Chapter 10
Biomass

Abstract Wood, agricultural crops, agricultural residues, herbaceous grasses, algae, sea plants, municipal solid waste, sewage, and animal waste are all forms of biomass that are being used in order to satisfy the energy demand of modern society. Biomass is still the principal fuel used for cooking and domestic heating in most agrarian societies and many developing nations, while in the industrialized nations it is primarily used for the production of other fuels, the *biofuels*, or it is burned for the production of electricity. The production of agricultural crops necessitates large areas of arable land and significant amounts of fresh water for irrigation, two scarce resources on Earth. The consumption of these crops to satisfy the energy demand of the population is fast becoming a controversial socioeconomic issue because of the direct competition of energy production with food production and food availability to the poorer segments of the society and poorer nations on the planet. This "*to eat or to burn*" dilemma in conjunction with the increasing population of Earth, is expected to introduce limitations on the use of agricultural crops and to increase the use of waste products for energy production. This chapter describes the types of biomass that are available as well as their energy content. It presents several useful calculations and facts on the conversion of biomass to transportation fuels and computes, as a special case, the energy balance related to the conversion of corn to ethanol. It appears that in the conversion of corn to ethanol, more energy goes into the materials and processes needed than the energy content of the produced ethanol. The chapter also investigates the environmental effects, social, economic and regulatory issues that will play an important role to the increased utilization of the various types of biomass as energy sources.

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10.1 Biomass

The term *biomass* encompasses all organic plant matter as well as organic waste derived from plants, humans, animals, and aquatic or marine life. The term is broad enough to include: fire wood; methanol derived from wood; alcohol made from grains; methane derived from the anaerobic decomposition of waste; aquatic plants, such as seaweed and kelp; algae; animal waste; municipal solid waste; sewage; and liquid fuel derived from the re-processing of spent engine oil or kitchen oil. Biomass, most notably wood, was the predominant fuel at the beginning of the industrial revolution when households used wood for domestic heating and cooking purposes. As the per capita energy consumption rose and the population of the Earth dramatically increased, burning of wood was insufficient to satisfy the energy needs of humans and was replaced first by coal and then oil and gas. The few areas that have not secured other energy resources to satisfy the growing energy needs of their populations, such as the Central Asian plateaus and parts of Africa, have suffered severe biomass depletion and deforestation, which has significant adverse environmental and micro-climatic implications.

In the beginning of the twenty-first century the use of biomass varies widely among countries: while in most of the OECD countries the use of biomass for energy production is less than 3%, several developing nations sill derive more than 30% of their energy needs from forestry or agricultural products. For example, Cuba produces more than 35% of its electricity from sugar cane; and Brazil uses sugar cane and corn for the production of biofuels and electricity to satisfy more than 25% of its total energy needs. In the OECD nations the most important forms of biomass that are used for the production of energy are:

a) wood for domestic heating and cooking;
b) alcohol, which is mixed with gasoline as transportation fuel;
c) diesel fuel derived from wasted liquid fuels, lubricants and cooking oil;
d) methane and combustible gases derived from the anaerobic decomposition of municipal and animal waste; and
e) forestry and lumber industry byproducts for the production of process heat.

Biomass is a natural method of solar energy storage in the form of chemical energy. Plants use the chlorophyll in their leaves as catalysts and large quantities of solar energy to convert atmospheric carbon dioxide and water into the complex molecules of glucose and fructose as, for example, in the following chemical reaction for the formation of glucose during the photosynthesis process:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \tag{10.1}$$

This reaction has many intermediate stages, where chlorophyll plays an important role. The overall reaction is highly endothermic with $\Delta G^0 = 480{,}000$ kJ per kmol of formed glucose. From glucose and fructose, plants form the more complex organic compounds, such as sucrose, starch and other complex organic

Table 10.1 Time for the formation of biomass in years

Biomass form	Time to form or regenerate (years)
Forest/timber, northern temperate zone	91
Forest/timber, southern temperate zone	25
Fast growing timber, Sycamore	2–3
Switch grass, corn and sugarcane	0.5
1 ton solid waste in USA per person	1.2
1 ton solid waste in the European Union per person	4.3

molecules with high chemical energy content. In general, plants form carbohydrates according to the general reaction:

$$xCO_2 + xH_2O \rightarrow carbohydrate\ molecule + xO_2 \tag{10.2}$$

From the thermodynamic point of view, plants may be considered as thermal engines that receive solar energy and store it as chemical energy in the form of complex organic molecules. Their conversion efficiency is in the range of 0.1–1.5%, which is significantly lower than that of photovoltaic solar cells or man-made power plants. However, the plants may be planted and grown with low capital cost, low technology, and, in producing carbohydrates they remove carbon dioxide from the atmosphere and release oxygen. For this reason, the production of biomass is beneficial to the environment because it removes CO_2 molecules. The combustion of biomass is neutral to the environment from the carbon footprint point of view, because it returns back to the atmosphere the same number of CO_2 molecules, which were removed during the production stages of the biomass.

Biomass is considered a renewable energy source because the plants and crops grow at short timescales in comparison to the human timescales. As a renewable source, the time of reproducibility of the various biomass forms is important. Table 10.1 shows the time, in years, for several types of biomass to reproduce themselves and regenerate. It is apparent that, while agricultural crops, wastes, and fast growing timber may be considered as renewable energy sources, forests and especially those grown in the northern latitudes do not regenerate fast enough and, thus, their classification as renewable energy sources is questionable.

It must be noted that fossil fuels, such as coal and petroleum, are also products of plants and animals. However, the time to produce or to regenerate the fossil fuels is of the order of millions of years, which is by far greater than the human lifetime or planning timeframe. For this reason, fossil fuels are considered depletable and not renewable energy sources. A glance at Table 10.1 proves that it is not prudent to use timber excessively for the production of energy, especially in the northern zones. Excessive use of timber from forests leads to deforestation, with all the adverse environmental and micro-climate effects that follow it. On the other hand, utilization of municipal or agricultural waste is not only beneficial for the production of energy, but also offers an alternative pathway for the reduction of

the volume of the waste and effectively removes the produced methane, which is a potent greenhouse gas (GHG).

The widespread use of biomass for energy production has several disadvantages, which may be summarized as follows:

A. *Periodic production with uncertain yield*. There are one or two harvests of crops every year, primarily in the warmer seasons, and the yield of the land depends significantly on the weather conditions of a particular season. Also, crops are only available during a 2–3 month period, during which all the material must be harvested and used, or put into storage to avoid spoilage. Another, auxiliary supply of fuel will be needed for the continuous operation of a power plant, which is designed to burn biomass.
B. *Diffuse nature of the energy source*: With a range of conversion efficiencies between 0.1 and 1.5%, a glance at Fig. 7.4 proves that the annually-averaged energy yield of the land is on the order of 1 W/m^2. While the total amount of energy available is large, the energy density is very low. This implies that large tracts of land must be used for the production of significant energy from biomass and that there are large costs for the collection, transportation, processing and delivery of the energy produced.
C. *Further processing is needed*: Energy in biomass is in the form of chemical energy, which must typically be processed, by fermentation or combustion, for its final use as transportation fuel or as fuel for power plants. In contrast, the yield of solar energy in W/m^2 is 20–30 times higher. In addition, solar energy is produced and may be used directly as electricity, while biomass must be processed to another fuel or burned to produce electricity. Direct conversion bypasses the Carnot limitations in the conversion of thermal energy.
D. *Competition with food production*: Several food crops, such as corn, sugar cane, and oily seeds are typically included in the biomass and are used for the production of energy. Socioeconomic considerations preclude the use of large areas of arable land for the production of energy when this practice would have the effect of rising food prices or making food scarce in several regions of the planet.
E. *Highly variable energy per unit mass or volume*: The energy content of biomass varies widely according to the type and origin of biomass and its moisture content. Dry agricultural products, such as rice hull and dry bagasse[1] have significantly higher energy density (in kJ/kg or in kJ/m^3), while municipal waste and sewage have lower energy density.

Two figures of merit that characterize a fuel are the high heating value (HHV) and the low heating value (LHV). Both are measured in terms of the mass of the fuel (kJ/kg). The former represents the maximum heat that may be extracted from

[1] Bagasse is the residual from sugar cane production, after the stalk is ground and pressed to release its recoverable sugar content.

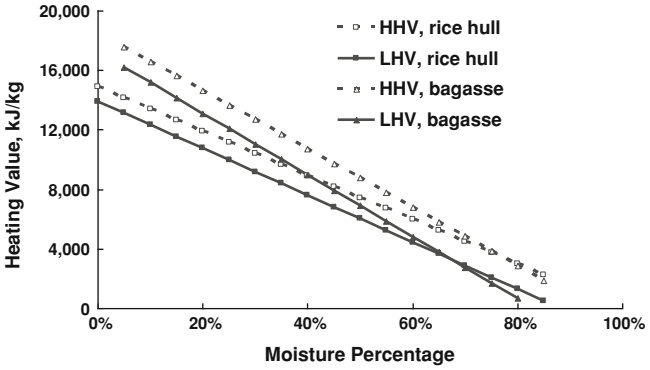

Fig. 10.1 Heating values of rice hulls and bagasse as functions of moisture

the combustion of a fuel when the water vapor from the combustion products condenses, while the latter is the heat released during the combustion when the water exits the combustion chamber as vapor. Essentially, the HHV is equal to $-\Delta h$ of the reaction with water as liquid and the LHV is equal to $-\Delta h$ when the water is vapor. It is easy to deduce that HHV > LHV. Figure 10.1 depicts the HHV and LHV of rice hulls and bagasse fuels as a function of their moisture. It is apparent from this figure that drying the biomass before its use increases significantly its energy density and its value as a fuel. Drying the biomass also reduces its volume and its weight and is highly recommended before biomass is transported over long distances. Table 10.2 shows the low heating value (LHV) of several types of biomass, most of which may be burned untreated. The pertinent numbers for anthracite are also given for comparison. While there is no standard convention on the term, oftentimes, the LHV, either in kJ/kg or Btu/lb, is referred to as the *energy density* of the fuel and this term will be used in the rest of this chapter.

10.1.1 Biomass Production, World Potential

As a renewable energy resource, the potential of biomass to contribute to the world energy challenge may be measured in terms of annual production rates. The current production of renewable biomass includes primarily agricultural byproducts, forestry byproducts, animal waste, and urban waste, including sewage. These may be called the currently *recoverable residuals* of biomass. In order to calculate the full potential of biomass one may include *energy crops*, which are crops grown for the production of biomass to be used solely for energy production. The energy crops include sorghum, energy cane, sugar cane, switchgrass, eucalyptus trees, miscanthus, giant reed, and leauceana lucacephala. Since a great deal of the Earth's land is not utilized, one may add to the total potential for biomass the

Table 10.2 Energy density (LHV) of several types of biomass

Biomass	Energy density (kJ/kg)	Energy density (Btu/lb)
Rice hull, 0% moisture	13,905	5,970
Rice hull, 30% moisture	9,175	3,940
Bagasse, 0% moisture	17,266	7,414
Bagasse, 30% moisture	11,038	4,740
Dry wood (average)	18,500	7,934
Municipal solid waste	4,000–8,000	1,715–3,430
Sewage/animal waste	1,164–1,863	500–800
Anthracite	31,952	13,720

Table 10.3 Potential annual production of biomass in several regions of the planet in Quads

Region/country	Recoverable residuals	Potential from energy crops	Total potential
North America	5.9	34.8	40.7
Europe	3.8	11.4	15.2
Africa	2.6	52.9	55.5
China	3.4	16.3	19.7
Japan	0.3	0.9	1.2
Total Earth[a]	31.2	267	298.2

[a] Estimate with all currently unutilized arable land plowed for energy crop production. It does not include the energy input for the growth of the crops.

energy crops these regions may produce. Table 10.3 shows the annual energy value of the recoverable residuals as well as the annual amount of energy that may be produced in the continents from land utilization for the production of energy. The third column in the Table, *potential from energy crops*, assumes that all arable areas, currently not used for the production of food are used for the production of energy crops. The latter, does not take into account the availability of water for agriculture.

The total global energy consumption in the beginning of the twenty-first century is approximately $480*10^{15}$ kJ/yr, of which $105*10^{15}$ kJ/yr (≈ 100 Quads) are consumed in the USA. It appears from Table 10.3 that biomass has the potential to supply more than 50% of the energy needs of the Earth's population and this has become an argument of the biomass proponents. However, this conclusion is misleading because the numbers in Table 10.3 do not include the amount of energy, which is needed for the seeding, fertilization, growth, harvesting, and processing of the energy crops. It will be seen in the section on the production of ethanol, that this energy input is significant and comparable to the energy content of the final product. Also, these numbers do not take into account the fresh water availability, which is necessary for the production of the energy crops. For example, the production of a single gallon of ethanol from corn requires the use of approximately 1,000 gallons of freshwater. In addition, about 90% of the total potential to produce energy ($267*10^{15}$ kJ/yr) stems from the rather doubtful

assumption that, all the currently available land may be harvested to produce energy crops. These lands are more valuable because they are needed to feed the growing population of the planet.

It is also apparent that several regions of the world, such as Africa, where the climate is favorable and large parts of the continent are underutilized, have very high potential to produce biomass for energy conversion. In other regions or countries, such as Japan, Belgium, and China, where most of the land is already used for agriculture and urban development, the potential to produce biomass energy is very limited. It must also be noted that, in estimating the potential for biomass, it is very difficult to assess the potential of certain regions, without considering impending future technological advances in agriculture. For example, how does one compare the biomass potential of the desert in the Middle East to the potential of the forested land in Indochina?

A significant amount of the recoverable residuals, approximately 10–20% in the OECD countries, stems from animal waste and urban waste. The latter includes sewage as well as solid waste. While, in terms of mass, the amount of waste is significant, its energy density is very low. Human and animal waste, if properly and efficiently processed, may provide a very small percentage of the urban energy needs. The real value of urban waste processing locally lies in the reduction of the volume of the waste, so that less volume/weight needs to be transported at the expense of more energy and cost. In addition, waste processing enables the containment and utilization of the methane, which is produced during waste decomposition. If untreated, urban waste products will produce more of this GHG, with all its adverse climatic consequences.

10.1.2 Methods of Biomass Utilization

The ways biomass is used for the production of electricity and biofuels have been adapted from the methods used for the combustion of fossil fuels as well as from methods for the chemical or physical transformation of fossil fuels to other forms of transportation fuels, e.g. coal gasification or coal liquefaction. The following are some of the ways of biomass utilization:

1. *Direct Combustion*: is used for cooking; space heating, e.g. in fire places or boilers; process heat in industrial plants; and steam generation for the production of electricity. Because the biomass contains a high percentage of humidity, temperatures achieved in biomass-only burners are significantly lower than conventional fossil fuel burners. When one considers the energy spent in the transportation of biomass, the efficiency of power plants that only use biomass is in the range 15–20%, roughly half of the conventional fossil fuel plants.
2. *Co-firing*: is the combustion of a small percentage (2–10%) of locally produced biomass and coal. Because coal is the principal fuel in a co-firing burner, steam

may be produced at high temperatures in the boiler and the efficiency of the power plant does not suffer.

3. *Gasification in air*: the product of gasification is typically a mixture of hydrocarbons, which is used for process heat, e.g. crop drying; running stationary engines in the immediate vicinity of the gasifier; space and water heating; and small electric power producing plants.
4. *Pyrolysis*: it produces combustible gaseous and liquid products, such as methane, ethane and methanol, which may be used in gas turbines, space and water heating as well as in transportation fuels.
5. *Hydrolysis and fermentation*: produce liquid fuels, such as methanol and ethanol. They are commonly used in mobile and stationary engines, gas turbines, generation of steam, and as gasoline or diesel additives.
6. *Anaerobic decomposition*: occurs naturally in municipal and agricultural waste sites, in sewage treatment plants and in animal waste plants. The decomposition produces a gas that is rich in methane, carbon monoxide and carbon dioxide. This artificial combustible gas has a low heating value, but may, nevertheless, be mixed with other fuels to be used in gas turbines or steam power plants. Vacuum pumps extract the mixture of gases from the heaps of waste in the disposal sites. The gas is transported to power plants via pipelines for combustion.

The co-firing of a coal power plant with agricultural or municipal solid waste is sometimes used as a way to reduce the amount of fossil fuel input to the power plant, thus reducing the cost of the fuel as well as the amount of CO_2 produced from coal. Some NO_x reduction is also achieved by co-firing. The co-firing of a small percentage, typically under 5% of the heat input, in a coal-fired power plant may be accomplished without any modification to the fuel supply system. The waste product, e.g. rice hull, bagasse, or tree clippings, may be directly fed to the coal pulverizer, where they are mixed with the coal and subsequently injected to the boiler. Such mixtures of coal and biomass produce the high temperatures required by the Rankine steam cycle. If the size of the biomass parts is more than 1 cm (0.4 inches) a hammer mill system is recommended to be installed. This system reduces the size of the biomass parts to less than 1 cm and prevents the "clogging" of the feed lines. For the co-firing of municipal solid waste, modifications have to be done to the feeding system of the power plants because of the significantly low heating value of the municipal waste. For the municipal waste, a second feed system is usually installed, which feeds the waste products directly into the boiler.

Table 10.4 shows the savings in coal and prevention of CO_2 pollution achieved by the co-firing of a 1,450 MW power plant with bagasse, which contains 46% moisture and has a heating value of 6,886 kJ/kg. The average rate of heat input in this power plant is 4,527 MW and its average overall efficiency is 32.03%.[2] The

[2] The numbers pertain to the Independence Steam Electric Station (ISES) coal-fired power plant in Arkansas, USA, which is owned and operated by Entergy Inc.

Table 10.4 Fuel savings and CO_2 production prevention by the use of biomass fuel in co-firing

Heat from biomass (%)	Heat from biomass (MW)	Coal input (kg/day)	Biomass input (kg/day)	Coal savings (kg/day)	CO_2 emission savings (kg/day)
0.00	0	16,439,805	0	0	0
0.50	23	16,344,361	284,035	95,445	179,692
1.00	45	16,248,916	568,070	190,889	359,383
1.50	68	16,153,471	852,105	286,334	539,075
2.00	91	16,058,027	1,136,139	381,779	718,766
3.00	136	15,867,137	1,704,209	572,668	1,078,150
4.00	181	15,676,248	2,272,279	763,557	1,437,533
5.00	226	15,485,359	2,840,349	954,447	1,796,916

Table proves that the use of biomass, which would have been otherwise wasted, not only saves fuel, but also reduces the net CO_2 emissions of the power plant.

10.1.3 Aquatic Biomass

Sea and surface waters cover almost 75% of the Earth's surface. Plants that grow in these aquatic areas include seaweed, kelp, and several types of algae. Because the amount of potable freshwater on the planet is only 0.3% of the total and because fresh water is becoming a scarce resource in several regions, it is not considered good environmental stewardship to devote large quantities of freshwater for energy plants or algae. However, the salt-water and brackish/marsh-water areas, which comprise 97.3% of the total water supply of the planet[3] is readily available for the production of biomass and biofuels. Harvesting marine organisms for the production of energy is a very sensible way to produce liquid fuel for transportation or solid fuel for the production of electricity because:

a) Aquatic biomass does not use any useful parts of land, which is a scarce resource.
b) No irrigation is necessary for the production of aquatic biomass.
c) Nutrient trace elements, such as K and P are abundant in the sea and, hence, no fertilizers are necessary.
d) Oftentimes, the food of aquatic bacteria and algae is sewage. This helps in the reduction of liquid waste and will lead to sewage reduction and possible elimination by feeding it to energy-rich algae.

Biologists have produced a number of synthetic bacteria and have discovered algae with high content of fatty oils, which thrive in aquatic environments. When these organisms are dried up, the fatty oils are processed to produce a fuel similar

[3] The remaining 2.7% of water is in the form of glaciers.

to diesel, which is often called *biodiesel*. Similarly, other sea plants may be dried to produce liquid or solid fuel.

One of the advantages of algae is that they may grow in very short times. For example, micro-algae can regenerate in 48–72 h and cyanobacteria can regenerate in 5–20 h. The short growth and harvesting times lead to better utilization of the solar energy in comparison to land crops and result in higher overall conversion efficiencies. For example, the production of biodiesel from algae in gallons per hectare per year is 10–20 times higher than that of palm oil or jastropha and 50 times higher than that of oilseed.

A significant disadvantage of the use of aquatic biomass for the production of energy is its water content. Drying the aquatic biomass is necessary before it is processed to produce biofuels or be burned in a boiler for the production of electricity. The high energy requirement of the drying process often exceeds the energy that may be obtained from the aquatic biomass itself. When solar energy is used for drying, the process is energy neutral but it is significantly slower and rather unreliable, especially during a wet, rainy season. Because of this, the contribution of aquatic biomass to the energy demand in the first decade of the twenty-first century is almost zero. Technological breakthroughs in the drying of algae, the extraction of oils and lipids from the algae cells and better engineered biological organisms are needed for aquatic biomass to contribute significantly to the energy challenge of the world.

10.2 Biofuels

The term *biofuels* refers to liquid fuels derived from biomass, which are used for transportation. It encompasses all types of liquid fuels derived from plants or animals, including methanol, ethanol and diesel fuel. Methanol, CH_3OH or wood spirit, has been produced for centuries from the distillation of wood products, natural gas or from coal. It is a liquid fuel, with boiling point 65°C. Its energy density of 21,000 kJ/kg is approximately 50% lower than that of gasoline. Because of this, when used in cars, the tailpipe NOx emissions are significantly lower. Small amounts of methanol, up to 10%, mixed with regular gasoline, may be used in the current fleet of vehicles without any significant modifications.

Ethanol, C_2H_5OH or alcohol has a boiling point of 78°C, is a colorless fluid and burns clean to produce water and CO_2. There is significant experience in the production of ethanol primarily as the main product of wheat or grape juice fermentation for the production of alcoholic beverages and distilled spirits. Ethanol as a fuel is produced primarily from corn or sugar cane. Figure 10.2 shows diagrammatically the physicochemical processes in the production of ethanol from corn. Yeast is a catalyst in the production of ethanol and accelerates the fermentation process. It must also be noted that the fermentation process releases some CO_2, which needs to be accounted for, when evaluating the environmental advantages of using ethanol. During fermentation, 1 bushel or 26 kg of corn yields

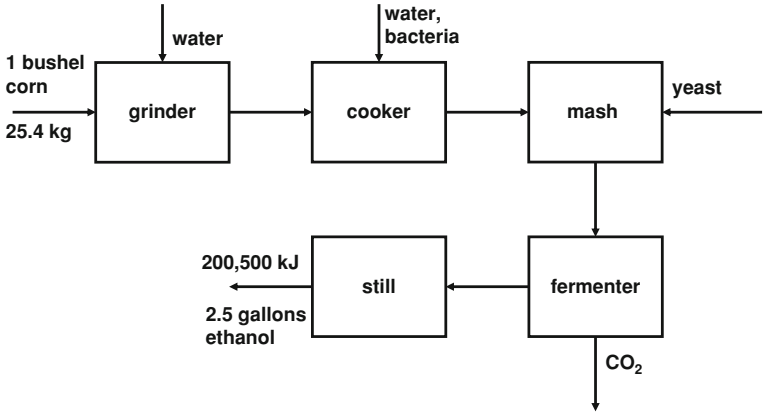

Fig. 10.2 The production stages of ethanol

approximately 2.5 gallons of ethanol, which has an energy value of 200,500 kJ (190,000 Btu). However, as it will be seen in the next section, growth of corn and the process of ethanol production also consumes a great deal of energy resources.

A mixture of 10% ethanol and 90% gasoline by volume, or E10, is called *gasohol* and is used as a transportation fuel in many states in the USA as well as in other parts of the world. This mixture may be used in all spark-ignition engines without any engine modification. E20 has been introduced in several states and countries, also without any significant engine modification. The use of higher percentage of ethanol in the fuel mixture requires modifications in the fuel supply system of the engine. A much richer in ethanol mixture, E85, is composed of 85% denatured[4] ethanol. It has been used in Brazil and was also introduced in the European Union, where it is primarily used in Sweden. The so called *flex-fueled engines* for cars and trucks that use this mixture have their engines modified to adjust electronically the air-to-fuel ratio and the ignition timing in order to use the E85 fuel. In general, the addition of ethanol in gasoline reduces the specific energy of the fuel, because the energy by volume of ethanol, e.g. in kJ/gal or kJ/l, is approximately 67% of the specific energy of common gasoline. Thus, a car running on E15 would achieve approximately 90% miles per gallon or 90% km per liter than if it were running on pure gasoline. On the positive side, this car would produce much less atmospheric pollution because ethanol burns cleaner, producing significantly lower amounts of NO_x and almost zero SO_x than gasoline.

Finally, biodiesel is a generic name given to liquid transportation fuels with a mixture of heavier hydrocarbons and alcohols, such as $C_{10}H_{22}$, $C_5H_{11}OH$, and $C_8H_{17}OH$. Biodiesel is produced from oily seeds grown in nature, such as cotton seeds, olive oil residue and pumpkin seeds. It may also be produced artificially,

[4] Denatured alcohol is ethanol that has additives to make it undrinkable. It may be toxic if consumed by humans or animals.

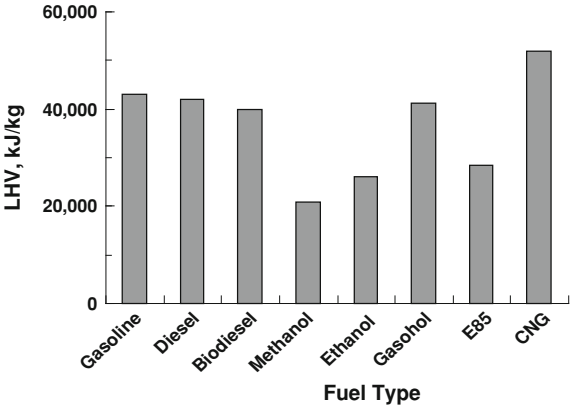

Fig. 10.3 LHV, in kJ/kg, of common fuels and biofuels

using waste products from industrial processes or from the food industry. For example, spent cooking oil and used engine oil may be refined and used as biodiesel for cars and trucks. Because biodiesel has almost the same composition and very similar transport and combustion properties as common diesel fuel, standard diesel engines do not need to be modified to run on biodiesel. Figure 10.3 shows the LHV of several common biofuels as well as common liquid fossil fuels used in the transportation sector. It is observed in this figure that the fuels, which are most commonly used in today's internal combustion engines, have LHV's close to 40,000 kJ/kg.

Another class of biofuels may be derived directly from agricultural products, especially oily seeds, such as cotton, peanut, flax, soybean, sunflower, safflower, sesame, palm, jastropha, and Chinese tallow. These seeds grow in both warm and cold areas of the planet, which means that almost all countries may produce one or more of these crops for the production of transportation fuels. However, because most of these crops have traditionally provided food sources for the population, their widespread use for the production of biofuel will become problematic if it is accompanied with a rise in food prices or food shortages.

10.2.1 Ethanol Production from Corn

The production, processing and use of biomass entail several energy-intensive processes. The energy consumption during these processes must come into the calculations of the net energy yield and the overall contribution of biomass in solving the energy challenge. For example, if corn is to be used for the production of ethanol, some of the processes needed are: plowing, seeding, fertilizing and harvesting of the fields; drying and transportation of corn; fermentation, removal of solids and purification; and transportation of the produced fuel. A complete energetic analysis of these processes is presented in the following paragraphs. The

Table 10.5 Preprocessing energy consumption for the growth of corn

Study	N_2	P	K	Lime	Herbicide	Insecticide	Total energy
Pimentel (2003)	9.388	0.924	0.785	0.930	0.886	0.063	12.976
Patzek (2004)	8.099	0.431	0.636	0.583	0.663	0.290	10.702
Shapouri et al. (2002)	6.120	0.257	0.740	0.469	1.235	0.059	8.880
Wang et al. (1997)	7.506	0.638	0.350	0.469	0.729	0.053	9.745
Average	7.778	0.563	0.628	0.613	0.878	0.116	10.576
% std. deviation	17	51	31	36	29	100	17

Energy inputs associated with the0 agricultural fertilizers and pesticides needed in GJ/ha
Piementel, *Natural Resources Res. Vol. 12, No. 2, 2003.*
Patzek, T., *Critical Reviews in Plant Sci. Vol. 2, No. 6*, 2004.
Shapouri, Duffield and Wang, *US Dept of Agriculture, Agricultural Economic Report, 2002.*
Wang, Saricks and Wu, *Argonne National Lab. Report, 1997.*

analysis is based on four pertinent studies conducted in four U.S.A. laboratories and gives the results on the energy inputs and outputs related to the production of ethanol from corn. The average and the percent standard deviation are also calculated and shown in the tables that follow.

Table 10.5 shows the energy, in GJ per hectare, which enters the production of the fertilizers (N_2, P, K, $CaCO_3$), pesticides and insecticides that are necessary for the production of corn. 1 hectare (ha) is approximately equal to 2.5 acres. It is observed that these energy inputs are very significant and average approximately 10,500 MJ/ha. The disagreement on the total energy between the studies is rather small as signified by the low value of the percent standard deviation, in all values except the one for the insecticides. This is not significant, however, because insecticides account for only 0.5–2% of the total energy at this stage of ethanol production. It is also observed that most of the energy at this stage is in the input of nitrogen, which represents a high percentage of the mass of the fertilizers.

Table 10.6 shows the energy inputs on the field. The field inputs include the liquid fuels that are consumed by the machinery used in the plowing, irrigation and harvesting processes. The term "other energy" includes natural gas and electricity, which is oftentimes used for field irrigation. One observed discrepancy between the four studies is that the first two take into account the energy that goes into the repair and manufacture of the equipment used in the production of corn, while the last two studies do not take this item into account. Proper accounting of all energy inputs should also include the energetic cost of producing and repairing of the heavy machinery used for the production and transportation of corn such as trucks, tractors, ploughs, cranes, railroad cars, locomotives, barges, etc. It must be noted that the "total pre-processing" column includes the sums of the total energy used in the field from Table 10.5.

Once the corn is produced, it must be transported to the ethanol plant for processing. Based on the calculated production of corn, Table 10.7 includes the yield of ethanol in liters per hectare (l/ha); the transportation energy input for the corn and the processing energy input for the production of ethanol in MJ/l of ethanol produced. At this stage, the most consuming energy processes are the

Table 10.6 Corn seeding, plowing, irrigation and harvesting energy needs including machinery utilization and repair GJ/ha

Study	Diesel	Gasoline	Seeds	Machinery	Other energy	Total preprocessing
Pimentel (2003)	3.8	2.3	2.6	8.9	3.2	33.8
Patzek (2004)	3.1	0.9	2.6	8.5	3.4	29.2
Shapouri et al. (2002)	3.7	1.2	2.6	0.0	5.9	22.3
Wang et al. (1997)	2.9	1.0	2.6	0.0	3.6	19.8
Average	3.4	1.4	3	4.4	4.0	26.3
Percent standard deviation	13	48	0	116	32	24

Table 10.7 Ethanol yield and energy inputs during corn transportation and ethanol processing

Study	Yield (l/ha)	Transport (MJ/l)	Fuel (MJ/l)	Total inputs (MJ/l)	Total processing (GJ/ha)
Pimentel (2003)	3,201	1.3	14.74	16.07	51.4
Patzek (2004)	3,175	1.7	14.45	16.19	51.4
Shapouri et al. (2002)	3,137	0.44	14.45	14.89	46.7
Wang et al. (1997)	3,189	0.43	14	14.39	45.9
Average	3,176	1	14	15	49
Percent standard deviation	1	66	2	6	6

milling of the corn and the distillation of the fermentation product. The energy content of byproducts of ethanol production is included in the credits column of this Table and given in MJ per litter of ethanol produced. The total processing energy consumption in GJ per hectare is given in the final column of Table 10.7. The very low value of the fractional standard deviation for the total processing energy signifies that, even though some of the partial numbers of the four studies do not agree well with each other, all four studies agree very well in the total energy used for the processing of corn.

The energetic study for the production of ethanol from corn is completed by adding all the energy inputs associated with the production of the final product and by comparing them with the energy output of the final product. The LHV and the HHV of ethanol, when expressed in terms of volume are: 21.1 and 23.3 MJ/l respectively. From these numbers, the LHV and HHV per hectare are calculated to be 67,000 and 74,000 MJ/ha, respectively. Table 10.8 shows the total energy inputs associated with the production of corn and the transportation and processing of ethanol. The sum of the energy inputs for the production of ethanol is given in the fourth column of the Table. The last two columns are the figures of merit for the production of ethanol from corn, which are defined as follows:

Table 10.8 Total energy inputs and output input ratio based on the LHV of 67,000 MJ/ha and HHV of 74,000 MJ/ha

Study	Total preprocessing	Total processing	Total energy consumption	LHV ratio	HHV ratio
Pimentel (2003)	33.8	51.4	85.2	0.79	0.87
Patzek (2004)	29.2	51.4	80.6	0.83	0.92
Shapouri et al. (2002)	22.3	46.7	69	0.97	1.07
Wang et al. (1997)	19.8	45.9	65.7	1.02	1.13
Average	26.28	48.85	75.13	0.90	1.00
Percent standard deviation	24	6	12	12	12

$$LHV\ ratio = \frac{67,000}{Total\ Energy\ Input\ in\ MJ/ha}\ and$$
$$HHV\ ratio = \frac{74,000}{Total\ Energy\ Input\ in\ MJ/ha}. \tag{10.3}$$

Obviously, if a figure of merit is less than 1, the corresponding study indicates that the ethanol from corn transformation consumes more energy than it produces. When the ratio is higher than 1, the ethanol produces more energy than what is required in its production. Of the two columns, the LHV ratio is of more relevance to the production of ethanol, because ethanol is primarily used as transportation fuel and the exhausts of vehicles do not condense the produced water vapor to recover the HHV. A remarkable observation on Table 10.8 is that three of the four studies indicate that the LHV ratio is less than one and the result of the fourth (1.02) is practically equal to one. Even if the HHV ratio were used, the resulting figures of merit are very close to 1. This demonstrates that, in the production of ethanol from corn and similar sources, which are based on starch, by the conventional method of fermentation, we usually consume more or an equal amount of energy than we actually obtain from the final product. Based on these studies, the production of ethanol from corn for its use as a transportation fuel is highly questionable as a viable energy saving or energy production method as well as a method to reduced the GHG emissions. Because this method of producing transportation fuels consumes more energy than it delivers, it should not be considered as a viable alternative to fuel production.

While the production of ethanol from starch is clearly an unacceptable option, another method of the production of ethanol, from cellulosic materials,[5] has a more favorable energetic analysis and may be a better alternative in the production of biofuels as explained in the study by Farrell et al. [1]. The favorable energetic analysis relies on the complete utilization of all the byproducts for the production of ethanol, which contain significant amounts of energy. However, the utilization

[5] Cellulosic materials consist of the fibers that are commonly called "wood." Their scientific name is lignocellulose, which is principally composed of cellulose, hemicellulose and lignin.

of these byproducts is not accomplished at present by ethanol producing installations because of the additional equipment needed, transportation costs, and the significant capital expense that is required.

10.3 Environmental Effects

In the early twenty-first century, the increased use of biomass has been advocated as a viable method to reduce pollution and liquid hydrocarbon independence in several OECD countries. Governmental programs and regulations have been adopted for the widespread use of the E10 fuel and economic subsidies have been offered for the production of biofuels. However, the widespread use of crops for energy becomes highly questionable when one considers the environmental and social effects of biomass use. The following sections examine critically these effects.

10.3.1 Land Use

The most important consequence of biomass production for energy is the use of agricultural land, which is a scarce resource in the planet. Agricultural crops and forests use a very large area and the development of energy crops would be very costly in the use of land. On the other hand, agricultural waste, such as bagasse, rice husk, or forestry waste is a very welcome source of energy because it is normally considered unwelcome waste and, in most cases, their producers will even pay for their removal. The widespread planting of switchgrass and eucalyptus trees for combustion or corn for the production of ethanol fuel entails the utilization of agricultural land that could have better been used for the production of additional food, which is still sorely needed in several countries. When in the years 2005–2008 a great deal of the US corn production was diverted to ethanol production, the price of feeding the livestock increased significantly. As a result, the price of milk doubled in the U.S.A. and several food items, including meat and cheese, became significantly more expensive.[6] The same cause in Mexico resulted in the tripling of the price of corn tortillas, which led to social unrest and obliged the Mexican government to impose price controls. Several countries, including most of East Asia and Africa, simply cannot afford to divert scarce agricultural land for energy crop production, because almost every parcel of land is currently needed to feed their populations.

[6] Other factors, such as higher energy and fertilizer costs as well as commodity speculation contributed to this increase. However, in all studies conducted on this topic, the use of corn for the production of ethanol was the primary variable that caused the rapid food price increase.

A wiser and much more effective use of land for energy would be the installation of photovoltaic cells to produce electricity. This energy may be stored in the form of hydrogen (see Sect. 12.5) and then exported in exchange for food. This exchange may be called the *food for energy trade*, and is based on the fact that photovoltaic energy conversion has much higher conversion efficiency (close to 20%) than natural plants (close to 0.5%). For example, Brazil has vast areas of arable land and, through its vast network of rivers, a great deal of freshwater for irrigation. This country has the capability to produce significantly more food than it does now. On the other hand, the countries in the Saharan West Africa (e.g. Chad, Mali, Niger and Mauritania) have very small areas of arable land, but are located in the best region for the production of solar power as may be seen in Fig. 7.4. The electric energy from the photovoltaic cells may be stored as hydrogen fuel and subsequently transported.[7] If food were produced in excess in Brazil and hydrogen in the Sahara, one may envision a trade route across the mid-Atlantic ocean carrying food from Brazil and bringing back the excess hydrogen fuel from the Saharan nations. Similarly, hydrogen fuel produced in the highlands of Ethiopia by solar energy may be traded for food grown in Mozambique or Tanzania. Even, when one calculates the externalities of this type of trade, such as the production, storage and transportation costs, the *food for energy trade* would result in a much better use of arable and non-arable land areas than, simply, the growth of energy crops. In addition, a stable food for energy trade would alleviate outbreaks of famine in the Saharan countries and other areas of the Earth.

10.3.2 Fresh Water Requirements

A significant environmental effect of the growth of biomass for energy is the high requirements of fresh water for irrigation and processing. For example, the production of a single gallon of ethanol from corn requires approximately 1,000 gallons of water. If all the available land were to be used for the growth of energy crops, this would require very high quantities of fresh water, which are not available in all regions. Unless the energy crops are planted close to large river systems with unused or underutilized agricultural land, such as the Amazon, the Mississippi, or the Siberian Rivers, the competition for the existing water resources would result in a significant strain to local populations. Planting energy crops in the Southwestern part of the USA is not feasible because of the scarcity of the water. Similarly, planting additional crops to be used for energy production along the Rhine in Germany, the Nile in Africa or the Mekong in Southeast Asia is impractical, because all of the agricultural land along these river systems is

[7] Of course this large scale production of electricity and hydrogen would entail significant capital cost and investment in the Saharan countries. This may be viewed as an investment that will in the future contribute to the economic development of this region and the employment of their populations.

currently utilized in the, more socially acceptable way, of food production. Simply, the irrigation requirements of energy crops lead to the conclusion that very few regions on the planet are suitable for the more widespread production of such energy crops.

The situation is entirely different if sea water were to be used for the production of energy crops: there are vast areas of land close to the ocean, which are not currently used for the production of food. A technological breakthrough that would allow irrigation of energy crops with sea water will change this situation and may make feasible and more socially acceptable the widespread production of energy crops in several coastal regions of the world.

10.3.3 Use of Fertilizers and Pesticides

The expected globally widespread use of fertilizers and pesticides is another significant environmental effect of more biomass production. The known energy crops are very fast-growing plants and need the input of large amounts of fertilizers, pesticides and insecticide chemicals. These chemicals contain phosphorous, sulfur, nitrates, arsenic and trace metals such as zinc, lead, and manganese. Many of these elements are toxic to humans or harmful to the environment. The widespread combustion of biomass will become another pathway that introduces these toxic elements to the atmosphere and to the living organisms.

In addition, all the chemical compounds in the fertilizers, pesticides and insecticides invariably find their way to the hydrosphere—rivers, lakes, estuaries, and oceans—following the runoff waters from rainfall. The addition of these chemicals in the hydrosphere alters the chemical composition of the freshwater and seawater. This is especially significant for the fragile ecosystems in lakes, estuaries, and bays with low water flow or circulation. The periodically observed *hypoxia*[8] in the northern Gulf of Mexico is caused by the high nutrient content in the waters of the Mississippi River, which carries fertilizers and other nutrients from 43% of the land mass in the USA. The water effluent alters locally the chemistry of the northern Gulf of Mexico, off the Louisiana coast and disturbs the ecological balance of the species. Similarly, lake *eutrophication*[9] in Europe and North America causes the depletion of oxygen by algae, which endangers other more complex species, such as fish and shellfish.

[8] Very low oxygen concentration that kills the larger fish.

[9] This is the uncontrolled growth of the algae population because of the high concentration of nutrients. The large population of algae consumes the dissolved oxygen at a fast rate and causes the death of fish and other large aquatic animals.

10.3.4 Unintended Production of Methane

A fourth environmental effect of biomass is the potential accelerated production of methane. If left untreated for periods of a few weeks, biomass decomposes naturally and produces carbon dioxide and methane. The latter is sixteen times more potent GHG than carbon dioxide. The anaerobic decomposition of biomass, e.g. when it is immersed in water or buried underground, always produces methane gas, which diffuses into the atmosphere and contributes significantly to global warming. If biomass is not used promptly and is left to decompose, either in the field or in storage facilities, it would cause significantly greater damage than the environmental benefit of removing some of the carbon dioxide from the atmosphere.

The Brazilian experience during the 2002–2008 period of uncontrolled and high demand for biomass products is a warning to what may happen to the land if only economic incentives for the growth of biomass are offered: Because of the high demand for biofuels that are produced from sugar cane and the high price of sugar cane, Brazilian farmers converted large parcels of land along the Amazon to biofuel producing crops. In addition, they cleared very large tracts of tropical forest near the Amazon River to establish farms for the production of sugar cane, corn and other high energy yielding crops. The result was that large trees were uprooted and were burned or, even worse, were left decomposing to produce methane. Bearing in mind that 30–40% of the mass of the tree is in the underground roots, this organized deforestation and conversion to arable land brought into the atmosphere a great deal more GHG's than what the subsequent biomass production removed.

10.3.5 Other Effects

Other, less significant environmental effects of expanded biomass production and production of energy crops include:

- Soil erosion and depletion of soil nutrients.
- Loss of biodiversity.
- Partial or total deforestation, which may lead to desertification.
- Growth of monocultures, which are highly vulnerable to agricultural diseases and bacteria.
- Higher river silt concentration and enhanced siltation rates that may lead to river or estuary eutrophication.
- Changes in land use and irrigation patterns, which may change the microclimate of the region.
- Dust production from plowing and harvesting.

It must be noted that almost all the adverse environmental effects of extensive biomass production are associated with the energy crops and not with the treatment

of agricultural, human and animal waste. The expanded production of energy from any type of waste and the reduction of the volume of waste on a global scale has beneficial environmental and ecological effects, in addition to producing needed energy.

10.4 Social, Economic and Other Issues for Biomass Utilization

The widespread use of energy crops is highly controversial. Unlike the other renewable energy sources, which may only be utilized for energy production, the use of biomass is intricately connected to food production, world poverty and malnutrition, high rates of freshwater use, high rates of arable land use, and agricultural land deterioration. Increased reliance of the world population on biomass-derived energy would certainly have adverse effects on the food and fresh water supply, with all the social consequences this would imply. For this reason, there are several key issues, which must be resolved before national or regional policies are formulated that encourage and further promote the higher utilization of energy crops. Some of these issues were identified earlier in this chapter, but are repeated here for clarity.

A. *Economic subsidies*: Food production and several agricultural products enjoy substantial subsidies from most national and regional governments. Farming subsidies are among the few items that are exempted from the international treaties brokered by the World Trade Organization (WTO). Frequently, the subsidies are in the form of tax credits. For example, in the U.S.A. there is a federal tax credit of $0.51 per gallon of ethanol that is used as a transportation fuel. Since biomass is essentially a farming product it enjoys very generous subsidies in most countries including: tax credits; direct grants; low-interest loans for its production and processing; exemption from taxation of the fuels used for its production; high depreciation rates and even subsidies on the equipment used for its production and processing.
   In the 1990s the real cost for the production of one gallon of ethanol in the U.S.A. and Europe was close to $11, yet because of the several subsidies, ethanol was mixed with gasoline to be sold at significantly lower prices. While this practice is a prime example of economic inefficiency, several of the agricultural subsidies may be justified socially when directed to small farmers, who in most countries live close to poverty levels and produce other staple foods for the benefit of the society at large. However, since the 1990s large enterprises and several multinational conglomerates have entered the biomass production industry and have derived very high profits from subsidized biomass production. In the latter case, the social, economic, and national interest in continuing and extending these subsidies become highly questionable.

Clearly, any current or future subsidies for energy crops must be justified on social, economic, and environmental grounds. While economic subsidies for the production of corn and wheat for food are justified, subsidies for the large scale production of these staples for their conversion to biofuels are highly questionable. The regulatory institutions that govern the production of biomass must ensure that any economic subsidies benefit the small farmers and not the large corporations, maintain affordable prices for the foodstuffs and do not result in environmental deterioration.

B. *Food scarcity*: The high expansion of ethanol production in the period 2001–2008, especially ethanol derived from corn, has been accompanied by a significant rise in commodity prices worldwide between 2003 and 2009. Even though economic studies on the effect of corn used for ethanol production on the increased food prices vary significantly, these studies attribute 15–60% of the increased food prices in the production of corn ethanol. This is an indisputable fact that the diversion of agricultural products for the production of energy drives the prices of food products higher. Simple demand and supply considerations dictate that the removal of corn from the marketplace for the production of ethanol will always increase its price as food. Concerns over food availability, especially in the famine-prone regions of the world, have the potential to stifle any use of food products for energy or to at least cause the removal of all subsidies.

   The popular press has reported that one billion people on Earth, or one out of seven Earth inhabitants, suffer from malnutrition and that in every six seconds, one child dies of malnutrition or outright starvation.[10] The rising food prices have affected citizens living at or near the poverty level even in the wealthier OECD nations. Under this light, the increased use of subsidized corn or other agricultural products to feed the engines of *Hummers*, *BMW's*, *Cadillacs*, and *SUV's* is neither socially responsible nor economically justifiable. The United Nations has issued a warning against the use of food crops for energy and several national governments are expected to follow by removing subsidies or placing restrictions on which agricultural products may be used for energy production. Because the viability of the biomass industry depends to a large extent on the levels of national and regional subsidies and grants, the regulatory environment and not the free markets will finally determine the expansion of several types of biomass for the use of energy. An international policy along the line "*do not burn what you can eat"* may justifiably become the cornerstone of the future of biomass use.

C. *Poverty levels worldwide*: Some of the concerns related to world-poverty over the price of food are partially offset by a worldwide increase in the agricultural incomes in the first decade of the twenty-first century. Because a large percentage of the population living in poverty levels derives its income from

[10] Associated Press, October 15, 2009.

agricultural employment, the increase in their incomes has been a welcome effect of biomass production and a rationale for several national and regional governments to continue with the agricultural subsidies. However, as explained in section A, in considering economic subsidies for the production of biomass, a government has to ensure that larger, for-profit corporations do not take unfair advantage of such subsidies, which are intended for the small farmers.

D. *Stability of energy prices*: The interest in biomass and biofuels is not new. The *energy crisis* of the 1970s and the oil embargo in Europe and North America caused a dramatic rise in the production of biomass, especially biofuels, that continued into the early 1980s. The interest in the conversion of biomass waned in the mid 1980s when energy prices dropped. Several biomass conversion plans were abandoned at that time and a great deal of investment capital was lost. It has become apparent that high energy prices are needed to stimulate higher biomass utilization. The OPEC production trends and the resumption of the higher oil demand in Asia in 2010 are indications that the energy prices will not tumble in the second decade of the twenty-first century as they did in the 1980s and 1990s. These indications point to rising biomass utilization in the future, especially biomass derived from waste products.

E. *Greenhouse gas policy*: GHG emission concerns are the primary reason for the increased use of all renewable energy sources, including biomass. Well-intentioned but injudicious regional and national regulations may require a higher use of biomass or biofuels. For example, the regulatory change from the E10 fuel (gasohol), which is currently used in most of the states in U.S.A., to E20 will almost double the demand for ethanol. Actually, a provision was included in the Energy Policy Act of 2005, which mandates that 7.5 billion gallons of renewable fuels be used in gasoline by 2012. Similar regulations in the European Union and other nations will further increase the production of ethanol and other biofuels. Given the energy balance for the production of ethanol from starch, such regulations will not always achieve their goal for the reduction of GHG emissions, unless it is also stipulated in the regulatory or legislative framework that ethanol may not be derived from the starch of foodstuff but from cellulosic plant materials, with LHV ratios significantly higher than 1.

F. *Technological advances*: These pertain to the growth as well as the processing of the biomass. Examples include: the engineering of algae and bacteria with higher fat content; the faster and more efficient drying of the aquatic biomass; higher crop yields of the land; energy crops that may grow with salt water; ethanol from cellulosic processes; catalytic pyrolysis at lower temperatures; and bacteria that process solid and liquid waste at a faster rate.

G. *Global and regional climate change*: It is rather ironic that climate change, the very cause for the increased use of biomass, will have a significant impact on the production of biomass and biofuels. Potential regional climate changes are a key issue in the crop yield of the land and the production of biomass. Warmer weather would increase the crop yield and the amount of biomass if it is

accompanied by sufficient rainfall. On the other hand, drier weather may spell the end of the use of biomass for energy because sufficient food supply will always have a priority over energy supply.

10.5 The Future of Biomass for Energy Production

It is apparent that the use of food crops for energy production, whether this is electricity or biofuels, is detrimental to the environment, it places a strain on water supply, and is economically inefficient and socially undesirable. Providing high subsidies for the production of energy crops in the industrialized countries is economically inefficient. In addition, complete and reliable energy balances, such as the ones in Sect. 10.2.1 for the production of ethanol from corn, indicate that the increased use of energy crops for energy production may actually increase, not reduce GHG emissions. The use of vast tracts of land for the production of energy crops is also a very inefficient as well as a detrimental use of the land area, especially in the industrialized and economically advanced countries, where capital for high-technology investments for energy production is available. For example, given the availability of capital for the investment, the same land may be covered with photovoltaic solar cells and be used at 20–30 times higher efficiency for the production of electricity.

Biomass derived from human, animal or agricultural waste and aquatic biomass are totally different. Wastes do not have an economic value, they must be disposed and, in general, they harm the environment. If left unattended they decompose and produce methane, a potent GHG. The reduction of the mass or the volume of the waste by extracting biofuels or directly burning them is environmentally beneficial and economically efficient. Similarly, the use of municipal sewage for the growth of algae that may be used for the production of biofuels and the use of agricultural and forestry wastes in a co-firing process makes good sense and, in most cases is economically justified. For this reason, it is believed that in the future, the production of biomass from energy crops will be curtailed, while the biomass from waste products will increase significantly. Technological advances that will lead to increased production of aquatic biomass and especially of marine biomass will materialize when faster and less energy consuming drying processes are invented, or when organisms, which are more suitable for energy or fuel production, are engineered.

Problems

1. In your opinion, what are the primary reasons for the large disparity of the solid waste production per capita in the U.S.A. and in Europe?
2. Use of biomass from fast growing trees, such as sycamore, is often advocated as an alternative to burning coal. Grown sycamore threes weigh 430 kg on

average and the heating value of their wood is 15,300 kJ/kg. Find out how much heat power is consumed annually by a 400-MW coal power plant with an overall efficiency 40%. If the entire amount of this heat input were to be supplied from harvested sycamore trees, how many grown sycamore trees would the power plant need to consume annually? You may assume that the energy for the planting, harvesting and transportation of the sycamore trees to the power plants is negligible.

3. The country of Estonia consumed 8.42 TWh of electricity in 2009 at an average overall thermal efficiency 32%. It has been suggested that Estonia produces all its electricity from locally grown pine trees. The average pine tree requires 11 m^2 to grow, becomes 400 kg in 8 years and has a heating value 13,700 kJ/kg. How much area is required for this solution to Estonia's energy problem? Is this alternative feasible? Assume that the energy for the planting, harvesting and transportation of the pine trees to the power plants is negligible.
4. How much electric energy (in Terajoules, TJ) was produced in your country? If this energy was produced by power plants with an average overall efficiency 32%, how much heat energy (in TJ) was consumed? Assume that the entire area of your country were planted with native trees that grow to 500 kg in 7 years, have heating value 14,000 kJ/kg and each requires an area 10 m^2 to grow. How much area for tree planting would your country need? Is this a feasible solution for the production of electricity in your country?
5. Rice-hull residue with 30% humidity is used in the boiler of a small thermal power plant. The plant produces 60-MW of electricity and has an average efficiency 34%. How many tons of rice-hull the power plant consumes every year? If the average distance for the transportation of the fuel is 58 miles, the transportation trucks carry 12 tons per trip and consume 5 miles/gallon of diesel on average, how many gallons of diesel are needed annually for this plant to operate?
6. A 600-MW coal electric power plant substitutes 8% of its fuel with "tree clippings," which are tree branches that are cut to clear roads as well as the access lanes (rights of way) of power lines. The tree clippings are fed in the boiler together with the coal. How much coal is saved annually by this practice and how much CO_2 emissions are prevented?
7. The New York metropolitan area has a population of approximately 10,000,000. If the New York population behaves like the average U.S. person, how many tons of solid waste do they produce every year? What is the range of the heating value of the solid waste for the region per year? If it were possible to use this waste in thermal power plants with 35% overall efficiency, how much power (in MW) would this waste produce?
8. Cuba produces 38% of its electric power from bagasse. In 2008, Cuba produced 14.67 TWh of electricity in power plants with overall efficiency 32%. How much bagasse was consumed?

9. What do you think will be the main parts and processes of a biodiesel plant that uses marine algae? Make a conceptual design of a plant that produces biofuels from marine organisms.
10. "We have enough land in this great country to produce enough corn and corn-based biofuels for us to become completely independent of foreign oil. We only need the will and a small amount of investment." Comment on this statement by writing a 250–300 word essay.
11. How many gallons of ethanol may be produced annually from a farm of 100 hectares (250 acres)? What are the inputs of fertilizers, pesticides and total energy that are required for such a farm?
12. "At a time when 50% of the children in the world are under-nourished, it is unconscionable of the leaders of the richer nations to divert food resources for the production of fuel for their high-mileage cars." Comment on this statement by writing a 250–300 word essay.

Reference

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