, artificial fertilizers, and methanol.

The amounts of fossil fuels are finite and they become depleted due to increased energy consumption, as described in Section 1.1.1. Figure 1.6 illustrates the existing proven reserves of coal, oil, and natural gas as well as reserves-to-production ratio for these fuels estimated for 2012. According to these estimates, the proven reserves-to-production ratio (R/P) is 109 years for coal, 53 years for oil, and 56 years for natural gas.

It should be noticed that the reported R/P ratios are estimated using the reserves and production data known in 2012. However, the prediction of fossil fuels depletion should be treated with some caution due to two future uncertain effects. First, the global energy consumption is expected to increase in the future that can reduce the estimated depletion time. Second, the possibility of new discoveries and exploration of ultimate resources can extend the depletion time. The historical fossil fuels reserves data indicate that over the past 20 years, the R/P ratio for coal has decreased from 229 to the current 109 years, whereas the respective values for oil has increased from 43 to the current value of 53 years and for natural gas the R/P ratio has remained almost constant (58 years in 1992 and 56 years in 2012) (BP, 2013).

Finally, it should be noticed that the global nuclear energy resources are more abundant than those for the fossil fuels; however, they are also limited (Fay and Golomb, 2002). The nuclear resource life is estimated about 50 years for high-grade uranium ores and several centuries for low-grade ores. On the other hand, a much longer resource life of several millennia is estimated for the global resources of thorium that can be used in breeder reactors.

1.1.4 Environmental Impact of Fossil Fuels Use

The massive use of fossil fuels has deleterious effects on the environment and human health. These effects are associated with all stages of a fossil energy chain, starting from the fossil fuels exploration, through transportation and storage, to the final use, namely, combustion. Moreover, the environmental degradation caused by fossil fuels takes place at various scales where fossil fuels are used, such as households, communities, regional, and global.

The first deleterious effects of fossil fuels on the environment already occur during fuel exploration. Mining of coal is associated with numerous fatal accidents

as well as landscape pollution by spoil heaps and water pollution by contaminants, such as heavy metals and acidic compounds. Transport of oil by tankers results in dangerous accidents that lead to serious water pollution problems.

The most serious environmental effects of fossil fuels are due to their combustion, namely, air and water pollution and global warming. Air pollution resulting from coal combustion was already observed from the beginning of fossil fuels use in the late nineteenth century as smog in large towns. During fossil fuels combustion, a number of pollutants are formed, such as sulfur dioxide, nitrogen oxides, carbon monoxide, and fine particles, which damage human health. Moreover, the above-mentioned primary pollutants can be converted by sunlight to photo-oxidants (ozone, ketones, and aldehydes), which have a negative impact on human health and some materials. Acidic air pollutants, such as sulfur and nitric oxides, can react with water present in the atmosphere to form sulfuric and nitric acids, which are deposited as acid rain on land, lakes, and rivers. Acid rain has harmful effects on soil quality as well as on aquatic life.

The use of fossil fuels also results in water and land pollution. Water quality can be deteriorated by acids and heavy metals drainage from coal mines, acid rains containing sulfur and nitrogen oxides from the fuel combustion in power plants, and by heating up surface waters, such as lakes and rivers as a result of heat removal from the power plants. Land pollution is mainly due to deposits from coal mining, particularly from the surface mining.

The most serious environmental problem due to the fossil fuel use occurs at the global scale as climate change, namely, the global warming. This problem was already known since the early 1960s, later often called in question, but in recent years widely recognized as caused by human activity. The global warming results in an increase of the average Earth's surface temperature due to the greenhouse effect. The greenhouse effect is caused by trapping of the outgoing solar radiation from the Earth's surface by "greenhouse gases" such as water, carbon dioxide, methane, and nitrogen oxides, which accumulate in the atmosphere. The increase of the concentration of greenhouse gases in the atmosphere, mainly carbon dioxide, is a consequence of combustion of fossil fuels.

Global carbon dioxide emissions from the consumption of energy increased from 2 billion ton CO₂ in 1900 to 19 billion ton CO₂ in 1980, and reached more than 31 billion ton CO₂ in 2010. Table 1.1 lists the CO₂ emissions from the consumption of energy for various countries. The largest CO₂ emissions correspond to countries that are the largest energy users as well as countries with the largest share of fossil fuels as primary energy source. In 2010, the largest CO₂ amounts were emitted by China (7,997 Mton), the United States (5,637 Mton), Russia (1,642 Mton), India (1,601 Mton), Japan (1,180 Mton), and Germany (793 Mton).

Figure 1.7 illustrates the increase of the atmospheric CO₂ concentration from 1000 till 2013. The historical data indicate that the atmospheric CO₂ concentration

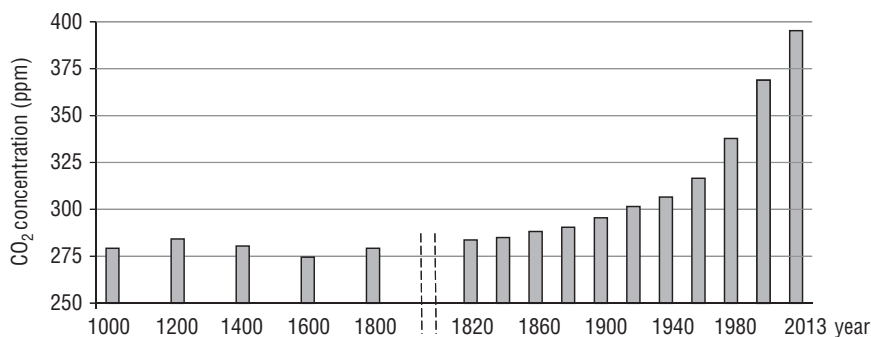


FIGURE 1.7
Atmospheric carbon dioxide concentrations, 1000–2013
(source: CDIAC, 2013).

was quite stable (about 280 ppm) until the beginning of the industrial revolution when the intensive use of fossil fuels began. Since 1900, the atmospheric CO₂ concentration increased gradually until the current level of almost 400 ppm. Based on the projections of the future increase of CO₂ concentration, it is expected that the average Earth's surface temperature can increase in the twenty-first century about 1–3°C (IPCC, 2013). The expected global changes due to this temperature increase are the sea level rise and climatic changes, such as altering precipitation patterns and increased frequency of hurricanes.

Global warming can be controlled by reduction of atmospheric CO₂ emissions from fossil fuels and replacing fossil with carbon-free renewable energy. Carbon dioxide emissions from fossil fuels can be reduced by energy efficiency improvement as well as CO₂ capture and sequestration. In the last years, various CO₂ reduction methods are under development, such as oxy-combustion, solvent separation, and membrane separation. After the capture, CO₂ can be sequestered in depleted oil and gas reservoirs or in deep oceans and deep aquifers (Fay and Golomb, 2002).

1.1.5 Renewable Energy

In recent years the interest in renewable energy is growing due to serious problems related to fossil fuels use, such as fast depletion and environmental damage. Many sources of renewable energy, such as biomass, hydropower, and wind have been used by humans for a long time before the fossil era began. At present the traditional renewable energy sources are further technologically advanced and new renewable sources, such as direct solar, geothermal, ocean, and tidal are being developed (Lund, 2014; Twidell and Weir, 2015).

Compared to fossil fuels, renewable energy has many advantages. Most renewable energy forms originate directly or indirectly from the solar radiation, are more uniformly distributed geographically, have a lower environmental impact, and are less subjected to price fluctuations. In 2011, all renewable energy sources were responsible for 13.3% of the global primary energy supply that corresponds to 73 EJ.

Figure 1.8 illustrates the shares of various energy sources in the global renewable primary energy supply. Biomass clearly dominates the current renewable energy pattern at a share of 79%. Biomass energy originates from photosynthesis that produces the organic matter present in a variety of plants, crops, algae, and trees. Although biomass energy is mainly limited to the traditional use as a cooking and heating fuel in developing countries, in the last decades biomass is increasingly applied to produce modern energy carriers as electricity, biofuels, and chemicals.

The second most significant renewable energy is hydropower at a share of about 18%. Hydropower utilizes the potential energy of water flowing in rivers and streams. Traditionally, hydropower was used to produce mechanical energy for irrigation, and later to drive various machines, mainly industrial mills. Presently,

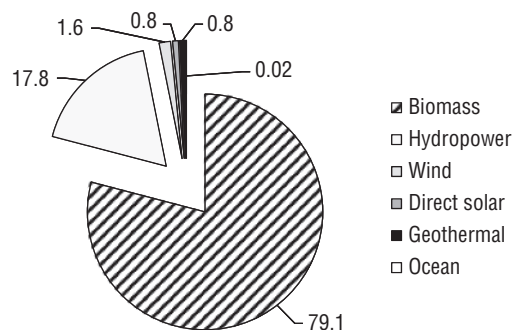


FIGURE 1.8
Shares (%) of energy sources in the global renewable primary energy supply in 2008
(source: IPCC, 2012).

hydropower is utilized to generate electricity at a variety of scales, ranging from small of few kilowatt to large of several gigawatt.

Wind is another traditional renewable energy that in the past was mainly utilized to produce mechanical power for grain milling and propelling ships. At present the kinetic energy of wind is converted in wind turbines to generate electricity and to produce mechanical power for water pumping. The generating capacity of wind turbines has increased from about 30 kW in the 1970s up to several megawatt in recent years. Modern wind farms that consist of many wind turbines are located either onshore or offshore in various parts of the world.

Direct solar energy can be utilized in a variety of ways to generate heat and electricity. The most common way to generate heat is by using solar thermal collectors whose surface is heated by irradiation. The produced heat can be either directly utilized for heat purposes, usually a hot water production, or to generate a high-temperature air or steam that can be used to generate electric power. Electricity can also be directly generated from solar energy using photovoltaic cells. Photovoltaics are currently used in small systems in houses (size 0.05–5 kW) or larger systems in solar power plants (10 kW–500 MW).

Geothermal energy can be recovered in many locations from the Earth's crust. The extracted heat is applied either directly for heating purposes or indirectly to generate electricity. Heat can be recovered at various temperature levels ranging from low (30–100°C) up to high temperatures (above 180°C). The most geothermal power plants operate in the United States, Philippines, Italy, Mexico, Indonesia, and Japan.

Various forms of renewable energy are based on effects occurring in the oceans. They include tidal energy, wave energy, and ocean thermal gradient. The tidal energy utilizes the regular tidal rise and fall of the ocean level due to gravitational forces between Earth, Moon, and Sun. Wave energy originates from winds blowing over the ocean whose kinetic energy is converted into wave movement. Ocean thermal gradient is a temperature difference between the temperature of the warmer ocean surface that is directly heated by the sun and much lower temperature in the deep ocean, below 1000 m. The temperature difference of 20–25°C can be utilized to generate electric power. At present several prototypes of tidal and wave energy plants are in operation, whereas there are no plants based on the ocean thermal gradient.

Table 1.2 lists the current use (2010) and the global technical potential of renewable sources estimated for 2050. It should be noticed that the reported estimates of the future potential are subjected to a wide range of uncertainties.

TABLE 1.2 Global Potential (2050) of Renewable Energy Sources

Renewable Energy	Current Use 2010 (EJ/year)	Potential 2050 (EJ/year)	Current Use 2010/Potential 2050 (%)	Potential 2050/Global Primary Energy Consumption 2010 (%)
Biomass	55	50–500	11–110	9–93
Hydropower	12.4	50–52 ^a	24–25	9–10
Wind	1.1	85–580 ^a	0.2–1.3	16–108
Direct solar	0.54	1,575–49,837	0.03–0.001	292–9,251
Geothermal	0.54	118–1,109 ^a 10–312 ^b	0.05–0.5 0.2–5	22–206 2–58
Ocean	0.011	7–331	0.03–0.2	1–61

Source: IPCC (2012).

^aElectricity.

^bHeat.

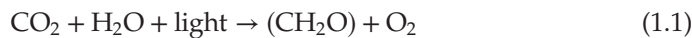
However, it can be concluded that a significant potential exists for all renewable energy sources that substantially exceed the current use. At present biomass and hydropower are the most used energy sources in comparison with their respective future potential. On the other hand, the direct solar and ocean energy show the lowest ratio between the current and potential uses.

Finally, it can be concluded that renewable energy sources can significantly cover the future global energy demand. Particularly, the direct solar energy is able to supply several hundreds to thousands percent more energy compared to the present global primary energy consumption (538.7 EJ/year, see Table 1.1). The future energy potential of other renewable sources, particularly biomass, wind, and geothermal, is comparable with the present global primary energy consumption.

1.2 BIOMASS AS A RENEWABLE ENERGY SOURCE

1.2.1 Introduction

Biomass is an organic material that is produced in plants (crops, trees, and algae) by photosynthesis. During photosynthesis, atmospheric carbon dioxide and water are converted by sunlight into organic compounds, according to the following general reaction:



The primary organic products of photosynthesis are simple carbohydrates (sugars) that are composed from the building blocks (CH_2O) and can subsequently be converted into a variety of organic products, such as polysaccharides (starch, cellulose, and hemicellulose), lignin, lipids, proteins, and other compounds.

Biomass always has been and is still used by the humanity for food and feed purposes as well as for energy and materials, as shown in Figure 1.9. At present biomass accounts for about 10% of the global primary energy consumption. The majority of biomass is used in the traditional way in the developing countries for cooking and heating. In recent years, there is an increased interest in modern use of biomass as a renewable energy source, which includes power and heat generation as well as production of transport fuels and chemicals.

Biomass as an energy source has numerous advantages. First, it is renewable and CO_2 neutral. Carbon dioxide that is formed during the final use of biomass is

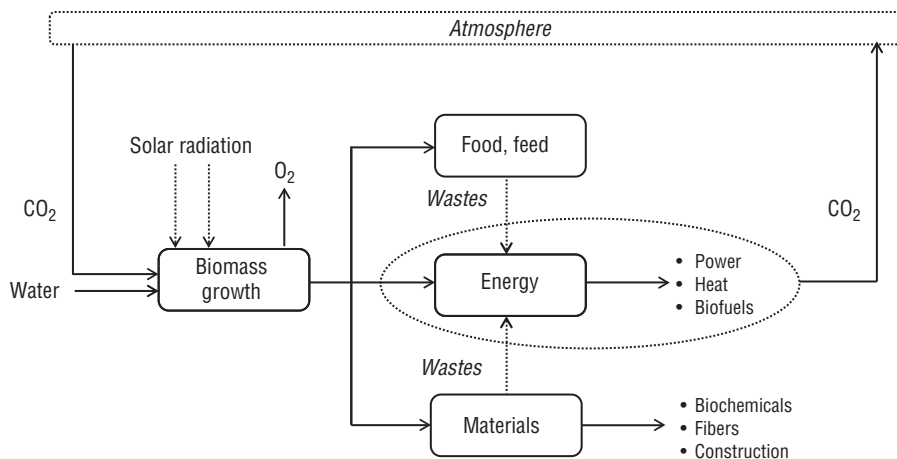


FIGURE 1.9
Biomass energy chain from growth to end-products.

released to the atmosphere and subsequently fixed back to the plants by photosynthesis, as shown in Figure 1.9. Second, biomass is the only renewable carbon source that can replace not only fossil fuels in the production of energy carriers but also many important chemicals. Third, biomass enables energy storage, similarly as fossil fuels, whereas this is not directly possible for many other renewable energy sources, such as wind or solar. Finally, a wide range of biomass resources are available in most parts of the world.

On the other hand, the use of biomass is accompanied by possible drawbacks, mainly limitations of land and water, and competition with food production. Therefore, it is attractive to use waste biomass from food, feed, and materials production (see Fig. 1.9) as feedstock for energy production.

The production of biomass involves high logistics costs due to the low-energy density of biomass. Moreover, biomass suffers from a very low conversion efficiency of sunlight into chemical energy through photosynthesis. For biomass-based systems, a key challenge is thus to develop efficient conversion technologies that can compete economically with fossil fuels.

1.2.2 Historical Development and Potential of Bioenergy

Biomass has always played an important role in the history of humankind. It has been used and will remain the principal source of our food and many materials. Furthermore, biomass was the primary fuel used by humankind for the thousands of years from the beginning of civilization until the nineteenth century when the fossil era began. The major use of biomass was as a fuel for cooking and heating. It is interesting to notice that at the beginning of the nineteenth century, the first automobiles were fueled by biomass-derived fuels, such as ethanol and peanut oil. Since the end of the nineteenth century, biomass was replaced by fossil fuels, first by coal and later in the twentieth century by oil and natural gas. The oil crisis in the 1970s has initiated the renewed interest in biomass and other renewable energy sources such as wind and solar.

At present biomass provides 55 EJ/year of the primary energy that corresponds to about 10% of the global primary energy consumption. Figure 1.10 shows the distribution of the primary biomass energy use that can be classified as the traditional as well as modern applications. The traditional biomass use as firewood for heating and cooking (76%) still dominates the current bioenergy pattern. Biomass is the main energy source in many developing countries where it is responsible for the major part of the residential energy use in Africa (85%), Asia (75%), and Latin America (45%) (Sagar and Kartha, 2007).

As shown in Figure 1.10, the modern biomass use accounts only for about 25% of the global primary biomass energy consumption. These include mainly a large-scale commercial generation of heat and electricity as well as production of

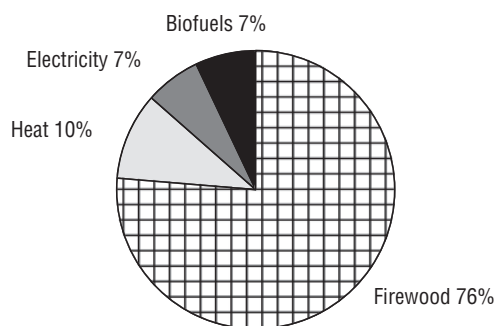


FIGURE 1.10
Primary biomass energy use in 2009 (source: GEA, 2012).

transport fuels such as bioethanol and biodiesel. In the developed countries, modern biomass applications account for 3–4% of the total energy consumption, although in some countries, such as Sweden, Finland, and Austria, biomass contribution reaches 15–20% (GEA, 2012).

In future biomass can contribute much more to the global primary energy consumption as the amount of new biomass formed by photosynthesis is significantly larger than the current yearly biomass consumption. Solar radiation is the main source of energy used in the photosynthetic production of biomass. The total amount of energy of the extraterrestrial solar radiation that reaches the Earth is enormous—174,000 TW (about 5.5 mln EJ/year). About half of the extraterrestrial solar radiation is lost in the atmosphere due to reflection and absorption effects. The remaining part of the solar radiation energy equal to 86,000 TW (about 2.7 mln EJ/year) is incident on the Earth's surface and is used for surface heating and water evaporation as well as it is available for photosynthesis. However, only a very small part of the incident solar radiation is transformed by photosynthesis into chemical energy in new biomass that amounts about 2870 EJ/year (90.9 TW), which is defined as the net primary productivity (NPP) (see Section 3.4.1).

The terrestrial part of the NPP amounts about 1960 EJ/year that corresponds to 68% of the global NPP. Currently, humans appropriate about 373 EJ/year of biomass, which is about 19% of the terrestrial NPP. Figure 1.11 illustrates the human appropriation of the global terrestrial biomass. Less than 60% of biomass is harvested, namely, as plant-based food (28 EJ/year), feed (129 EJ/year), wood (36 EJ/year), and other uses (26 EJ/year). More than 40% of the remaining part of the biomass (154 EJ/year) is destroyed by human-induced fires or left unused as underground biomass, cropland residues, felling losses in forests, and harvest losses. The final biomass use as food for humans, timber, and paper and bioenergy accounts for about 40% of the harvested biomass.

Most energy scenarios refer to 2050 and significantly differ in estimates of the future global bioenergy availability, ranging from low values of about 40 EJ/year up to high values of about 1100 EJ/year. These discrepancies result from different assumptions made regarding future land availability, population growth, food consumption, biomass yield, and bioenergy conversion efficiency. The lowest biomass potential estimate (about 40 EJ/year) corresponds to the pessimistic scenario in which no more land is available for energy farming, whereas the highest estimate (about 1100 EJ/year) corresponds to the optimistic scenario of the intensive agriculture concentrated on better quality soils. The most realistic estimate that is based on the review of several studies assumes the bioenergy potential in 2050 ranging from 250 to 500 EJ/year (Heinimö and Junginger, 2009). According to this estimate, the future biomass feedstocks will be available mainly

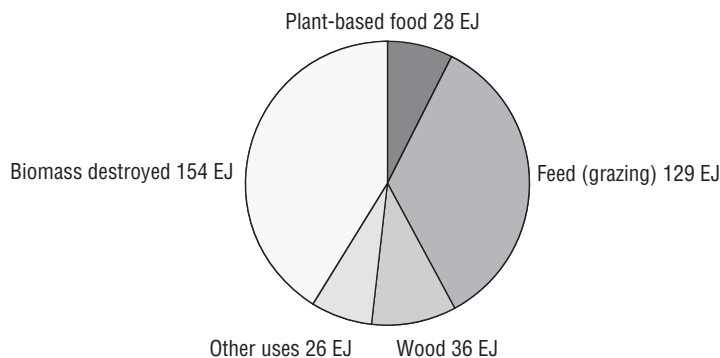


FIGURE 1.11
Human appropriation of the global terrestrial biomass in 2000 (source: GEA, 2012).

as energy crops cultivated on current agricultural land, biomass produced on marginal lands, forest and agricultural residues, dung, and organic wastes.

The projected potential for biomass will be mainly available in the climate regions that favor biomass growth, such as Latin America, Sub-Saharan Africa, Eastern Europe, and North and North-East Asia, whereas most of the biomass will be converted in industrial OECD countries, such as the United States, Europe, and Japan. This will stimulate the international trade in bioenergy and development of biomass markets.

1.2.3 Biomass Resources

Biomass feedstocks are very diverse as they originate from various sources and therefore can be classified in different ways. From the viewpoint of the biomass origin, feedstocks can be classified as virgin (naturally growing terrestrial and aquatic crops) and waste biomass (by-products from biomass processing). Biomass also differs in the content of its constituting components, such as carbohydrates, lignin, lipids, and proteins, which results in a classification into sugar, starch, oil, and lignocellulosic crops. In this section, we classify biomass feedstocks based on their economic competition as an energy source compared to the traditional biomass use for food and materials.

Table 1.3 shows the classification of biomass feedstocks that are grouped into first-, second-, and third-generation feedstocks as well as waste biomass. The first-generation biomass includes food and fodder crops that are essential for the food chain, such as sugar, starch, and oil crops. At present some of these crops are used for production of biofuels, such as ethanol and biodiesel. The competition between various uses of the first-generation biomass has led in the past to a food versus fuel debate that has negatively influenced the social picture of biofuels.

Therefore, more promising are next-generation feedstocks, particularly the second-generation lignocellulosic and the third-generation aquatic biomass. The

TABLE 1.3 Classification of Biomass Feedstocks

Feedstock			
Generation	Type	Crops	Examples
First	Food and fodder crops	Sugar crops	Sugarcane, sugar beet, sweet sorghum
		Starch crops	Corn, wheat, potato, rye, cassava, triticale
		Oil crops	Soybean, rapeseed, oil palm, cottonseed, peanut, sunflower
Second	Lignocellulosic crops	Fodder	Lucerne, grass
		Woody	Short-rotation crops: willow, poplar, eucalyptus, acacia
		Herbaceous	Miscanthus, switchgrass, reed canary grass
Third	Aquatic	Microalgae	<i>Chlorella</i> , <i>Spirulina</i>
		Macroalgae	Seaweed, kelp
		Water plants	Water hyacinth, salt marshes, sea grass
Wastes	Natural	Agricultural	Animal manures, field residues, processing residues
	Man-made	Forest	Logging residues, excess small pole trees
		Municipal	Municipal solid waste (MSW), sewage sludge, demolition wood, food waste, waste oil
		Industrial	Pulp and paper industry (black liquor), sludges

second-generation lignocellulosic biomass are energy crops that can be cultivated on a large scale. They include short-rotation woody crops, particularly willow, poplar, and eucalyptus, as well as herbaceous crops, particularly fast-growing grasses, such as switchgrass, miscanthus, and reed canary grass. The lignocellulosic biomass does not compete with food crops; however, it requires land that is a scarce resource and large energy plantation can have a negative environmental impact due to the land use change.

Aquatic biomass is an attractive energy source as it does not compete with food and land use. It includes various categories, such as microalgae, macroalgae, and water plants. Cultivation of microalgae is particularly promising due to very high yields exceeding that of most terrestrial crops.

Biomass wastes are the last group of feedstocks that can be divided into natural and man-made wastes. Large volumes of agricultural wastes are generated during harvesting and processing of crops, such as straw and corn stover as well as from livestock farming such as animal manures. Forest residues are a significant source of lignocellulosic biomass that is collected as logging residues or forest slash. Man-made waste biomass, such as residential wastes (municipal solid waste (MSW) and sewage sludge) as well as various industrial wastes, particularly from the paper and pulp industry (black liquor), are abundant and nonexpensive biomass feedstocks.

1.2.4 Biomass Properties

The most important biomass properties that determine the suitability of feedstocks for conversion process are proximate and ultimate analysis, energy content, and chemical composition. Table 1.4 lists the above-mentioned parameters for typical biomass feedstocks, including woody and herbaceous biomass, aquatic biomass, and biomass residues and wastes.

Proximate analysis specifies a content of moisture, organic matter, and ash in biomass feedstocks. The moisture content in fresh biomass (as received) is usually quite high, typically about 50% for green wood, 50–80% for green crops, such as maize, sugarcane, and rapeseed, and very high (more than 80%) for aquatic biomass and liquid wastes. Moisture content in wet biomass is usually reduced to few percent either by natural or thermal drying. On the other hand, a slightly wet biomass is a suitable feedstock for steam gasification or even a wet biomass for the supercritical water (SCW) gasification (see Section 6.7).

Ash content is typically about 1% for woody biomass, several percents for herbaceous and aquatic biomass, and much higher for biomass wastes and residues. During biomass conversion, the high ash content can cause serious operating problems, such as ash melting and sintering during combustion of herbaceous biomass (grasses and straw). Ash contains many metal oxides, particularly calcium, potassium, phosphorus, magnesium, and silicon.

Organic fraction of biomass is a source of crucial elements, such as carbon and hydrogen, and energy for all chemical and biochemical conversion processes. It is quite interesting to note that carbon, hydrogen, and oxygen content of most terrestrial biomass feedstocks fall in a relatively narrow range, despite a wide variety of plants, wood, and crop species. Carbon content for the virgin terrestrial biomass varies in the interval of 48–52 wt%, oxygen: 40–44 wt%, and hydrogen 5–7 wt%. On the other hand, aquatic and waste biomass feedstocks contain more nitrogen and sulfur and less oxygen compared to the virgin biomass.

Energy content of biomass feedstocks is usually expressed either as the lower heating value (LHV) or the higher heating value (HHV). The difference between both heating values is due to various assumptions regarding the reference state of water in biomass combustion products that is either vapor (LHV) or liquid (HHV).

TABLE 1.4 Typical Proximate and Ultimate Analysis and HHV of Biomass Feedstocks

Feedstock	Proximate Analysis (wt% ar)			Ultimate Analysis (wt% daf)					HHV (MJ/kg dry)
	Moisture	Organic Matter	Ash	C	H	O	N	S	
<i>Wood</i>									
Oak wood	6.5	93.0	0.5	50.6	6.1	42.9	0.3	0.1	20.1
Pine chips	7.6	86.9	5.5	52.8	6.1	40.5	0.5	0.1	19.5
Poplar	6.8	91.2	2.0	51.6	6.1	41.7	0.6	0	20.0
Spruce wood	6.7	92.8	0.5	52.3	6.1	41.2	0.3	0.1	20.5
Willow	10.1	88.5	1.4	49.8	6.1	43.4	0.6	0.1	29.8
<i>Grass</i>									
Miscanthus	11.4	85.9	2.7	49.2	6.0	44.2	0.4	0.2	20.1
Reed canary grass	7.7	84.1	8.2	49.4	6.3	42.7	1.5	0.2	18.9
Switchgrass	11.9	83.6	4.5	49.7	6.1	43.4	0.7	0.1	19.8
<i>Residues and wastes</i>									
Straw	12.4	81.1	9.5	48.8	5.6	44.5	1.0	0.1	17.1
Rice husks	10.6	73.3	16.1	49.3	6.1	43.7	0.8	0.1	16.0
Sugarcane bagasse	10.4	87.7	1.9	49.8	6.0	43.9	0.2	0.1	19.4
Manure	43.6	39.2	17.2	50.2	6.5	34.6	5.2	0.9	14.2
Sewage sludge	6.4	50.3	43.3	50.9	7.3	33.4	6.1	2.3	10.7
<i>Aquatic</i>									
Water hyacinth	90.0	7.8	2.2	53.0	6.8	37.2	2.5	0.5	16.0
Giant brown kelp	90.0	6.1	3.9	45.3	6.1	46.1	2.0	0.6	10.0
<i>Other</i>									
Bituminous coal	7.3	84.6	8.1	75.6	5.9	15.7	1.8	1.1	28.3
Pure cellulose	0	100	0	44.4	6.2	49.3	0	0	17.5

Sources: Klass (1998); Ptasinski et al. (2007); Song et al. (2011); Vassilev et al. (2010).

For most biomass feedstocks, typical HHV values range from 10 to 20 MJ/kg of dry feedstock, whereas the lower values correspond to aquatic and waste biomass and the higher values to virgin terrestrial feedstocks.

The energy content of biomass feedstocks can be estimated from several correlations based on the ultimate analysis of biomass. The HHV of biomass (in MJ/kg dry) can be estimated with a reasonably good accuracy (+/-3%, but worse for wastes) from a simple correlation (Klass, 1998):

$$HHV = 45.71 z_C - 2.7 \quad (\text{MJ/kg dry}) \quad (1.2)$$

where z_C is the mass fraction of carbon in biomass on dry basis.

A more accurate correlation (absolute error 1.5%) for biomass fuels having a wide range of elemental composition is proposed by Channiwala and Parikh (2002):

$$HHV = 34.91 z_C + 117.83 z_H + 10.05 z_S - 10.34 z_O - 1.51 z_N - 2.11 z_A \quad (\text{MJ/kg dry}) \quad (1.3)$$

where z_i denote the mass fractions of C, H, S, O, N, and ash in biomass on dry basis.

Chemical composition of biomass is important for biochemical conversion processes, such as production of biofuels (ethanol and biodiesel) and biorefinery

TABLE 1.5 Chemical Components of Selected Biomass Feedstocks (wt%)

Component	Sugarcane	Maize	Rapeseed	Oil Palm	Grass	Willow Tree
Simple carbohydrates	33.4	32.3	1.7	0	10.9	0
Complex carbohydrates C6	27.6	23.9	25.4	28.0	29.8	49.5
Complex carbohydrates C5	22.6	14.8	16.8	10.4	21.3	22.8
Lignin	4.8	9.7	5.7	11.1	2.9	22.9
Proteins	2.9	10.6	26.3	3.1	19.2	2.0
Lipids	1.3	1.7	16.0	38.1	4.3	0
Ash	7.4	7.1	8.1	9.4	11.6	2.9

Source: Brehmer (2008).

processes. Table 1.5 summarizes main chemical components of typical biomass feedstocks. Most biomass is composed of carbohydrates (saccharides) that exist in biomass as various chemical compounds, such as simple carbohydrates (sucrose, fructose, and starch) and complex carbohydrates (cellulose, hemicellulose, and pectin). The classification of carbohydrates into simple and complex corresponds to their processing ability by fermentation to ethanol (Brehmer, 2008). Carbohydrates can be further divided into C6 and C5 carbohydrates depending on the number of carbon atoms in simple sugar molecules, which are the building blocks of complex carbohydrates.

Most terrestrial biomass feedstocks shown in Table 1.5 are composed of cellulose (C6 carbohydrates) and hemicellulose (mixture of C6 and C5 carbohydrates). Woody biomass has the highest cellulose and hemicellulose content and is also rich in lignin (aromatic polymers). On the other hand, sugar and starchy crops, such as sugarcane, sugar beet, and corn, are abundant in simple carbohydrates and therefore are used as feedstocks for bioethanol production. Chemistry of processing of simple and complex carbohydrates into ethanol is described in more detail in Section 8.1.4.

Other important chemical biomass compounds are proteins and lipids. Proteins are large complex compounds built from amino acids whose carboxyl ($-\text{COOH}$) and amino ($-\text{NH}_2$) groups are held together by peptide bonds. Protein-rich biomass feedstocks are rapeseed, sunflower, lucerne, and grasses. Proteins derived from biomass can play an essential role in the production of nitrogen compounds in future biorefineries (see Chapter 17).

Lipids are various chemical compounds, mainly triglycerides of fatty acids, which are used for production of biodiesel fuels (see Chapter 7). The most important triglycerides are present in vegetable oils of crops such as rapeseed, soybean, sunflower, and oil palm. The chemistry of triglycerides is discussed in more detail in Section 7.1.3.

1.2.5 Environmental Impact of Bioenergy

Biomass as a renewable energy source has several positive environmental impacts. The most important environmental effects result from the replacement of fossil fuels and the associated benefits, such as reduction of greenhouse gases (GHG) emissions, environmental pollution, and saving depletable fossil energy. However, the use of biomass, similarly as other renewable energy, also has some negative impact on the environment, which should be quantified using preferably the life cycle assessment (LCA) if the renewable energy would replace fossil fuels in the future.

Biomass should be completely carbon neutral as carbon dioxide generated from the final use of bioenergy, which is principally combustion, is fixed back to crops by

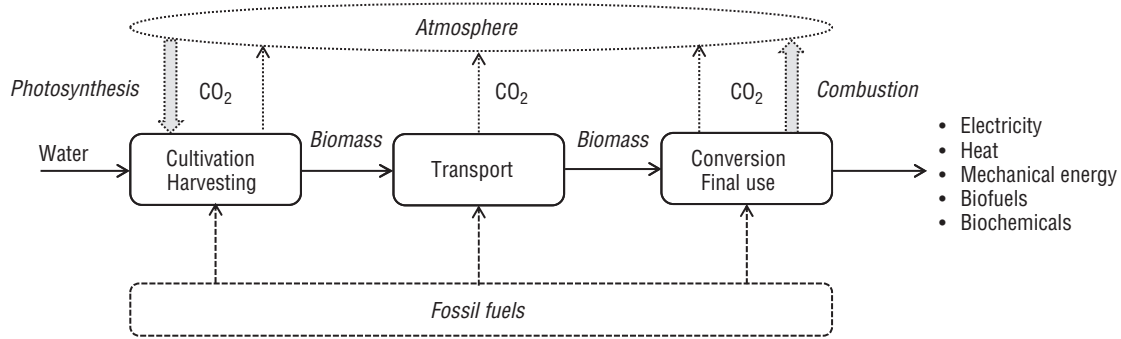


FIGURE 1.12 Carbon flows for bioenergy systems.

photosynthesis. However, at present fossil fuels and related fossil carbon flows are also used in all stages of bioenergy chain, as illustrated in Figure 1.12. During biomass cultivation and harvesting, fossil energy is used for the production of fertilizers and pesticides, as well as a fuel for water management systems (irrigation and drainage) and harvesting machinery. Subsequently, biomass feedstocks are usually transported to processing facilities where they are converted into electricity, heat, biofuels, or biochemicals. Transport of biomass feedstocks requires fossil fuels for trucks, trains, and ships. During biomass conversion, an additional fossil energy is used as heat or electricity.

All the above-mentioned fossil carbon flows result in the atmospheric carbon dioxide emissions from bioenergy chains in addition to the main CO_2 flows due to combustion and photosynthesis, indicated in Figure 1.12 with the gray arrows. The majority of fossil CO_2 emissions from bioenergy chains originate from the production of fertilizers and pesticides, as discussed in Chapter 4.

It is generally recognized that life cycle GHG emissions from bioenergy chains are remarkably lower than the corresponding emissions from fossil energy chains. The lowest GHG emissions are from the generation of bioelectricity that are about 15–30 g CO_2 eq/MJ compared to the range of 100–200, 200–300, and 300–500 g CO_2 eq/MJ for the electricity generated from natural gas, oil, and coal, respectively (IPCC, 2012). Similar results are obtained for heat generation from biomass where the GHG emissions are in the range of 5–20 g CO_2 eq/MJ compared to 70–85, 90–120, and 100–200 g CO_2 eq/MJ for heat generated from natural gas, oil, and coal, respectively.

In case of biofuels, GHG emissions are also reduced compared to fossil fuels but the reductions are lower than those for electricity and heat. Life cycle GHG emissions for sugarcane ethanol and corn ethanol ranges from –15 to 70 g CO_2 eq/MJ compared to that for petroleum gasoline of 85–110 g CO_2 eq/MJ. Similarly, life cycle GHG emissions from biodiesel range from –25 to 125 g CO_2 eq/MJ, whereas that for petroleum diesel are 75–120 g CO_2 eq/MJ.

The above-described GHG emissions do not account for the additional CO_2 emissions due to land use changes when biomass growing on the existing land is replaced by the new one. The global amounts of carbon fixed in the soil are twice that of the carbon present in the atmospheric CO_2 and the land use change can result in a significant altering of the carbon balance. The additional carbon emissions occur when land with natural biomass is converted into intensive agriculture with annual crops. On the other hand, conversion of land with annual crops into land with perennial crops results in more carbon deposit into the soil.

Generally, waste biomass feedstocks perform environmentally better than the virgin biomass that is due to two effects. First, use of wastes as biomass feedstocks

solves the waste disposal problems. Second, energy content of waste biomass is quite high that results in a generation of the additional energy. Moreover, waste biomass feedstocks do not require new land and do not compete with food production.

1.2.6 Economics of Bioenergy

An exact comparison between costs of bioenergy and fossil energy is quite difficult. First, biomass feedstocks and conversion technologies are very diverse and have different costs and benefits. Second, fossil fuel prices are subjected in last decades to frequent and great fluctuations due to various factors, such as economic development and regional or political situation. Finally, the current fossil prices do not represent the true cost as some negative externalities associated with fossil energy due to environmental and health impact, military actions, cannot be exactly quantified.

Generally, currently made bioenergy products are more expensive than the fossil ones. However, some biofuels, such as sugarcane ethanol, as well as electricity and heat generated from waste biomass are already competitive with fossil energy. On the other hand, bioenergy is expected to offer several economic and social advantages when it will replace on a full scale fossil fuels in future. The development of new biomass production and conversion facilities will stimulate employment in agriculture, forestry, and chemical processing. Biomass production and conversion are more geographically distributed than fossil fuels and, therefore, more countries will profit from this new economic development.

Feedstock costs represent a major part for most bioenergy products, such as electricity, heat, and biofuels. The range of biomass feedstock cost is relatively wide, typically from €1 to 16/GJ, depending on feedstock type, its supply cost, production scale, and world region. Typical first-generation feedstock costs in Europe range from €5–15/GJ for starch, sugar, and oil crops and €1.5–4.5/GJ for the second-generation lignocellulosic energy crops (de Wit and Faaij, 2010). The cost range for agricultural residues is €1–7/GJ, whereas that for the forest residue is €2–4/GJ. This can be compared with fossil fuel prices that in the last 5 years have fluctuated in the range of €1.8–3.0/GJ for coal and €2.0–6.5/GJ for natural gas. On the other hand, waste biomass costs, such as of municipal and organic household wastes or manure, are very low or sometimes even negative due to tipping fees.

The estimated production costs of bioenergy products, such as electricity, heat, and biofuels also vary significantly, depending on feedstock types, conversion method, and production scale. Typical levelized costs of electricity generation from commercial power plants range from 3 to 32 UScents₂₀₀₅/kWh (about US\$₂₀₀₅8–89/GJ). The lowest values correspond to power generation from cofiring plants and combined heat and power (CHP)–internal combustion engine (ICE) plants and the highest to CHP–organic Rankine cycle (ORC) plants (IPCC, 2012). The costs of heat generation range from US\$₂₀₀₅2 to 78/GJ, with the lowest cost corresponding to CHP plants that are fueled by municipal solid wastes (MSW) and the highest to domestic wood pellet heating systems.

The levelized cost of first-generation biofuels is from US\$₂₀₀₅4 to 42/GJ for ethanol and from US\$₂₀₀₅9 to 48/GJ for biodiesel. The lowest costs correspond to sugarcane ethanol produced in Brazil in the integrated plants that also produce sugar and electricity. The highest costs correspond to biodiesel that is produced from palm oil (IPCC, 2012). Sugarcane ethanol produced in Brazil can be competitive with petroleum gasoline for the crude oil prices above US\$35/barrel, while corn ethanol produced in the United States for the oil prices higher than US\$55/barrel (Worldwatch Institute, 2007). Transport biofuels that are produced in Europe can be competitive with petroleum fuels for the oil prices above US\$90/barrel in case of biodiesel and above US\$75–100/barrel for ethanol.

Future bioenergy costs are expected to decline over the near- to midterm. This is due to several effects, such as expected lower costs of biomass energy feedstocks and reduced processing costs due to the development of more advanced technologies. The projected production costs for 2020–2030 range from US\$₂₀₀₅13 to 19/GJ for electricity generated from the biomass integrated gasification combined cycle (BIG/CC), from US\$₂₀₀₅6 to 30/GJ for liquid biofuels produced from lignocellulosic feedstocks, and from US\$₂₀₀₅6 to 12/GJ for gaseous biofuels, such as substitute natural gas (SNG) and hydrogen. In case of biofuels and chemicals produced from aquatic biomass, the expected future costs are very high, ranging from US\$₂₀₀₅30 to 140/GJ, due to high production and conversion costs (IPCC, 2012).

1.3 BIOMASS CONVERSION PROCESSES

1.3.1 Introduction

Biomass feedstocks are very diverse, which is reflected in a variety of conversion processes. Figure 1.13 presents main conversion routes of biomass to final products, such as heat, electricity, fuels, and chemicals. Some biomass properties are not ideal for common conversion processes and usually have to be upgraded by an appropriate method, which can include size reduction, densification, drying, and torrefaction. The primary biomass conversion pathways can be classified as thermochemical, biochemical, and chemical methods.

Currently, dominant biomass conversion methods are based on thermochemical processing that include combustion, gasification, and pyrolysis. Compared to biochemical and chemical methods, thermochemical conversion methods are less specific from the point of view of chemical biomass composition as they can process almost any kind of (dry) biomass either into heat (combustion) or simpler

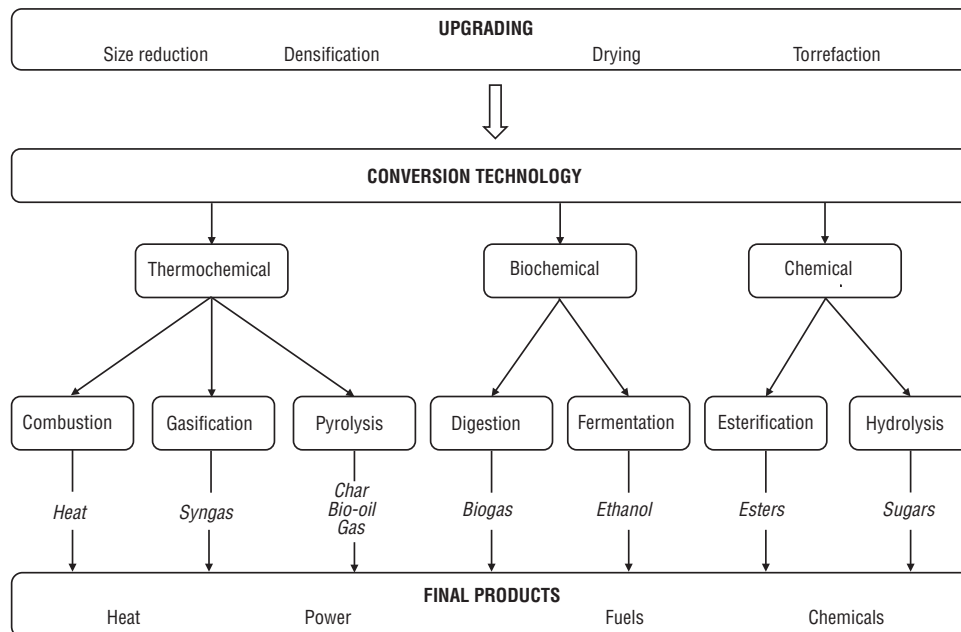


FIGURE 1.13 Main biomass conversion methods.

chemical molecules (gasification). Thermochemical biomass conversion can lead to many final products, including heat, electricity, fuels, and chemicals.

Biochemical conversion methods use microorganisms, such as yeasts and bacteria, for partial decomposition and conversion of biomass into useful chemical compounds. Typical examples of biochemical conversion are fermentation of sugars into ethanol and production of methane or hydrogen-rich biogas by fermentation or digestion.

Chemical methods are specific for selected components of biomass feedstocks that are converted by chemical reactions into more valuable semi or final products. The most common chemical conversion methods are transesterification of triglycerides of fatty acids present in vegetable oils and animal fats by alcohols into biodiesel, and hydrolysis of hemicellulose and cellulose present in lignocellulosic feedstocks, such as wood, by acids or bases into sugars, which subsequently can be fermented into ethanol.

1.3.2 Upgrading Technologies

The advantages of biomass as a chemical feedstock are the convenient chemical composition such as a relatively high carbon and hydrogen content in addition to a variety of chemical compounds, such as carbohydrates, lipids, and proteins. However, some physical biomass properties, such as low bulk and energy density and high moisture content are inconvenient for biomass logistics and processing. Moreover, from the point of view of chemical composition, biomass differs from the common fossil fuels (coal, oil, and natural gas) as it contains more oxygen. Biomass properties can be upgraded using various physical processes, such as size reduction, densification, drying, and thermochemical treatment, such as torrefaction.

Size reduction of biomass is practiced in order to facilitate transportation and prepare biomass for a direct use in a specific conversion equipment. The most popular biomass size reduction methods are cutting, crushing, and shearing (Klass, 1998; Brehmer, 2008; McGowan et al., 2009). For some agricultural crops, the initial size reduction is already applied during harvesting. The final size reduction is performed in a variety of equipment, including grinders, shredders, and chippers. Compared to cutting, crushing and shearing lead to finer feedstock particles, typically below 1 cm. Typical crushing and shearing equipment include various hammer and burr mills. Generally, size reduction of biomass is an energy-intensive step as it consumes 0.08–1.1 GJ per ton of the processed feedstock.

Most biomass feedstocks have a low bulk density that in combination with a low energy density results in high transportation costs. Particularly, harvested agricultural crops have a very low bulk density, such as 18 kg/m³ for loose wheat straw or 50 kg/m³ for corn stover, which can be compared with a bulk density of coal of 750 kg/m³. Bulk density of agricultural crops can be increased by baling or pelletizing, which results in a much higher bulk density, such as about 100 kg/m³ for baled straw or 600 kg/m³ for straw pellets. The most popular are wood chips and pellets that have a bulk density of about 250 and 650 kg/m³, respectively, and become commonly traded bioenergy commodities.

Many biomass feedstocks have high moisture content and dewatering and drying enable their economic utilization. Particularly wet feedstocks are waste biomass streams, such as sewage sludge or manure as well as aquatic biomass whose moisture content exceeds 95 wt%. The moisture content of agricultural crops at harvested conditions ranges from relatively low values of 10–30 wt% for switchgrass, soybean, and rapeseed up to high values of 70–85 wt% for cassava, potato, grass, and sugarcane (Brehmer, 2008). Green trees also contain a lot of moisture that ranges from 50 wt% in trunks up to 90 wt% in leaves. High moisture content in

biomass results in high transportation costs, storage difficulties, and reduced thermal efficiency of energy conversion (Liu et al., 2012). Typical dewatering and drying methods include mechanical dewatering using filters, centrifuges, or hydrocyclones as well as drying using natural air or thermal dryers. On the other hand, some biomass conversion methods such as supercritical water gasification or anaerobic digestion are suitable for wet biomass feedstocks.

Torrefaction is a recently developed biomass upgrading method that results in improving many physical and chemical biomass properties (Prins et al., 2006a, 2006b, 2006c; van der Stelt et al., 2011). During torrefaction, biomass is heated at temperatures 230–300°C under an inert atmosphere that results mainly in removing of some amounts of water and carbon dioxide. This can lead to mass losses of about 30%, whereas energy losses are limited to about 10% and consequently improves an energy density of biomass with 10–30%. From the chemical viewpoint, the most important is that the oxygen content in the torrefied biomass decreases, which improves chemical biomass properties, as discussed in Section 6.3.1. Due to the reduced oxygen content, the efficiency of gasification of torrefied biomass is also improved. Moreover, the torrefied biomass is more hydrophobic than the virgin one that improves its handling, storage, and transportation properties.

1.3.3 Thermochemical Conversion Processes

Currently, the most common conversion of biomass into useful products is by thermochemical processes, such as combustion, gasification, and pyrolysis. All these processes have in common that they are carried out at high temperatures (450–1200°C); however, they substantially differ in the amount of applied oxygen. Biomass combustion involves a complete fuel oxidation, gasification—only a partial oxidation, and pyrolysis is a thermal biomass degradation in the absence of oxygen.

Combustion is the oldest thermochemical biomass conversion method that is practiced from the early discovery of fire. During biomass combustion, carbon and hydrogen are completely oxidized to carbon dioxide and water, respectively, that result in the release of large amounts of heat. It means that the chemical energy of organic compounds from a biomass fuel is converted into the thermal energy that has a lower quality and, therefore, the efficiencies of combustion systems are also relatively low.

Biomass combustion produces hot gases at a temperature of 800–1000°C, which can be used either directly for heating purposes or indirectly to generate steam and subsequently electric power. The scale of biomass combustion ranges from small-scale woodstoves through medium-scale incinerators up to large-scale modern boiler systems. A classical application of biomass combustion is for the domestic and district heating, particularly in Scandinavian countries, Austria, Germany, and France. Currently, biomass combustion using a Rankine cycle is the dominant method for bioelectricity generation. For this purpose, biomass can also be cocombusted with coal in the traditional coal-fueled power plants. In developing countries, biomass is still traditionally burnt for heating and cooking purposes.

Gasification is a partial oxidation of biomass at a temperature range of 750–1100°C using oxidizers, such as air (oxygen), water (steam), or carbon dioxide. The main product of biomass gasification is a synthesis gas (syngas) that contains carbon monoxide, hydrogen, and methane as the main components, together with carbon dioxide, water, and nitrogen when air is used as a gasification agent. The history of gasification is almost 200 years old and began with coal gasification. The development of biomass gasification has started before and during the Second World War due to a fuel shortage in Europe.

Biomass gasification can be successfully applied for various purposes, which include generation of electricity and production of fuels such as methanol, ethanol, Fischer–Tropsch hydrocarbons, dimethyl ether (DME), hydrogen, and substitute natural gas (SNG). Moreover, almost all biomass feedstocks can be gasified provided they are sufficiently dry. Typical biomass gasifiers include a small-scale fixed-bed as well as a large-scale fluidized-bed and entrained flow gasifiers. A disadvantage of biomass gasification is the presence of contaminants in syngas, such as tars and ashes, which must be removed by a gas cleaning system (Devi et al., 2002).

Currently, biomass gasification is mostly applied for electricity generation using a variety of systems, ranging from small-scale fixed-bed gasifiers integrated with internal combustion engines up to large-scale fluidized-bed gasifiers integrated with gas turbines, such as biomass integrated gasification combined cycle (BIG/CC) systems. The efficiency of the latter systems is much higher compared to the combustion-based Rankine systems. The efficiency of electricity generation can still be improved by the integration of biomass gasification with fuel cells.

Biomass pyrolysis is a thermal degradation of organic matter present in biomass in the absence of oxygen. Pyrolysis can be carried out at a wide range of temperatures, such as 300–1000°C, commonly at 500–600°C (Albertazzi et al., 2007; Babu, 2008). During this process, usually three various product fractions are formed, such as solids (char), liquid (bio-oil), and gas. The relative amounts of solid, liquid, and gaseous fractions depend mainly on the biomass heating rate, in addition to temperature and reaction time. At slow pyrolysis (heating rate of 30°C/min, reaction time minutes to hours), mainly charcoal is formed (up to 35%), whereas at fast pyrolysis (heating rate of 300°C/min, reaction time few seconds or less) mainly liquid fraction is formed (50–60%) in addition to solid (20–30%) and gaseous (20–30%) fractions.

The most valuable product from the fast pyrolysis is bio-oil, which is a homogeneous mixture of (mainly) oxygenated organic compounds and water. However, due to the high concentration of oxygenated compounds (organic acids), bio-oil is highly corrosive to common construction materials. After stabilization or upgrading, bio-oil can be combusted in boilers, engines, or turbines to produce heat or electricity or converted to transport fuels or chemicals (Bridgwater, 2003).

1.3.4 Biochemical Conversion Processes

In biochemical conversion processes, various enzymes and microorganisms, such as yeasts and bacteria, are used for breakdown and conversion of organic compounds present in biomass feedstocks into valuable chemicals. The mechanism of biochemical processes is quite complex and is usually a part of the microorganisms' metabolic function. Compared to thermochemical and chemical methods, biochemical conversion processes are carried out at lower temperatures but also at lower conversion rates. The advantages of biochemical processes are a low consumption of energy and additional chemicals as well as the nonpolluting character. There are two main biochemical routes that are applied commercially on a large scale: fermentation of sugars present in biomass crops to ethanol and anaerobic digestion (AD) of biomass wastes to methane. Many other biochemical conversion processes are under development, such as hydrogen production from biomass by a combination of dark fermentation and photofermentation.

The oldest but also the largest-scale biochemical process is ethanol production from various biomass feedstocks by anaerobic fermentation. The traditional ethanol fermentation applies sugar crops, such as sugarcane, sugar beets, or sweet sorghum, from which simple carbohydrates (sugars) such as saccharose are extracted and fermented to ethanol by yeasts and bacteria. Most of the commercial fermentation processes are carried out at room temperature and atmospheric pressure and apply

yeasts such as *Saccharomyces cerevisiae* or bacteria *Zymomonas mobilis*. Ethanol can also be produced from starchy crops, such as corn or wheat as well as lignocellulosic biomass, such as wood, but complex carbohydrates present in these crops must first be converted into simpler sugars before they can be fermented to ethanol.

Anaerobic digestion (AD) of various wet biomass feedstocks is applied for many years to produce a methane-rich biogas. Typical biomass feedstocks for the AD are animal manures, food-processing wastes, organic fraction of MSW, and agricultural residues. Numerous microorganisms are involved in AD, such as bacteria, archaea, fungi, and protozoa (Yu et al., 2010). Most AD reactors apply wet feedstocks with a solid content lower than 15% and operate at a temperature range of 37–55°C.

The mechanism of the AD comprises several stages, such as hydrolysis of polymeric biomass (polysaccharides, proteins, and lipids), followed by fermentation to organic intermediates and H₂, and final methanation to CH₄ and CO₂. The produced biogas is a mixture of methane (50–70%) and CO₂, and also contains small amounts of ammonia and H₂S. The lower heating value (LHV) of biogas is about 20–25 MJ/Nm³. The biogas can be used either directly for cooking and heating or indirectly to generate electricity using internal combustion engines, gas turbines, and microturbines. Moreover, biogas can be injected to the natural gas grid after upgrading by methane enrichment and desulfurization.

Microorganisms can also produce hydrogen from biomass and currently various biochemical hydrogen methods are under development (Das and Veziroğlu, 2001; Hallenbeck and Benemann, 2002; Nath and Das, 2004). Moreover, some microorganisms, such as algae and cyanobacteria, are capable of catalyzing water splitting using sunlight to hydrogen and oxygen. In this case, organic substances from biomass feedstocks are not involved in the biochemical conversion process.

Two main processes for the biochemical hydrogen production based on the fermentation of organic compounds present in biomass comprise photofermentation and dark fermentation. The preferred feedstocks for both processes are wet and waste biomass streams. In the dark fermentation, anaerobic bacteria (e.g., from the genus *Clostridium*) convert carbohydrates present in the biomass in the absence of oxygen into hydrogen, CO₂, and organic acids. Contrary to the dark fermentation, the photofermentation requires input of light energy for conversion of organic compounds (preferably organic acids) to hydrogen and CO₂ using photosynthetic bacteria, such as *Rhodobacter capsulatus*. The most promising process is a combination of dark fermentation and photofermentation as it results in a high conversion degree of biomass into hydrogen (Claassen and de Vrije, 2006).

1.3.5 Chemical Conversion Processes

Biomass is composed of a variety of chemical components, such as carbohydrates, lipids, proteins, and lignins, and many other organics, such as alkaloids, pigments, resins, terpenes, and waxes, which are present in some biomass feedstocks. A wide range of chemical processes are used for selective conversion of chemical compounds present in the biomass either directly into valuable final products or indirectly into intermediates that can be further processed by biochemical or chemical methods into useful chemicals.

The most commercially significant *direct* chemical conversion process is the transesterification of triglycerides of fatty acids present in oil crops into biodiesel. The important *indirect* chemical conversion is the hydrolysis of hemicellulose and cellulose to simple sugars that can be subsequently fermented to ethanol. Moreover, in recent years, a number of new chemical conversion routes that aim to synthesize important bulk and specialty chemicals from biomass is under development in the context of chemical biorefinery concept, as discussed in Section 1.4.5 and Chapter 17.

Biodiesel is produced from triglycerides of fatty acids (lipids) present in oilseed crops (soybean, rapeseed, and sunflower) and animal fats (tallow). Triglycerides are esters of glycerol and three (different) fatty acids and cannot be directly used as a fuel in a diesel engine due to their high viscosity caused by their high molecular weight. The common way to improve properties of triglycerides is the transesterification with alcohols, mainly methanol or ethanol. During the transesterification reaction, alkyl (methyl or ethyl) esters of fatty acids are formed (called biodiesel) that are suitable as a fuel in compression-ignition engines.

The biodiesel production process begins with an extraction of vegetable oils from oilseed crops that contain triglycerides. In the next stage, triglycerides are converted to biodiesel by the transesterification with alcohol, catalyzed by acids and alkalis. A by-product of transesterification is glycerol that can be used in pharmaceutical, cosmetic, and food applications. At present biodiesel production is a well-established technology. In Europe the preferred biodiesel feedstock is rapeseed oil, whereas in the United States biodiesel is mainly produced from soybean oil. Biodiesel is usually blended (5–30%) with the conventional diesel; however, a straight use of biodiesel is also possible after some engine modification.

The hydrolysis of hemicellulose and cellulose present in large amounts in lignocellulosic biomass, such as wood or grass, is a promising method for efficient ethanol production. Hemicellulose and cellulose are complex carbohydrates (polysaccharides)—polymers of simple sugars. Cellulose is built from C6 glucose units, whereas hemicellulose from C5 pentoses (xylose and arabinose) and C6 hexoses (galactose, glucose, and mannose). Contrary to simple C6 and C5 sugars, complex carbohydrates cannot be fermented to ethanol. In recent years, there is an increased interest in the development of chemical hydrolysis of polysaccharides to simple sugars that subsequently can be used for ethanol production.

Hydrolysis of polysaccharides takes place in the presence of excess water and is catalyzed by acids and bases (Lange, 2007). Hemicellulose with an amorphous structure can be easily hydrolyzed compared to cellulose that is highly crystalline and moreover protected in biomass by a complex structure of hemicellulose and lignin. The best results are achieved by hydrolysis using diluted or concentrated inorganic acids (H_2SO_4) that proceeds in two steps. In the first step, lignin and hemicellulose are removed from the biomass matrix and hemicellulose is hydrolyzed into C5 and C6 sugars. In the second step, cellulose is hydrolyzed into glucose. Finally, simple C5 and C6 sugars are fermented to ethanol, but the fermentation of pentoses (C5) sugars is quite difficult compared to the traditional easy fermentation of hexoses (C6) sugars.

In recent years, several demonstration plants have been operational in the United States, Canada, and Europe (Denmark, Germany, and Spain) for conversion of lignocellulosic biomass to ethanol (Viikari et al., 2012). The capacities of these plants are about several million liters ethanol per year. The main advantage of lignocellulosic ethanol is that this method does not compete with food production; however, the present production costs are higher compared to ethanol from sugar and starch crops.

1.4 UTILIZATION OF BIOMASS

1.4.1 Introduction

A large variety of biomass feedstocks and their conversion methods make biomass a versatile fuel. Biomass can be used to produce almost all commonly used energy carriers, including not only the traditional ones as heat and electricity but also a number of modern transport fuels and chemicals. Biomass can be utilized in

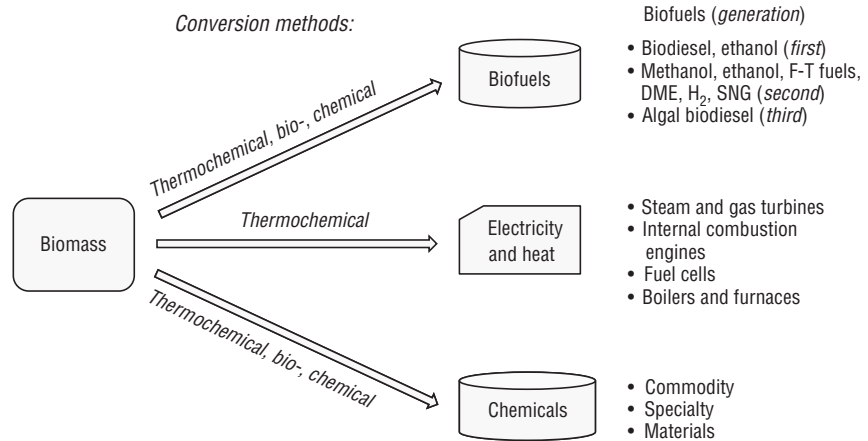


FIGURE 1.14
Main end uses of biomass for energy and chemicals.

different scales, ranging from small-scale household uses up to large-scale industrial applications. A variety of products that can be obtained from biomass make it unique from among other renewable energy sources, which usually can be converted only to a single-energy carrier, such as electricity in case of hydro- or wind power. Moreover, biomass is the only renewable carbon source and this way has a potential to replace in future fossil fuels and fossil-derived chemicals.

In Section 1.2, we mentioned that currently about three-fourths of the global primary biomass energy is used in the developing countries for traditional cooking and heating purposes. The remaining one-fourth of the global biomass primary energy is used for modern applications and converted into biofuels, energy carriers (electricity and heat), and chemicals, as illustrated in Figure 1.14.

A number of biofuels can be produced from biomass and interest in biofuels is still growing as they can replace conventional fossil transport fuels (gasoline and diesel). Biofuels are usually classified as first-, second-, and third-generation fuels, depending on the nature of a biomass feedstock used for their production. The first-generation biofuels, such as biodiesel and ethanol, are produced from edible biomass, such as soybean or sugarcane, and currently dominate the commercial biofuel production. The main disadvantage of the first-generation biofuels is their competition with food production. This is not the case for the second-generation fuels that are produced from lignocellulosic and waste biomass feedstocks. At present production methods of various second-generation biofuels, including liquid (methanol, lignocellulosic, and thermochemical ethanol, and Fischer-Tropsch fuels) as well as gaseous fuels (DME, hydrogen, and SNG), are under development. Finally, the third-generation biofuels include fuels produced from aquatic biomass, such as algae, which do not compete with the terrestrial biomass production.

Heat and power generation from biomass is the oldest end use as it dates back to the discovery of fire (heat) and the industrial revolution (power). The main conversion route for power and heat generation from biomass is based on thermochemical conversion, mainly combustion. The majority of biomass-fueled power plants operate using a relatively low-efficient steam Rankine cycle that applies steam turbines. More efficient power generation from biomass includes biomass gasification and gas turbines, particularly the biomass integrated gasification combined cycle (BIG/CC). Recent developments in bioelectricity generation include fuel cells where biomass-derived fuels, such as syngas or hydrogen, are directly converted to electricity by electrochemical oxidation that results in high energy efficiency.

Finally, numerous chemicals can be produced from biomass that comprises the entire range of organic compounds currently produced from the fossil fuels. These

include commodities, such as methanol, ethanol, ethylene oxide, glycerol, lactic acid, and acetone, and specialties, such as lubricants, flavors, food additives, and surfactants. Moreover, a variety of materials can be obtained from biomass, such as plant fibers, isolated and modified biopolymers (cellulose and its derivatives), composites, and biodegradable plastics.

1.4.2 Biofuels

Biofuels can play an important role in the future energy pattern as transportation sector is responsible for about 21% of the world's primary and 27% of the secondary energy consumption (Hamelinck and Faaij, 2006). Currently, transport fuels are almost exclusively produced from fossil fuels, mainly oil, whereas the share of biofuels in transportation sector is limited to about 1.5% (Mandil and Shihab-Eldin, 2010). Future energy scenarios foresee that biofuels use will increase to about 7 and 12% of road fuels in 2020 and 2030, respectively, and about 15% of aviation fuels in 2030 (IEA, 2009).

Table 1.6 summarizes current and future biofuels that are classified into first-, second-, and third-generation, depending on the nature of the biomass feedstock used for the biofuels production. Current biofuels are dominated by the first-generation biofuels (ethanol and biodiesel) that are produced from edible biomass. Production of the first-generation biofuels involves either biochemical methods, such as fermentation of sugar crops, or chemical conversion methods, such as transesterification of triglycerides of fatty acids derived from oilseed crops. The most familiar currently produced biofuel is ethanol whose share is about 94% of the global biofuels production. The largest ethanol producers are Brazil and the United States that produce more than 79% of the world ethanol. Biodiesel is the second large biofuel produced today, mainly in Europe (Germany, France, and Italy) where it is made from rapeseed and in the United States where soybean is the primary feedstock.

The second-generation biofuels are considered as future transport fuels as they can be produced from lignocellulosic (wood and grasses) and waste biomass (forestry and agricultural residues). Various second-generation biofuels are currently under development that include liquids, such as methanol, ethanol, and

TABLE 1.6 First-, Second-, and Third-Generation Biofuels

Biofuel	Biomass Feedstock	Production Method
<i>First-generation</i>		
Biodiesel	Oilseed crops Animal fats	Transesterification Hydrogenation
Ethanol	Sugar and starch crops	Fermentation
<i>Second-generation</i>		
F-T fuels	Lignocellulosic and wastes	Gasification and chemical synthesis
Methanol	Lignocellulosic and wastes	Gasification and chemical synthesis
Lignocellulosic ethanol	Lignocellulosic	Hydrolysis and fermentation
Thermochemical ethanol	Lignocellulosic and wastes	Gasification and chemical synthesis
Dimethyl ether (DME)	Lignocellulosic and wastes	Gasification and chemical synthesis
Hydrogen	Lignocellulosic and wastes Wastes	Gasification and chemical synthesis Fermentation
Substitute natural gas (SNG)	Lignocellulosic and wastes	Gasification and chemical synthesis
<i>Third-generation</i>		
Biodiesel	Algae	Transesterification

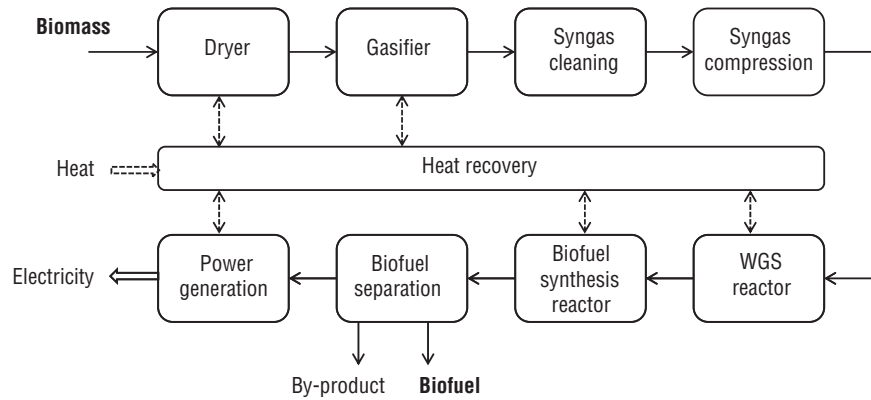


FIGURE 1.15
Schematic flow sheet of the thermochemical biomass-to-biofuel conversion.

Fischer–Tropsch hydrocarbons, as well as gaseous fuels, such as DME, hydrogen, and SNG.

The most promising production method of the second-generation biofuels is a two-stage process that integrates thermochemical and chemical biomass conversion, as illustrated in Figure 1.15. In the first stage, biomass after drying is gasified with air, oxygen, or/and steam into synthesis gas (syngas). The main components present in syngas are CO, H₂, CO₂, CH₄, H₂O, and N₂. Carbon monoxide and hydrogen are the building blocks to synthesize different biofuels. In the second stage, syngas reacts in a catalytic synthesis reactor where specific biofuels, such as Fischer–Tropsch hydrocarbons or methanol are produced.

The synthesis of most biofuels from syngas is usually a high-pressure process and, therefore, syngas after a cleaning unit is compressed up to the desired reactor pressure. In case of hydrogen production, only a water-gas-shift (WGS) reactor is sufficient and no further specific synthesis reactors are needed. The biofuel formed in the synthesis reactor is separated from the by-products in a separation unit. The remaining by-products usually have high energy content and they can be used to produce electricity in a power generation unit or process steam in a heat integration unit. The heat recovery is particularly desired as in the overall process the syngas is cooled from a high temperature in the gasifier to much lower temperature in the biofuel synthesis reactor.

The second-generation lignocellulosic ethanol is produced by a combination of chemical and biochemical conversion processes that comprise a two-stage process, namely, a combination of hydrolysis of hemicellulose and cellulose to simple sugars and subsequent fermentation of sugars to ethanol. A variety of hydrolysis processes that are catalyzed by acids, bases, or enzymes are currently under development, particularly in the United States. In the second fermentation stage, the well-known technology is applied to convert sugars into ethanol.

Methanol and ethanol (alcohols) are oxygenated fuels that can be used in spark-ignition internal combustion engines (Otto cycle), either blended with gasoline or as pure (neat) fuels. Fischer–Tropsch fuels are mixtures of hydrocarbons that are compatible with the currently produced traditional fossil fuels (gasoline or diesel). Dimethyl ether (DME) is the simplest organic ether with the formula CH₃OCH₃ whose properties are very similar to LPG. DME is a flexible fuel as it can be used as a transport, household cooking, and gas turbine fuel for power generation. Hydrogen is considered as a universal energy carrier in the future hydrogen economy concept, due to its wide application range that includes a transport fuel, generation of mobile and stationary power, and important chemical for a variety of chemical processes. SNG contains mainly methane and can be used as a renewable replacement of natural gas.

The third-generation biofuels use algae as a feedstock and do not compete with terrestrial biomass production. Algae are microorganisms that are cultivated in water using sunlight, carbon dioxide, and some simple nutrients. Compared to the terrestrial biomass, algae grow very fast and produce large amounts of triglycerides of fatty acids that can be used as a feedstock for biodiesel production. The additional advantage of algae is that industrial carbon dioxide streams (e.g., commonly emitted from power plants to the atmosphere) can be utilized for algae cultivation.

1.4.3 Electric Power Generation

Generation of electric power from biomass has a history longer than two centuries that began after the discovery of the steam engine. The first biomass fuel used for power generation was wood that dominated till the end of the nineteenth century when it was replaced by coal and later by oil and natural gas. Currently, more than two-thirds of the world's electricity is generated from fossil fuels, namely, coal (41%), natural gas (22%), and oil (5%), followed by hydro (16%), nuclear (13%), and renewable sources (3.7%) (IEA, 2009). The present share of biomass in the generation of global electricity is about 2% and is stable over the last 20 years (Evans et al., 2010). Most of the electricity from biomass is generated in the developed countries such as the United States, Germany, and Japan whose contribution to the global production is 26, 15, and 7%, respectively.

Table 1.7 summarizes the main electric power generation methods from biomass and indicates that the thermochemical biomass conversion methods dominate the present technology. A small amount of electricity is generated based on the biochemical biomass conversion, which is the anaerobic digestion of waste biomass to biogas.

The principal technology for generating electric power from biomass today is a Rankine cycle that comprises biomass combustion in a boiler and expansion of the high-pressure steam through steam turbines. Unfortunately, this technology has a very low efficiency of about 20% that can be improved by cogeneration of heat in combined heat and power (CHP) plants. Heat from biomass combustion that has lower temperature compared to fossil fuels combustion can be conveniently utilized for the electricity generation using an organic Rankine cycle (ORC) or directly in a Stirling engine. An interesting option is the use of externally fired gas

TABLE 1.7 Electric Power and Heat Production Methods from Biomass

Biomass conversion	Intermediate Fuel	Power Prime Mover	Heat Generation
Combustion	Flue gas	Steam turbine (Rankine cycle) Organic Rankine cycle (ORC) Stirling engine Externally fired gas turbine (EFGT)	Boiler
Gasification	Syngas	Gas turbine Externally fired gas turbine (EFGT) Internal combustion engine (ICE) Fuel cell	
Pyrolysis	Bio-oil	Gas turbine Internal combustion engine (ICE)	Boiler
Digestion	Biogas	Steam turbine Internal combustion engine (ICE) Gas turbine	Boiler

turbines (EFGT) in which the combustion heat is used to produce a hot air that is expanded through a gas turbine. Alternatively, biomass can be cofired with coal in existing power plants. Such biomass utilization offers low investment costs as only small plant modifications are required, whereas the relatively high overall efficiency can still be attained.

The most promising technology for a large-scale generation of electricity from biomass is based on biomass gasification integrated with gas turbines, such as the BIG/CC. Biomass gasification and gas turbines substantially improve electrical generation efficiency, but syngas has to be carefully cleaned from various impurities before it can enter gas turbines that increases investment costs. Biomass gasification can also be applied for electricity generation using other prime movers, such as internal combustion engines and EFGT.

Finally, biomass gasification can also be integrated with a fuel cell where chemical energy of syngas or hydrogen derived from the syngas is converted directly to electricity using an electrochemical gas oxidation. This way a very high overall electricity generation can be obtained; moreover, fuel cells are solid-state devices, without mechanical parts and noise production. The applications of fuel cells for electricity generation comprise stationary systems based on a high-temperature solid oxide fuel cell (SOFC) and mobile applications based on a low-temperature proton exchange membrane fuel cell (PEMFC).

1.4.4 Heat Production

Today, heat production for various purposes (cooking, residential heating, and industrial steam production) is clearly the largest application of biomass as a fuel. There are two ways of using biomass fuel for heating: a traditional use by households in the developing countries, mainly in cook stoves and open fires, and the modern use in the developed countries for residential heating.

Currently, more than three-fourths of the global biomass fuel is simply combusted in developing countries for cooking, space heating, and lighting. Biomass is the principal fuel for about one-third of the world's population (Sagar and Kartha, 2007). A variety of biomass fuels is applied, such as agricultural and animal wastes (dung), as well as wood. All these fuels are burned very inefficiently that contributes to an indoor air pollution, specifically by the increased carbon monoxide and particulate matter concentrations. Such emissions negatively relate to health problems, such as acute respiratory infections and increased mortality (Tyagi et al., 2013). There are various approaches to eliminate the negative impact of an inefficient biomass combustion in the developing countries, such as the development of improved cook stoves, replacement of traditional biomass fuels by biogas from anaerobic digestion, or modern fuels (LPG or DME).

Biomass is also applied as a fuel for residential heating in the developed countries that corresponds to about 10% of the global biomass primary energy consumption. Biomass-fueled domestic and district heating systems are particularly used in countries with colder climate (Scandinavia, Austria, and Germany). To this end, a variety of systems are applied that range from fireplaces and small furnaces used for domestic heating to complex boiler systems and combined heat and power (CHP) generation for district heating (Faaij, 2006). Modern domestic heating systems apply a quite advanced technology, including high level of automation and gas cleaning, and standardized fuels, such as wood pellets. However, the use of biomass for the residential heating remains the least efficient way of using this fuel. The main problem is an incorrect match between the quality of energy supply and demand, which means that heat from biomass combustion has a higher quality (temperature) than that needed for a space heating.

A significant part of the industrial energy consumption is devoted to a process steam production, particularly in sectors such as food processing, pulp and paper, and chemicals. Similarly, biofuels production involves various high-temperature processes that require process steam for heating. To this end, fossil fuels can be combusted, but this will negatively impact the renewability of biofuels due to the increased overall input of fossil energy to a biofuel production. Various industrial process residues provide a more efficient alternative for the process steam generation. The classical example is the steam (and power) generation in the ethanol industry using sugarcane bagasse as a fuel, which is a lignocellulosic feedstock and cannot be used for ethanol production in the fermentation process.

1.4.5 Chemical Biorefinery

The present use of biomass is mainly limited to a fuel for heat and power generation and feedstock for transport biofuels. Such biomass applications do not fully utilize its chemical value that results from a variety of chemical constituents containing renewable carbon. It should be noticed that many other renewable energy sources, such as hydro, wind, geothermal, and solar, are also suitable for production of heat and power for the stationary and mobile applications, whereas they do not represent any chemical value.

On the other hand, the core of our current chemical industry is a transformation of organic compounds that are present in fossil fuels into more valuable carbon-based chemicals and materials. Currently, conversion of carbon compounds takes place in many petrochemical refineries. The disadvantages of fossil-derived chemicals remain the same as those for fossil fuels, namely, a fast depletion and negative environmental impact.

In the 1990s, the idea of a “biorefinery” has arisen as an answer to more sustainable chemical production. The principle of biorefinery is illustrated in Figure 1.16 and is based on the same concept as existing petrorefineries. In a biorefinery, various biomass feedstocks are upgraded into a variety of valuable products, such as food and feed, power and heat, fuels, and chemicals. It should be noticed that in this integrated biomass utilization, the emphasis is on the chemical value of biomass feedstocks that are converted into commodity and specialty chemicals, whereas generated energy (power and heat) are considered as by-products.

In recent years, various biorefinery concepts have been proposed that mainly depend on the biomass feedstocks used (Kamm et al., 2010). In many biorefineries, food and feed production will have the top priority, whereas the remaining materials can be processed into non-food applications that can be arranged into

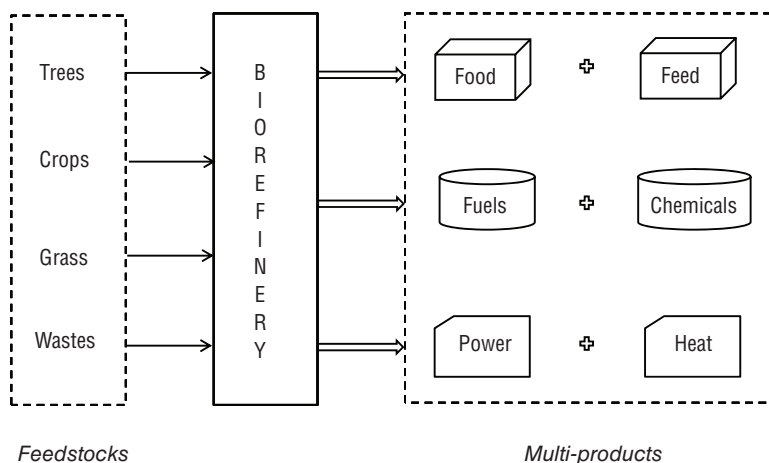


FIGURE 1.16
Simplified schematic diagram of a biorefinery.

two stages. First, biomass can be separated into the constituent chemical components (carbohydrates, lignin, proteins, and lipids), which subsequently can be converted into valuable chemicals as main products and power and heat as by-products.

Generally, biorefinery processes will involve all kinds of conversion methods such as thermochemical, biochemical, and chemical. Lignocellulosic feedstocks that are the most promising for future large-scale biorefineries can be converted using chemical methods into a variety of products and materials, including important chemicals such as levulinic acid and furfural—a starting material for nylon 6.

1.5 CLOSING REMARKS

Biomass is a sustainable energy source that can replace currently used fossil fuels. Nowadays it is the fourth largest energy resource in the world, after oil, gas, and coal. Biomass can be converted to power, heat, transport fuels, and chemicals using various thermochemical and biochemical methods. The key features of biomass are renewability and neutral CO₂ impact. Moreover, biomass is the only renewable carbon source and enables energy storage contrary to other sustainable energy forms, such as wind or solar. However, the use of biomass is accompanied by several drawbacks, such as limitation of land and water and competition with food production. Therefore, a key challenge is to develop efficient conversion technologies that can compete with fossil fuels and other renewable energy forms.

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