Future Energy: Opportunities and Challenges

Part II. Energy Sources

Chapter 7. Biofuels

Future Energy:
Opportunities and Challenges

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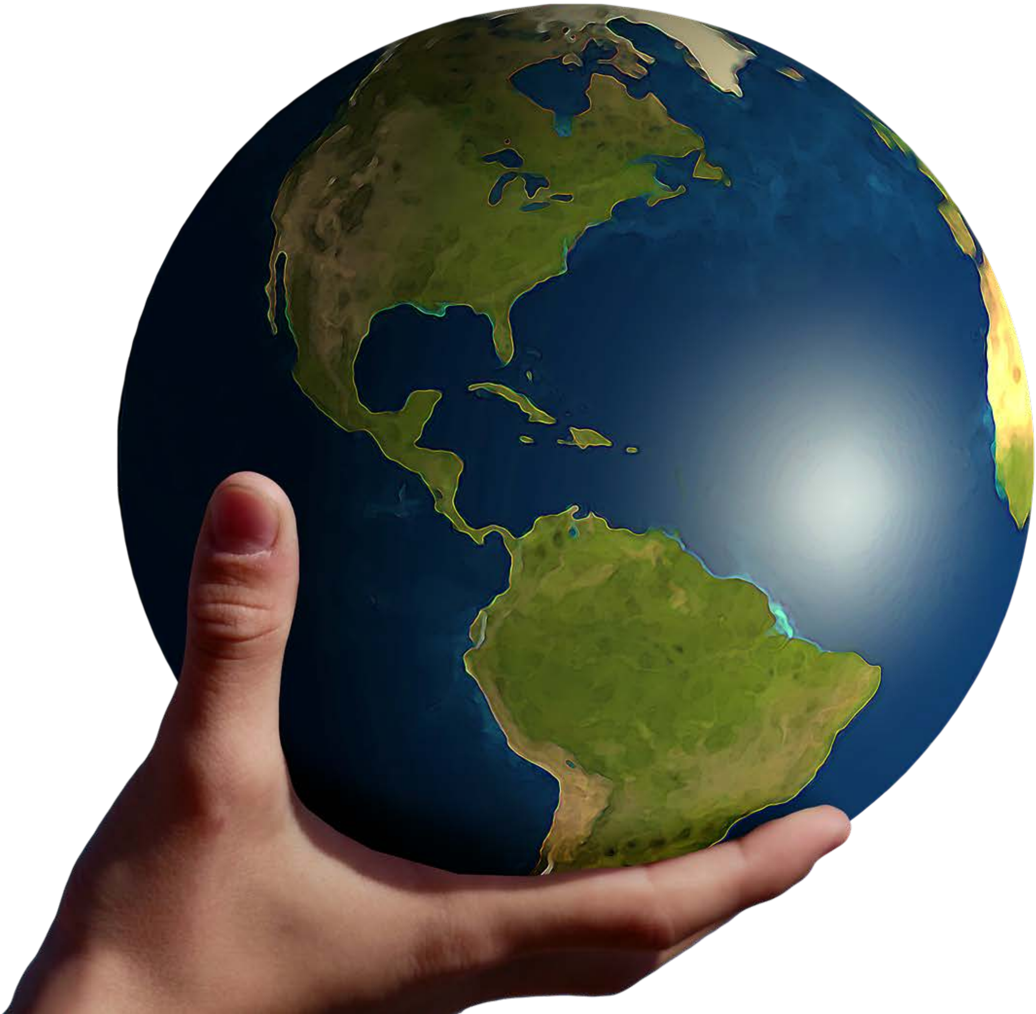

7
Biofuels

The Main Points

- **Terrestrial plants convert 1 to 2 percent of incident solar energy into chemical energy by photosynthesis.**
- **Terrestrial plant yields and energy content per unit weight vary over a small range.**
- **The energy used to grow biomass and to process biomass into biofuel reduces the net energy available in biofuel.**
- **Replacing 100 percent of current oil use with biofuel from terrestrial plants is impossible because of the amount of land required to grow sufficient biomass.**
- **Algal biofuel can be produced photosynthetically or by fermentation of biomass.**
- **Chemical, biochemical, and thermochemical processes exist for converting biomass into biofuel.**
- **Ethanol can be produced from cellulose, hemicellulose, and lignin, as well as from starch.**
- **Ethanol is the main focus of current biofuel development efforts, but other biofuel production technologies are potentially superior.**

7.1 Introduction

The production of fuels from biomass usually involves disassembling the molecules comprising plant matter and producing new molecules from the contained carbon, hydrogen, and (in the case of some biofuels) oxygen. (The exception is the direct use of oils from some plants as fuel.) The most desirable transformation would be one that yields hydrocarbons with two to four hydrogen atoms per carbon atom. These products could serve as a direct replacement for oil and natural gas. The preferred transformation would involve enzymes so as to achieve simplicity and low cost. Scientists are actively seeking new enzymes for achieving this goal.

Biofuels that can be made by processing plant materials include alcohols, hydrocarbons, esters, and ethers. Three broad categories of processes are used to accomplish the transformations: biochemical processes, thermochemical processes, and chemical processes.

Biochemical processes are those that use living organisms to enable and/or facilitate reactions. Thermochemical processes use high temperature to decompose biomass molecules. Chemical processes are those with reactions between compounds that include neither a biochemical nor a thermochemical involvement. In addition, hybrid processes involve a combination of process types.

This chapter addresses the main currently-known technologies for producing useful biofuels in each of these process categories.

7.2 Plants and Energy

Plants use sunlight for the energy needed to combine water and carbon dioxide to produce carbohydrates. Only a small fraction of the solar energy striking a plant's leaves is captured and used for photosynthesis. Energy capture efficiencies for terrestrial plants are typically around 1 to 2 percent[1].

Plant matter releases energy when it oxidizes and converts back into water and carbon dioxide. The energy released in oxidation is equal to the solar energy absorbed initially during photosynthesis. The plant matter that exists between the time that it is formed by photosynthesis and the time that it is eventually oxidized may be viewed as a storehouse of energy. The stored energy can be used directly by burning, or indirectly by converting the material into other chemicals before oxidation. In either case, the maximum energy available is the solar energy that was originally absorbed by the plant in photosynthesis.

The energy contained in biofuel per acre of land used to grow terrestrial biomass is given by the product of three factors:

- The biomass energy contained per ton of dry biomass
- The tons of dry biomass that can be produced per acre
- The fraction of the contained biomass energy that appears in the biofuel produced

Biomass materials have a wide range of properties, but the energy contained is quite uniform (12.9 to 16.4 million BTU per dry ton)[2]. The crop yields for terrestrial plants are currently 5 to 8 dry tons per acre. Some analysts predict crop yield increases for some plants to 12 dry tons per acre by the middle of the twenty-first century.

The most uncertain factors in projecting the number of acres required for biofuels are future crop yields and conversion efficiencies. Crop yields are determined by plant genetics, sunlight availability, water availability, carbon dioxide concentration in the air, soil nutrient concentration (mainly nitrogen, but including other elements), and soil physical characteristics (sand, clay, rock, etc.).

Table 7-1 shows the land requirements for a range of assumptions for these factors. The specific energy content of biomass used in the calculations for Table 7-1 was taken to be 14.5 million BTU per ton. This is roughly the mid-point of the range of reported values (12.9 to 16.4 million BTU per ton). Values of biomass-to-biofuel conversion efficiency selected for the table are 0.3 and 0.6 (the range of efficiencies potentially achievable) so as to bracket future possibilities. The table shows estimated land requirements to produce 1 Quad and 27 Quads (the current annual U.S. energy production for transportation from crude oil).

The results in Table 7-1 show the land required for replacing the oil used for transportation (27 Quads) with biofuel is large compared to total U.S. land area (1.9 billion acres for the continental U.S.). For example, even the most optimistic assumption results in an acreage requirement of 260 million acres to replace oil for transportation at its current rate of use. This acreage is 59% of total current cropland area (around 441 million acres) and is too great to be feasible. It is clear that devoting this much land to growing biomass for biofuel or even just to harvesting waste biomass is unfeasible.

Table 7-1. Land Requirements for Biofuel Production

Biomass Yield (dry tons per acre)	Biomass to Biofuel Conversion Efficiency	Biomass Energy Productivity (million BTUs per acre)	Land to Produce 1 Quad (million acres)	Land to Produce 27 Quads (million acres)
5	0.3	22	45	1,220
8	0.3	35	29	780
12	0.3	52	19	520
5	0.6	44	23	610
8	0.6	70	15	390
12	0.6	104	10	260

Biofuel production from terrestrial plants could be important in reducing import expenditures and dependence on foreign sources, for producing domestic jobs, and for conserving oil resources, but it clearly is incapable of totally replacing current U.S. oil consumption because of the huge land area that would be needed.

As we will see in Section 7.4.4, algae grow much faster than terrestrial plants. Furthermore, some algae provide high yields of hydrogen, triglycerides, or hydrocarbons. Consequently, there is now great interest in developing practical processes to produce biofuel from algae.

7.3 Plant Characteristics

Plant characteristics determine the possibilities for processing into useful biofuels. The components in plant matter that comprise the raw material for biofuel production are carbohydrates, lignin, and plant oils (see Section 2.10).

Carbohydrates are compounds composed entirely of carbon, hydrogen, and oxygen. Sugars, starches, cellulose, and hemicellulose are all carbohydrates.

The basic building block of all carbohydrates is the sugar molecule. Simple sugars involved in carbohydrate synthesis, called *monosaccharides*, contain either five or six carbon atoms arranged in a ring structure. Five-carbon sugars are called *pentoses,* and six-carbon sugars are called *hexoses*. The monosaccharides contain two hydrogen atoms and one oxygen atom for every carbon atom. Therefore, the formula for pentose is $C_5H_{10}O_5$, and the formula for hexose is $C_6H_{12}O_6$.

Larger carbohydrate molecules (starch, cellulose, and hemicellulose) are formed by linking sugar molecules. Carbohydrates with two linked sugars are called *disaccharides,* and those with more than two linked sugars are called *polysaccharides*. Consider the linking of two hexose sugars to make a disaccharide. The linkage requires the elimination of one water molecule (H_2O). The formula for the resulting disaccharide is $C_{12}H_{22}O_{11}$. The process may be represented as follows:

$$2C_6H_{12}O_6 \rightarrow C_{12}H_{22}O_{11} + H_2O$$

The removal of water is called *dehydration*.

In some biomass-to-biofuel processes, it is necessary to convert polysaccharides into monosaccharides before further processing. Since converting polysaccharides into monosaccharides involves reacting water with the polysaccharide, the process is called hydrolysis.

Starch is a polysaccharide composed of hexose sugar links. Cellulose is also a polysaccharide of hexose sugars, but the structural arrangement of the atoms differs from the structure in starch. Basically, the starch and cellulose molecules are chains of ring-shaped links. In the starch molecule, all the rings face the same way. In the cellulose molecule, each link faces the opposite way relative to adjacent links. (Visualize a chain of connected dinner plates. In starch, each plate faces "up," and in cellulose, plates alternate facing "up" and "down.") The structural difference accounts for the different properties of starch and cellulose. It should be noted that any process that breaks the chain in starch or cellulose molecules yields the same simple sugar molecule and provides the same opportunity for further processing by processes such as fermentation into ethanol. Hemicellulose is a polysaccharide composed of linked pentose and hexose sugars.

Plant stems, stalks, trunks, branches, and leaves all contain cellulose and hemicellulose. These plant components are inedible by humans, but some animals and insects can digest them. The cellulose and hemicelluloses in plants are encased in a tough, fibrous material called *lignin*. Lignin is not a carbohydrate, but it is a complex organic polymer.

Some plants also produce oils. Section 7.6.2 and Appendix L present information about vegetable oil properties and processing.

7.4 Biochemical Processes

Five important biofuels may be produced biochemically. These are ethanol, butanol, hydrogen, hydrocarbons, and methane.

7.4.1 Ethanol

Ethanol is a liquid biofuel that can serve as a replacement for gasoline (see Appendix M). It is a clear liquid at normal temperatures, it is less dense than water, it mixes readily with water and with gasoline, and its energy content per pound is about two-thirds that of gasoline. The chemical formula for ethanol is C_2H_5OH.

The biochemical route to bioethanol involves three steps:

1. Enzymatic conversion of carbohydrates into monosaccharides (hydrolysis)

2. Enzymatic conversion of the resulting monosaccharides into ethanol (fermentation)

3. Separation of ethanol from the water used in the process

The technology for producing monosaccharides from biomass depends on the type of carbohydrate being processed. Starch processing may be accomplished with common and inexpensive enzymes. Enzymes for hydrolyzing cellulose and hemicelluloses are known, but suitable inexpensive strains are not yet available. Current genetic engineering work on developing new strains of enzymes for hydrolyzing cellulose and hemicellulose is expected to provide the required biochemical capability. In the meantime, known processes that use acid to hydrolyze cellulose and hemicellulose can be employed. The conversion of cellulose and hemicellulose using the acid process is actually part of a hybrid biochemical-chemical process (see Section 7.7).

The enzymatic conversion of monosaccharides into ethanol is called *fermentation*. Fermentation is an old, well-known technology.

The third step involves removing water from the ethanol-water mixture in a two-step process. Distillation removes most of the water. The remaining water is removed by dewatering with materials that selectively absorb water.

Initial efforts at large-scale production of bioethanol for use as a fuel focus on using the starch in corn. Using corn has some serious drawbacks, mainly competition for its use as food for humans and animals. Consequently, there is intense effort underway to develop economical processes for converting plentiful cellulose and hemicellulose into bioethanol. Appendix M provides more detailed information on bioethanol production, its potential as a significant replacement for oil, and the practicality of its production and use.

7.4.2 Butanol

Butanol is less well-known than ethanol, but it shows promise for use as a biofuel. It is a clear liquid at normal temperatures; its density is less than that of water but is greater than that of ethanol; it is immiscible with water; and its energy content is about 86 percent of that for gasoline. Butanol is a four-carbon alcohol whose formula is C_4H_9OH.

A biochemical process for producing butanol operates in two stages, with a different enzyme for each stage. The first stage enzyme causes conversion of biomass into butyric acid ($C_4H_8O_2$) and hydrogen. In the second stage, another enzyme converts butyric acid into butanol. This process does not involve the hydrolysis of starch, cellulose, or hemicellulose into simple sugars. It can use the lignin as well as the carbohydrate components of biomass. The two-stage process produces butanol and hydrogen, both useful in energy production. Additional details appear in Appendix N.

7.4.3 Methane

Methane is a colorless, odorless gas at normal temperatures. It exists in natural gas from underground formations; it may be produced from other hydrocarbons; and it may be produced by the anaerobic digestion of biomass.

The decomposition of dead biomass (animal and vegetable) is accomplished by microbes. If the dead biomass is exposed to air, aerobic microbes digest the material and produce carbon dioxide and water. If the dead biomass is isolated from air by overburden or water, anaerobic microbes digest the material and produce mostly methane and carbon dioxide. This gas is called *biogas*. Biogas production occurs in natural settings such as forests and wetlands and in man-made landfills. Some landfills have been fitted with biogas extraction systems, thereby gaining valuable fuel and preventing methane, a powerful greenhouse gas, from entering the atmosphere.

Additional information appears in Appendix O.

7.4.4 Algal Processes

Some work has been done on growing algae for biofuel feedstock. Algae are aquatic plants, and they require sources of carbon, hydrogen, oxygen, and energy for growth.

In photosynthetic algal growth, the source chemicals are carbon dioxide and water, and the energy comes from sunlight. Algae can also grow without sunlight. Certain algae can obtain all of the essential carbon, hydrogen, oxygen, and energy from biomass fed to the reactor. Therefore, they can grow in the dark and are called "dark process" algae. Sugars derived from the biomass provide the energy needed for the biochemical reactions.

The photosynthetic process results in the production of new algal biomass, and the dark process results in the fermentation of biomass (typically terrestrial biomass) into algal biomass with suitable properties for biofuel applications.

The energy contained in photosynthetic algae cannot exceed the energy captured from the sun. The energy contained in dark process algae cannot exceed the energy contained in the biomass used in producing the algae. As expected, the capture of solar energy always limits the energy content of biofuels.

Certain algae can produce hydrogen, triglycerides, or hydrocarbons. These are a potential source of large quantities of fuels to replace traditional fossil fuels. Major research efforts focus on genetic engineering to produce strains of algae that maximize the production of useful biofuels.

Algae grow much faster than terrestrial plants. The naturally high growth rates of photosynthetic algae can be increased in an environment that is rich in carbon dioxide. Designs have been formulated that feed carbon dioxide into algal growth chambers[3]. Industrial processes with large carbon dioxide production (such as fossil-fueled power plants, ethanol fermentation facilities, and breweries) could provide the carbon dioxide needed to increase algae growth rates. Commercializing this approach would require locating the algae farm and the carbon dioxide producer close to one another, and the yields would have to be high enough to justify the investment in growth chambers.

Initial prototype systems have demonstrated the dark process route to biofuel production. This work shows the capability of this process to yield a range of useful chemicals, including biodiesel and jet aircraft fuel. Since sunlight is not needed in the dark process, there is no shading by peripheral material, and the reaction proceeds throughout the reaction vessel. On the other hand, in the production of photosynthetic algae, growth occurs only on the surface where sunlight is available.

The photosynthetic process and the dark process described above can produce useful biofuels. These processes are still in the developmental stage, but they show promise for providing significant quantities of useful biofuels. However, it remains to be seen whether the rate of production will be great enough to justify the investment in special facilities required to produce the algal biomass.

7.5 Thermochemical Processes

7.5.1 Introduction

Thermochemical processes used for producing biofuels are those that use heat to convert solid carbonaceous materials into gases and/or liquids[4]. Thermochemical processes are designated as gasification processes or pyrolysis processes. Gasification processes are those that occur with limited oxygen present. Pyrolysis processes are those that occur with no oxygen present. Gasification and pyrolysis processes are typically part of multi-stage processes in which gasification is the first step. Subsequent processing, usually involving a chemical process, yields the desired biofuel.

7.5.2 Gasification

The gasification of biomass produces a synthetic gas called syngas. (See Section 4.7.) Syngas is a mixture composed mostly of hydrogen and carbon monoxide. Currently, most syngas is made from methane, but interest in switching from fossil fuels to renewable fuels has created motivation for addressing syngas production from biomass. Since syngas made from biomass is identical with syngas made from fossil fuels, all of the processes using syngas in the production of other fuels (as discussed in Chapter 4) are also applicable to syngas made from biomass.

Syngas is a fuel and also is a suitable intermediate in producing an array of other fuels by chemical transformations. Some potentially important transformations were outlined in Section 4.7.

7.5.3 Pyrolysis

The pyrolysis of biomass involves heating it in the absence of oxygen to break down the molecules comprising the biomass and to yield new compounds. Any biomass can be pyrolyzed. The specific mix of products obtained depends on the biomass used and the pyrolysis conditions. Pyrolysis yields char (solid carbon) and various gases. The proportions of char and gases depend on the residence time in the pyrolysis reactor. Short residence times favor gas production over char production. This is called fast pyrolysis. Fast pyrolysis followed by rapid cooling of the resulting gases yields bio-oil (also called pyrolysis oil), a liquid that may be used directly as fuel oil or may be further processed to yield other liquid fuels.

Bio-oil is a mixture of compounds that range in color from green or dark red to black. It has a high heating value (HHV) ranging from about 75,000 to 82,000 BTU per gallon. Bio-oil can be used mixed with or as a replacement for conventional heating oil. It can be transported and handled in the same fashion as heating oil, but it degrades with time, requiring limited storage duration.

Bio-oil processing to yield more desirable liquid fuels is in the developmental stage. The purpose is generally to reduce or eliminate oxygen and to produce hydrocarbons with a hydrogen-to-carbon ratio of about two. The adaptation of processes used in petroleum refineries is one of the goals of bio-oil researchers[5].

Bio-oil production is viewed as a valuable waste disposal technology as well as a bioenergy source. Municipal wastes, farm wastes, food processing wastes, and medical wastes are sources of human pathogens. Pyrolysis of these waste streams can eliminate health hazards while providing bioenergy.

7.6 Chemical Processes and Applications

7.6.1 Introduction

Chemical processes are defined here as those processes that alter chemical compositions without biochemical or thermochemical involvement. The yields of chemical processes often depend on pH, catalysts, pressure, and temperature (though high temperatures are not used to decompose source chemicals as in thermochemical processing).

7.6.2 Lipids

Lipids include vegetable oils and animal fats. Some lipids may be used directly as fuel. For other lipids, it is necessary or desirable to modify them to obtain fuel with desired properties.

The chemical form of a plant's energy reservoir is starch or oil. Animals store energy in the form of fat. Vegetable oil and animal fat consist of organic molecules called *triglycerides*, members of the chemical family called *esters*. Triglycerides are molecules with three chain-like components connected to a spine (see Appendix L). The spine is an alcohol called *glycerol*, $C_3H_5(OH)_3$. The chain-like components are fatty acids, basically hydrocarbons with a carboxyl group at one end. A carboxyl group is a section containing one carbon atom, one oxygen atom, and one hydrogen atom.

Triglycerides may be saturated or unsaturated. A saturated triglyceride has the maximum number of hydrogen atoms per carbon atom that is chemically possible. An unsaturated triglyceride has less than the maximum number of hydrogen atoms per carbon atom than is chemically possible. Most animal fats are saturated and are solid at room temperature, while most vegetable oils are unsaturated and are liquid at room temperature.

Vegetable oils may be used as a fuel without modification. Unmodified vegetable oil fuel is usually called straight vegetable oil or SVO. Vegetable oils and animal fats may also be modified to provide new compounds with properties that overcome some of the practical problems with the use of SVO (mainly high viscosity and thickening or solidification at low temperature). Modified triglygerides are usually referred to as biodiesel fuels even though straight vegetable oil is also a biofuel that can also be used in diesel engines.

The modification of triglycerides requires breaking the chemical bond between the spine and the fatty acid chains to yield smaller molecules composed mostly of hydrogen and carbon. This modification may be accomplished by any of three processes: basic transesterification, acid transesterification, and hydroprocessing. Appendix L describes these processes.

Many plants produce vegetable oils. Unlike the large quantities of crop residues and forest residues available for producing cellulosic ethanol, biomass for vegetable oil production requires dedicated cropland to grow oil-bearing plants. The main oil-bearing crop in the U.S. is soy, but the energy content of soy beans is much lower than that of some other crops, especially those grown in tropical regions such as jatropha and palm. Vegetable oil crops in the U.S. yield 20 to 100 gallons of biodiesel per acre.

It is also possible to harvest vegetable oil from algae grown in an aqueous environment. As has been mentioned, algae naturally grow faster than terrestrial plants, and this rate can be increased in engineered environments where CO_2 and/or nutrients are supplied. Yields of algal oil are much greater than yields of vegetable oil from terrestrial plants.

Animal fats are obtained as waste from food production. They are a suitable source material for producing biofuels, but the quantity of available animal fats is much smaller than the potential quantities of vegetable oil.

The energy content of vegetable oil diesel is about 125,000 BTU per gallon (about 10 percent less than petroleum-based diesel). Consequently, the energy yield for soy oil is 2.5 to 12.5 million BTU per acre. For example, a plant energy yield of 10 million BTU per acre corresponds to a land requirement of 100 million acres to produce plants containing 1 Quad of energy.

Using SVO as a diesel fuel imposes some constraints on the engine and on fuel storage in the vehicle. Standard diesel engines must be modified to use SVO. Special kits are available for the required modification. SVO thickens or solidifies at low temperature, making it unusable without a means to heat it. One approach is a two-tank system in which petroleum-based diesel fuel is used for starting. Engine heat is used to raise the temperature of the SVO, then the fuel tank for engine operation is switched to SVO. SVO may also react with gaskets and seals made of certain materials. Exhaust gases from SVO-fueled vehicles pollute less than those from vehicles fueled with petroleum-based fuel except for a slight increase in oxides of nitrogen. SVO is biodegradable, so spills are less of a problem than for petroleum-based diesel fuel.

To put the potential biodiesel contribution to U.S. energy requirements into perspective, replacing all of U.S. use of petroleum for transportation with vegetable oil biodiesel from soy would require almost 3 billion acres of cropland. Remember that the entire land area for the lower 48 states is 1.9 billion acres. Contributions from animal fats would increase the biodiesel supply slightly, but it is clear that although biodiesel from terrestrial plants may be an important potential energy resource for the future, its contribution can only be a small fraction of current U.S. consumption.

Algal biofuels may become important energy sources, but the most promising production methods require construction of special growth chambers. Achieving significant production will require a major investment in facilities.

Biodiesel may be used alone or in combination with petroleum-based diesel fuel. Mixed fuels carry the designation "B" followed by a number. B designates biodiesel, and the number indicates the percentage of biodiesel in the mixture.

7.6.3 2,5-Dimethylfuran

Another biomass-derived compound that has potential for serving as a biofuel is 2,5-dimethylfuran (DMF). DMF can be produced from biomass, though practical commercial production has not been demonstrated. Recent research[6] shows that DMF, whose chemical formula is C_6H_8O, has properties that make it attractive as a biofuel. The heating value of DMF is about 40 percent greater than that of ethanol; it is insoluble in water, and it does not absorb water from the air.

7.7 Hybrid Processes

Hybrid processes are those that use a combination of biochemical, thermochemical, and/or chemical transformations.

For example, ethanol may be produced by acid hydrolysis of cellulose and hemicellulose (a chemical transformation described in Appendix M) followed by fermentation of the resulting sugars (a biochemical transformation).

However, most of the hybrid processes currently under development have syngas production as a first step. Syngas can be used in numerous processes to produce fuels and/or chemicals. For example, the following processes are possible:

- Alcohol production (methanol, ethanol, and other alcohols)
- Hydrocarbon production (gasoline, diesel fuel, jet fuel, and fuel oil)
- Hydrogen production

- Ammonia production
- Acetic acid production
- Other secondary products derived from the chemicals listed above

Heating biomass breaks up the organic molecule to yield syngas, a mixture of hydrogen, and oxides of carbon[7]. The process operates in two stages. In the first stage, biomass is heated to temperatures below 1100°F (600°C) in the presence of air, oxygen, or steam. Thermochemical reactions produce a mixture of carbon dioxide, carbon monoxide, tar, hydrogen, water vapor, char, and ash. In the second stage, the char is heated to 1440–1530°F (800–850°C). Reactions with oxygen, steam, and hydrogen yield carbon monoxide, carbon dioxide, and hydrogen. The overall reaction provides syngas as follows:

$$\text{Biomass+oxygen} \rightarrow CO+CO_2+H_2$$

Syngas may be used as a fuel or as a feedstock to produce a wide array of fuels and chemicals. Some of the products made from syngas that are potentially important in energy supply are outlined below, along with their associated processes.

7.7.1 Ethanol

One possible use of syngas is the production of ethanol by Fischer-Tropsch synthesis (see Section 4.7).

7.7.2 Methanol

Fischer-Tropsch synthesis can also produce methanol from syngas (see Section 4.7).

7.7.3 Dimethyl Ether

Dimethyl ether, a potential transportation fuel, can be produced from methanol from Fischer Tropsch synthesis as described in Section 4.7.

7.7.4 Hydrocarbons

Hydrocarbons, including compounds constituting gasoline, can be produced by the Mobil M-gas process described in Section 4.7.

7.8 Biofuels Requiring No Processing

Biomass can release energy by burning, the oldest use of plant matter for energy production.

A small, but growing, application is the use of wood for home heating. Burning logs in fireplaces is a common, but not very efficient, home heating option. A newer home heating method is the use of furnaces designed specifically to burn wood efficiently.

Biomass may also be burned to provide process heat in some biomass-to-biofuel processes. Lignin, which cannot be hydrolyzed into simple sugars, is suitable for use as a process heat source.

Straight vegetable oil requires no processing for use in properly-equipped vehicle engines.

7.9 Biomass-to-Biofuel Process Overview

Various biomass-to-biofuel processes have been developed or are under development. These processes are summarized in Table 7-2.

Table 7-2. Biomass-to-Biofuel Technologies

Biofuel	Biomass Used	Transformation Process*	Maturity of Technology
BIOCHEMICAL PROCESSES			
Ethanol	corn, sorghum & sugarcane	enzymatic hydrolysis & fermentation	commercial
Ethanol	cellulose & hemicellulose	enzymatic hydrolysis & fermentation	developmental
Butanol	biomass	enzymatic conversion & fermentation	developmental
Biogas	any organics	anaerobic microbial digestion	small-scale commercial
Hydrogen	algae	photosynthesis	developmental
Methane	algae	photosynthesis	developmental
Triglycerides	algae	photosynthesis	developmental
Hydrocarbons	algae	photosynthesis	developmental
Hydrogen	biomass	algae by dark fermentation of biomass	developmental
Triglygerides	biomass	algae by dark fermentation of biomass	developmental
Hydrocarbons	biomass	algae by dark fermentation of biomass	developmental
THERMOCHEMICAL PROCESSES			
Pyrolysis Liquids	any biomass	pyrolysis	early commercial
Syngas	any biomass	gasification	developed, but not fully commercial
CHEMICAL PROCESSES			
Biodiesel	vegetable oils, fats & greases	transesterification	commercial
HYBRID PROCESSES			
Bioethanol	cellulose & hemicellulose	acid hydrolysis & fermentation	developed, but not commercial
Bioethanol	biomass	gasification & Fischer-Tropsch synthesis	commercial

Table 7-2 continued

Biofuel	Biomass Used	Transformation Process*	Maturity of Technology
Biomethanol**	biomass	gasification & Fischer-Tropsch synthesis	commercial
Gasoline	biomass	biomass to dimethyl ether to gasoline	early commercial
Hydrocarbons	triglycerides	decomposition and hydrogenation	developmental
Syngas Liquids (including gasoline, diesel fuel, jet fuel, and fuel oil)	any biomass	gasification & Fischer-Tropsch	developmental
Dimethyl Ether	any biomass	gasification, methanol synthesis, catalytic conversion	developed, but not yet commercial
BIOFUELS REQUIRING NO MOLECULAR RESTRUCTURING			
Straight Vegetable Oil (SVO)	vegetable oil	Pressing oil from biomass and food preparation residues	early commercial
Combustible Biomass	any dried biomass	Cutting, chipping or grinding	developed, but limited

*Many processing variations exist or are envisioned. The processes mentioned are typical rather than specific.

**Methanol is a potential biofuel, but it has some undesirable properties (most notably, toxicity) that will limit its use.

7.10 Looking Ahead

Biofuels will certainly be a part of our future energy supply, mainly for our transportation energy needs. It is not yet clear which of the many processes under development will dominate. Their use will depend partly on their cost relative to other options, including electricity to charge batteries or to produce hydrogen. However, the amount of land required to grow enough terrestrial biomass to produce adequate biofuel for current transportation requirements is far too large to enable it to completely replace oil-based fuels. Algae can also provide suitable biomass for biofuel, but exploiting its high growth rates depends on developing cost-effective processes and facilities. Biofuels will satisfy only part of the U.S. need for transportation unless drastic curtailment of fuel consumption occurs.

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Exercises

7-1. An important study of biofuel energy potential is called the “Billion Ton Study.” (The study and numerous updates and critiques can be found by a web search for “Billion Ton Study”.) Estimate the biofuel energy recoverable from 1 billion tons of biomass if the conversion of biomass energy to biofuel energy is 30 percent. How does this amount of energy compare with current amount of energy used for transportation?

7-2. Biofuel production requires the transport of large quantities of biomass to processing facilities. Consider a plant that produces 100,000 gallons of ethanol per day. If 20 percent of surrounding farmland supplies the biomass, what is the maximum hauling distance? What is the average hauling distance? If the trucks used for hauling use 3,000 BTU per ton mile, how much energy is used for hauling? (Remember the trips by empty trucks to pick up the biomass.) If the biofuel produced is ethanol with energy content of 76,300 BTU per gallon, what fraction of the energy contained in the ethanol product is used for hauling?

7-3. Discuss similarities and differences between starch molecules and cellulose molecules.

7-4. Why is water always involved in the biochemical production of ethanol?

7-5. What are the arguments for and against the production of bioethanol fuel?

7-6. Use the Internet to discover the current status of the search for effective, economical enzymes for producing cellulosic ethanol. Discuss your findings.

7-7. Compare the arguments for and against biobutanol production over bioethanol production.

7-8. Use the Internet to determine current production and trends in bioethanol production. Discuss your findings.

7-9. Discuss the relative merits of terrestrial plants and algae in biofuel production.

7-10. How does the dark process for growing algae manage without sunlight?

7-11. Why are dark process algae growth chambers smaller than photosynthetic algae growth chambers of equal production rates?

7-12. Discuss the role of dimethyl ether in biofuel production.

7-13. Pretend that you are a journalist for a newspaper. Prepare an article on "How Much Oil Will Biofuels Replace in 2050?" You may use facts and your personal opinion, but identify which statements are based on facts and which are based on opinion.