CHAPTER TWO

What Is Bioenergy?

Bioenergy refers to renewable energy produced from biomass, which is organic material such as trees, plants (including crops), and waste materials (e.g., wood waste from mills, municipal wastes, manure, landfill gas (LFG), and methane from wastewater treatment facilities).

- **Biopower** refers to the use of biomass to produce electricity. Biomass can be used alone or cofired with another fuel, typically coal, within the same combustion chamber.
- **Bioheat** refers to the use of biomass to produce heat.
- **Biomass combined heat and power (CHP)** refers to the cogeneration of electric energy for power and thermal energy for industrial, commercial, or domestic heating or cooling purposes through the use of biomass.
- **Biofuels** are fuels (often for transportation) made from biomass or its derivatives after processing. Examples of commercially available biofuels include ethanol, biodiesel, and renewable diesel.
- **Bioproducts** are commercial or industrial products (other than food or feed) that are composed in whole or in significant part of biomass. Examples of bioproducts include soy ink, cellophane, food utensils, and paints made from biomass-based materials.

DOCUMENT MAP

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Bioenergy is becoming an increasingly attractive energy choice because of high or volatile fossil fuel prices, concerns about national energy independence, the impacts of conventional energy use on the environment, and global climate change. More production and use of bioenergy can improve environmental quality (provided best available technologies and pollution controls are used); provide opportunities for economic growth, often in rural areas; support state energy and environmental goals; and increase domestic energy supplies, which will enhance U.S. energy independence and security.

The basic process for using the energy in biomass to produce biopower, bioheat, biofuels, or bioproducts is shown in Figure 2-1.

2.1 WHAT ARE BIOMASS FEEDSTOCKS?

A feedstock is a material used as the basis for manufacture of another product. Biomass feedstocks are sources of organic matter that are used as key inputs in production processes to create bioenergy. Both agricultural/energy crops and waste/opportunity fuels can be used as biomass feedstocks.

AGRICULTURAL/ENERGY CROPS

Several traditional crops that are grown for food and other uses can also be used to produce bioenergy, primarily as biofuels. Crops currently used as biomass feedstocks include:

- **Corn**. Corn is the primary biomass feedstock currently used in the United States to produce ethanol (and co-products, as described in Section 2.2.2).
- **Rapeseed**. Rapeseed is the primary feedstock used in Europe to produce biodiesel (EERE, 2008).
- **Sorghum**. Sorghum is used in the United States as an alternative to corn for ethanol production. As of 2008, 15 percent of U.S. grain sorghum is being used for ethanol production at eight plants (Biomass Research and Development Initiative, 2008).
- **Soybeans**. Soybeans are the primary biomass feedstock currently used in the United States to produce biodiesel from soybean oil.
- **Sugarcane**. Brazil uses sugarcane to produce ethanol and uses the sugarcane residue for process heat.

Other crops that are planted and harvested specifically for use as biomass feedstocks in the production of bioenergy are referred to as “energy crops.” Energy crops are fast-growing and grown for the specific purpose of producing energy (electricity or liquid fuels) from all or part of the resulting plant. The advantages of using crops specifically grown for energy production include consistency in moisture content, heat content, and processing characteristics, which makes them more cost-effective to process efficiently (U.S. EPA, 2007a). Emerging energy crops include:

- **Microalgae**. The oil in microalgae can be converted into jet fuel or diesel fuel (National Renewable Energy Laboratory (NREL), 2006). Microalgae with high lipid content are best suited to production of liquid fuel.

FIGURE 2-1. STAGES OF BIOENERGY PRODUCTION

Source: Biomass Research and Development Board, 2008

Microalgae are highly productive, do not use agricultural land or products, and are carbon-neutral (Mayfield, 2008). More than 50 companies are researching microalgal oil production, including development of new bioreactors and use of biotechnologies to influence microalgal growth (NREL, 2008).

- **Switchgrass; poplar and willow trees**. These energy crops are not yet being grown commercially in the United States for bioenergy, but may have the greatest potential for dedicated bioenergy use over a wide geographic range. The U.S. Department of Energy (U.S. DOE) estimates that about 190 million acres of land in the United States could be used to produce energy crops such as switchgrass and poplar and willow trees (U.S. EPA, 2007a; Antares, 2003). Several states in the Midwest and South could produce significant biopower using switchgrass, which is currently grown on some Conservation Reserve Program[1] acres and on hay acres as a forage crop (U.S. EPA, 2007a; Ugarte et al., 2006).

WASTE/OPPORTUNITY FUELS

Biomass feedstocks from waste materials are often referred to as "opportunity" fuels because they would otherwise go unused or be disposed of; bioenergy production is an opportunity to use these materials productively. Common opportunity fuels include:

- **Biogas**. Biogas, consisting primarily of methane, is released during anaerobic decomposition of organic matter. Facilities that deal with large quantities of organic waste can employ anaerobic digesters and/or gas collection systems to capture biogas, which can be used as a source of on-site bioheat and/or biopower. Major sources of biogas include:

    - ***Wastewater treatment plants (WWTPs)***. Anaerobic digesters can be used during treatment of wastewater to break down effluent and release biogas, which can then be collected for subsequent use as a source of bioenergy. According to an analysis by the U.S. EPA Combined Heat and Power Partnership, as of 2004, 544 municipal WWTPs in the United States use anaerobic digesters. Only 106 of these facilities utilize the biogas produced by their anaerobic digesters to generate electricity and/or thermal energy. If all 544 facilities were to install CHP systems, approximately 340 megawatts (MW) of biogas-fueled electricity could be generated (U.S. EPA, 2007a).

    - ***Animal feeding operations***. EPA's AgSTAR Program has identified dairy operations with more than 500 head and swine operations with more than 2,000 head as the most viable candidates for anaerobic digestion of manure and subsequent methane capture (U.S. EPA, 2007a). As of April 2009, 125 operators in the United States collect and use their biogas. In 113 of these systems, the captured biogas is used to generate electrical power, with many of the farms recovering waste heat from electricity-generating equipment for on-farm use. These systems generate about 244,000 MWh of electricity per year. The remaining 12 systems use the gas in boilers, upgrade the gas for injection into the natural gas pipeline, or simply flare the captured gas for odor control (U.S. EPA, 2009b).

      For more information on how anaerobic digestion is used to produce biogas for bioenergy, refer to Section 2.2.1 — Conversion Technologies for Biopower and Bioheat.

    - ***Landfills***. As the organic waste buried in landfills decomposes, a gas mixture of carbon dioxide (CO_2) and methane (CH_4) is produced. Gas recovery systems can be used to collect landfill emissions, providing usable biogas for electricity generation, CHP, direct use to offset fossil fuels, upgrade to pipeline quality gas, or use in the production of liquid fuels. As of December 2008, EPA's Landfill Methane Outreach Program estimated that, in addition to the approximately 445 landfills already collecting LFG to produce energy, 535 landfills are good candidates for landfill gas-to-energy projects (U.S. EPA, 2008a).

- **Biosolids**. Biosolids are sewage sludge from wastewater treatment plants. Biosolids can be dried, burned, and used in existing boilers as fuel in place of coal, or co-fired with coal to generate steam and power. Biosolids can also be converted into biogas for bioenergy (see Biogas section above). The high water content of most biosolids can present challenges for combustion. As a result, biosolids must generally go through a drying process prior to being used for energy production.

- **Crop residues**. More than 300 million acres are used for agricultural production in the United States. As of 2004, the most frequently planted crops (in terms of average total acres planted) were corn, wheat, soybeans, hay, cotton, sorghum, barley, oats, and rice. Following

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[1] *The Conservation Reserve Program, administered by USDA, provides technical and financial assistance to eligible farmers and ranchers to address soil, water, and related natural resource concerns on their lands in an environmentally beneficial and cost-effective manner. For more information see www.nrcs.usda.gov/programs/CRP/.*

the harvest of many traditional agricultural crops, residues such as crop stalks, leaves, cobs, and straw are left in the field. Some of these residues could be collected and used as bioenergy feedstocks (U.S. EPA, 2007a).

- **Food processing wastes**. Food processing wastes include nut shells, rice hulls, fruit pits, cotton gin trash, meat processing residues, and cheese whey, among others. Because these residues can be difficult to use as a fuel source due to the varying characteristics of different waste streams, the latter two of these food processing wastes are often disposed of as industrial wastewater. Work is under way in the food processing industry to evaluate the bioenergy potential of these residues, including collection and processing methods to allow more effective use as biomass feedstocks. Utilities and universities have used food wastes such as peanut hulls and rice hulls for biopower. Many anaerobic digester operators are currently adding agricultural and food wastes to their digesters to provide enhanced waste management and increased biogas generation (U.S. EPA, 2007a).

- **Forest residues**. Residues from silviculture (wood harvesting) include logging residues such as limbs and tops, excess small pole trees, and dead or dying trees. After trees have been harvested from a forest for timber, forest residues are typically either left in the forest or disposed of via open burning through forest management programs because only timber of a certain quality can be used in lumber mills and other processing facilities. An advantage of using forest residues from silviculture for bioenergy production is that a collection infrastructure is already in place to harvest the wood. Approximately 2.3 tons of forest residues are available for every 1,000 cubic feet of harvested timber (although this number can vary widely); these residues are available primarily in the West (U.S. EPA, 2007a).

- **Forest thinnings**. Forest thinnings can include underbrush, saplings, and dead or dying trees removed from dense forest. Harvesting, collecting, processing, and transporting loose forest thinnings is costly. The use of forest thinnings for power generation or other facilities is concentrated in the western United States; in other areas not already used for silviculture, there is no infrastructure to extract forest thinnings. Typically, the wood from forest thinnings is disposed of through controlled burning due to the expense of transporting it to a power generation facility (U.S. EPA, 2007a).

CELLULOSIC FEEDSTOCKS

Cellulosic feedstocks include opportunity fuels (e.g., wood waste, crop residues) and energy crops (e.g., switchgrass, poplar, and willow trees). In using cellulosic feedstocks, the fiber, or cellulose, is broken down into sugars or other intermediate products that can be converted to bioenergy. Using cellulosic feedstocks such as wood waste and municipal solid waste for ethanol or other biofuel production or bioproducts development could reduce the waste stream in the United States. Ethanol production from cellulosic feedstocks has not yet occurred on a commercial scale but is actively under development (see Section 2.2.2 — Conversion Technologies for Biofuels). For discussions of the benefits and challenges of ethanol production, see Chapter 3, Benefits, Challenges, and Considerations of Bioenergy.

- **Municipal solid waste**. Municipal solid waste (MSW)—trash or garbage—can be collected at landfills, dried, and burned in high-temperature boilers to generate steam and electricity. Mass burn incineration is the typical method used to recover energy from MSW, which is introduced "as is" into the combustion chamber; pollution controls are used to limit emissions into the air. Some waste-to-energy facilities have been in operation in the United States for more than 20 years. More than one-fifth of incinerators use refuse-derived fuel (RDF), which is MSW that has been thoroughly sorted so that only energy-producing components remain (U.S. EPA, 2008b). RDF can be burned in boilers or gasified (U.S. DOE, 2004). (See the related section above on biogas, which describes collection of biogas from landfills for use as bioenergy.) The waste-to-energy industry currently generates 17 billion kilowatt-hours (kWh) of electricity per year. However, based on the total amount of MSW disposed of in the United States annually (250 to 350 million tons), MSW could be used as fuel to generate as much as 70 to 130 billion kWh per year (U.S. EPA, 2008e).

- **Restaurant wastes**. Used vegetable oils, animal fats, and grease from restaurants can be used as biomass feedstocks to produce biodiesel. Small-scale efforts have been successfully implemented in a number of cities, counties, and universities across the country. For example, San Francisco initiated a program to use restaurant wastes to fuel the city's fleet of more than 1,600 diesel vehicles, which were retrofitted to accept the biodiesel (City and County of San Francisco, 2007). The use of restaurant wastes may be less expensive than using new vegetable oil as the feedstock to produce biodiesel if collection costs can be minimized—collection of small volumes from numerous locations can increase costs (Commonwealth of Massachusetts, 2008).

- **Wood waste**. Wood waste includes mill residues from primary timber processing at sawmills, paper manufacturing, and secondary wood products industries such as furniture makers. It also includes construction wood waste, yard waste, urban tree residue, and discarded consumer wood products that would otherwise be sent to landfills (U.S. EPA, 2007a). Wood wastes such as woodchips, shavings, and sawdust can be compressed into pellets, which offer a more compact and uniform source of energy (Biomass Energy Resource Center, 2007).

  - ***Mill residues***. Mill residues include bark, chips, sander dust, edgings, sawdust, slabs, and black liquor (a mixture of solvents and wood byproducts, usually associated with the pulp and paper industry manufacturing process). They come from manufacturing operations such as sawmills and pulp and paper companies that produce lumber, pulp, veneers, and other composite wood fiber materials. Almost 98 percent of mill residues generated in the United States are currently used as fuel or to produce wood pellets or fire logs, or fiber products, such as hardboard, medium-density fiberboard, particle board, and other wood composites (U.S. EPA, 2007a). The U.S. Department of Agriculture (USDA) estimates that 2 to 3 percent of mill residues are available as an additional fuel resource because they are not being used for other purposes. The largest concentrations of mill residues are in the West and Southeast (U.S. EPA, 2007a).

  - ***Construction (and demolition) wood waste***. Wood waste comprises about 26 percent of the total construction and demolition waste stream; about 30 percent of that debris is uncontaminated by chemical treatment and available for recovery (U.S. EPA, 2007a).

  - ***Discarded consumer wood products***. These products include discarded wood furniture, cabinets, pallets, containers, and scrap lumber (U.S. EPA, 2007a).

  - ***Yard trimmings***. Yard trimmings can be generated from residential landscaping and right-of-way trimming near roads, railways, and utility systems such as power lines. Yard trimmings comprise about 14 percent of the MSW stream. Approximately 36 percent of yard trimmings are recoverable, and thus about 5 percent of the total MSW waste stream is yard trimmings that could be useable as a feedstock (U.S. EPA, 2007a).

» **For more information about biomass feedstocks, see EPA's CHP Biomass Catalog of Technologies at *www.epa.gov/chp/basic/catalog.html#biomasscat*.**

WOOD PELLETS

Wood pellets, briquettes, fire logs, and other compressed wood products are made from byproducts of forest products manufacturing, forest management, and recycled urban wood waste. These products are held together by the lignin in the wood when they are condensed through subjection to heat and pressure. Pellets are manufactured in uniform sizes and shapes (usually between 1-1½ inches by approximately 1/4-5/16 inches in diameter) and have a higher energy content by weight (roughly 7,750 Btu per pound at six percent moisture content) than many other biomass feedstocks due to their high density and low-moisture content. These characteristics alleviate many of the potential issues associated with storing biomass residues. Wood pellets are sold in different grades based on the ash produced during combustion relative to the amount of fuel fed into the wood pellet boiler (ranging from 1 to 3 percent). States regulate the disposal and/or subsequent use of the ash.

Source: Biomass Energy Resource Center, 2007

2.2 POTENTIAL FOR INCREASED PRODUCTION AND USE OF BIOMASS FEEDSTOCKS

CURRENT PRODUCTION AND USE

In 2006, renewable energy accounted for 7 percent of the nation's energy supply; of that, biomass was the source of 49 percent of renewable energy consumption (see Figure 1-1). Wood (used as fuel wood), forest residue, and wood waste feedstocks supplied the most bioenergy in 2005 (64 percent), followed by other types of wastes (e.g., MSW, LFG, agricultural residues, biosolids) (18 percent), and corn and soybean oil used to produce biofuels and related coproducts (18 percent) (EIA, 2008a; EIA, 2008b).

FUTURE PRODUCTION AND USE

Significant potential exists to increase the production and use of many different types of biomass feedstocks. In 2005, U.S. DOE and USDA convened an expert panel to assess whether the land resources of the United States could produce a sustainable supply of biomass sufficient to displace 30 percent of the nation's current petroleum consumption (U.S. DOE, 2005). The panel concluded that by the mid-21st century:

- The amount of wood, forest residue, and wood waste feedstocks sustainably produced for bioenergy each year could be increased nearly three times.
- The amount of agricultural feedstocks sustainably harvested while continuing to meet food, feed, and export demands each year could be increased five times.

The panel believes the potential increases in all of these biomass feedstocks can occur with relatively modest changes in agricultural and forestry practices and land use, including technological advances that increase feedstock yields, adoption of certain sustainable crop cultivation practices (e.g., no-till), and land use changes that allow for large-scale production of perennial crops.

For more information on determining the potential for increased use of feedstocks in a particular state, refer to Chapter 4, How Can States Identify Bioenergy Opportunities?

2.3 HOW ARE BIOMASS FEEDSTOCKS CONVERTED INTO BIOENERGY?

The processes, or "conversion technologies," used to convert biomass feedstocks from solids, liquids, or gases into bioenergy are shown in the middle column of Figure 2-2. This figure illustrates how different biomass feedstocks are converted into power, heat, fuels, and products.

All of the technologies shown in Figure 2-2 can and have been used for converting biomass; however, not all are currently deployed on a commercial scale. Table 2-1 indicates the commercialization status of some of the more commonly used conversion technologies for bioenergy production.

The conversion technologies listed in Figure 2-2 and Table 2-1 are described in Section 2.3.1.

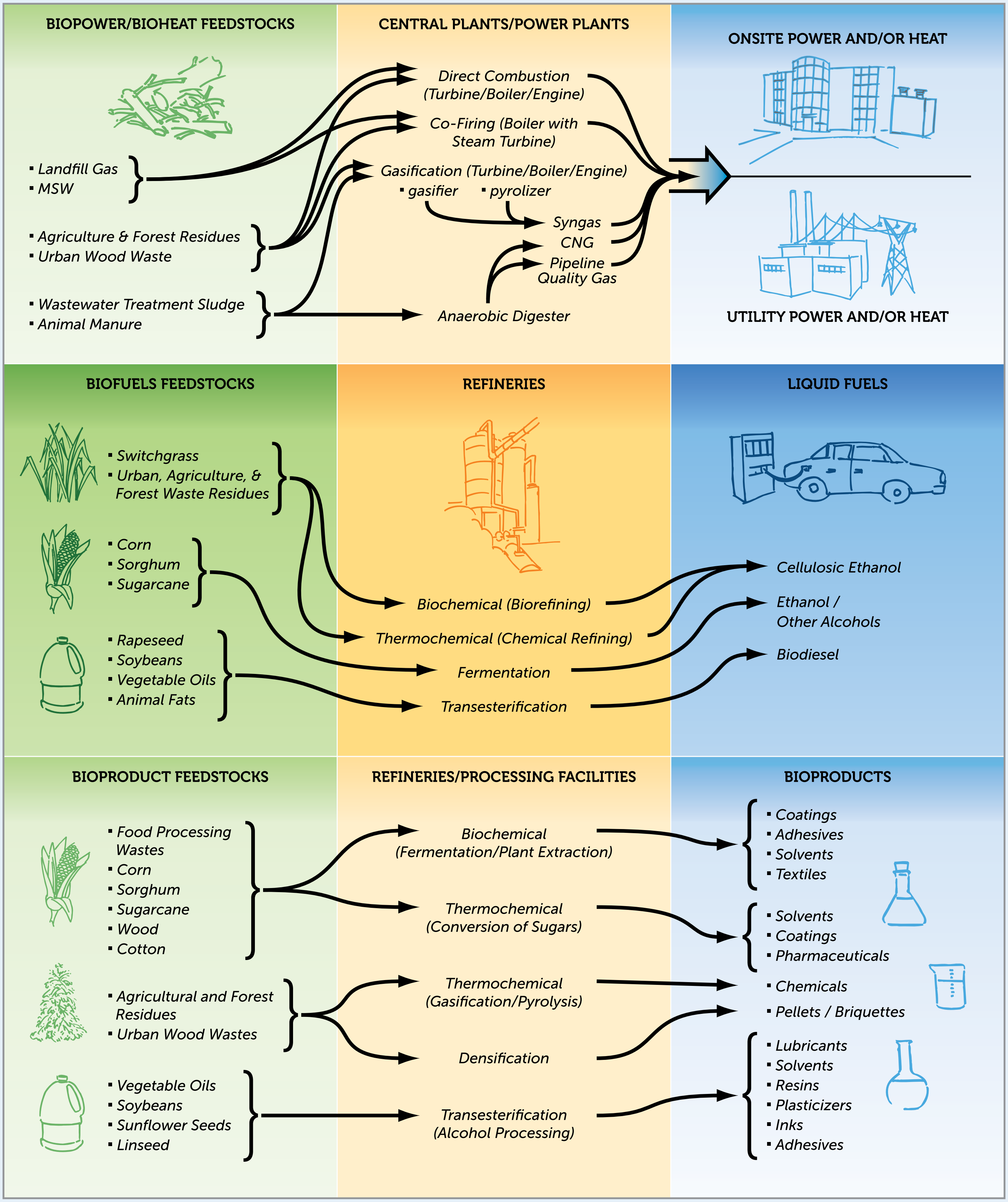
BIOREFINERIES

A biorefinery integrates biomass conversion technologies to produce biopower, biofuels, and/or bioproducts. A biorefinery is similar in concept to a petroleum refinery, producing multiple fuels and products. Biorefineries may play a key role in developing a domestic, bioenergy-based economy. Ideally, a biorefinery would be highly flexible, capable of using a variety of biomass feedstocks and changing its processes as needed, based on product demands. Such flexibility will help make biorefineries economically viable. Successful biorefineries already exist in the forest products and agricultural industries, producing food, feed, fiber, and/or chemicals (including plastics), as well as on-site power generation or CHP for facility operations (U.S. DOE, 2003).

TABLE 2-1. COMMERCIALIZATION STATUS OF COMMON BIOENERGY CONVERSION TECHNOLOGIES

Conversion Technology	Commercialization Status of Technology
Direct combustion	Commercially available
Cofiring	Commercially available
Landfill Gas systems	Commercially available
Anaerobic digestion	Commercially available
Gasification (thermochemical process)	Emerging technology
Pyrolysis (thermochemical process)	Emerging technology
Thermochemical conversion of sugars	Commercially available
Plant extraction (biochemical process)	Emerging technology
Transesterification	Commercially available
Fermentation (biochemical process)	Commercially available for conventional ethanol production and bioproducts Emerging technology for cellulosic ethanol production

FIGURE 2-2. BIOMASS CONVERSION TECHNOLOGIES



2.3.1 CONVERSION TECHNOLOGIES FOR BIOPOWER AND BIOHEAT

The three main types of conversion technologies used for producing electricity and heat are direct combustion, cofiring, and gasification systems. An important smaller scale conversion technology is anaerobic digestion.

Direct Combustion

Solid Fuels to Electricity, Heat, or CHP. In direct combustion systems used to produce **electricity**, a solid biomass feedstock (e.g., agriculture residues, forest residue, municipal solid waste, wood waste) is combusted with excess oxygen (using fans) in a boiler to produce steam that is used to create electricity. Direct combustion, commonly used in existing fossil-fuel power plants, is a dependable and proven technology, and is the conversion technology most often used for bioenergy power plants. However, the typically small size of bioenergy power plants (often due to high costs of transporting feedstocks), coupled with the low efficiency rates associated with the direct combustion process, can result in higher costs to produce electricity than with conventional fossil-fueled power plants (U.S. DOE, 2007). Some new combustion technologies are using compressed hot air (either directly or indirectly through a heat exchanger) to fire a combustion turbine.

In direct combustion systems used to produce **heat**, biomass feedstock loaded into a boiler or furnace can be used to create steam, hot water, or hot air which is then used for thermal applications. Large open buildings can be heated very efficiently with wood-fired furnaces or hydronic heating systems such as radiant floors. Direct combustion technologies for producing heat can utilize modern, computer-controlled systems with automatic fuel feeders, high-efficiency boilers, and add-on controls to reduce particulate matter (PM) and toxics emissions to relatively low levels (provided best available technologies are used). These systems are typically less expensive to operate than systems that use electricity, fuel oil, or propane but more expensive than natural gas systems (U.S. EPA, 2007a). However, all economic comparisons are site-specific.

CHP systems generate electricity and recapture waste heat from the electricity generation process, resulting in higher efficiency of fuel use. The electricity and heat can be used by the entity producing them as on-site power and heat, sold to others (such as an electric utility company), or in some combination of the two approaches. The forest products, chemical, and food-processing industries use on-site CHP systems widely. Increased use of biomass in CHP systems at pulp and paper mills has contributed to bioenergy surpassing hydropower as the leading source of renewable energy in the United States since 1999 (EIA, 2008a). Increasingly, on-site CHP (and to a limited degree, biomass CHP) is also being used at ethanol production facilities due to its increased efficiency and lower fuel costs (U.S. EPA, 2007b).

» **For more detailed information on direct combustion technologies used for combined heat and power from biomass, see EPA's CHP Biomass Catalog of Technologies (U.S. EPA, 2007a) at *www.epa.gov/chp/basic/catalog.html#biomasscat*.**

Gaseous Fuels to Electricity, Heat, or CHP. As solid waste decomposes in a landfill, a gas is created that typically consists of about 50 percent methane and 50 percent CO_2.[2] The gas can either disperse into the air or be extracted using a series of wells and a blower/flare (or vacuum) system. This system directs the collected gas to a central point where it can be processed and treated. The gas can then be used to generate **electricity**, **heat**, or **CHP** via direct combustion; replace fossil fuels in industrial and manufacturing operations; be upgraded to pipeline quality gas, compressed natural gas (CNG) or liquid natural gas (LNG) for vehicle fuel; or be flared for disposal. As of December 2008, approximately 490 LFG energy projects were operational in the United States. These 490 projects generate approximately 11 million megawatt-hours (MWh) of electricity per year and deliver more than 230 million cubic feet per day of LFG to direct-use applications. EPA estimates that approximately 520 additional landfills present attractive opportunities for project development (U.S. EPA, 2007a, U.S. EPA, 2009c).

» **For more information about LFG systems, see information on converting LFG to energy from EPA's Landfill Methane Outreach Partnership at *www.epa.gov/landfill/overview.htm#converting*.**

Cofiring

Solid Fuels to Electricity. Cofiring to produce electricity involves substituting solid fuel biomass (e.g., wood waste) for a portion of the fossil fuel (typically coal) used in the combustion process. In most cases, the existing power plant equipment can be used with only minor modifications, making this the simplest and

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[2] The amount of methane generated by a landfill over its lifetime depends on the composition of the waste, quantity and moisture content of the waste, and design and management practices of the facility.

most economical option for biopower. Pulverized coal boiler systems are the most widely used systems in the United States; cofiring is also used in other types of boilers, including coal-fired cyclones, stokers, and fluidized bed boilers.

To evaluate the efficacy of biomass cofiring, a study by U.S. DOE and the Electric Power Research Institute (EPRI) modeled the performance of a pulverized coal power plant using only coal and the same power plant operating with biomass cofiring. The study identified a 15 percent biomass cofiring rate as realistic given biomass resource limitations and requirements to maintain unit efficiency. Cofiring biomass for up to 15 percent of the fuel was demonstrated during preliminary testing to result in little or no loss in boiler efficiency (EPRI and U.S. DOE, 1997).

» **For more information on cofiring, see EPA's CHP Biomass Catalog of Technologies (U.S. EPA, 2007) at *www.epa.gov/chp/basic/catalog.html#biomasscat*.**

Gasification and Pyrolysis

Solid Fuels to Electricity, Heat, or CHP. Gasification, plasma arc gasification, and pyrolysis are thermal degradation processes that can convert solid biomass feedstocks to a gas.

- **Gasification** is a chemical or heat process that converts a solid fuel to a gas. To create bioenergy, solid biomass feedstocks (e.g., wood waste) are heated above 700 degrees Celsius inside a gasifier with limited oxygen, which converts the feedstock into a flammable, synthesis gas (syngas). Depending on the carbon and hydrogen content of the biomass and the gasifier's properties, the heating value of the syngas can range from about 15 to 40 percent of natural gas. Syngas can be burned in a boiler or engine to produce electricity and/or heat. Syngas can also be converted thermochemically to a liquid fuel (Kent, 2007).

  Gasification has high efficiencies and great potential for small-scale power plant applications. Because the gas can be filtered to remove potential pollutants, the process can produce very low levels of air emissions.

» **For more information on gasification, see EPA's CHP Biomass Catalog of Technologies at *www.epa.gov/chp/basic/catalog.html#biomasscat* or DOE's Biomass primer at *www.eere.energy.gov/de/biomass_power.html.***

- **Plasma Arc Gasification** is a waste treatment technology that uses the high temperatures of an electrical discharge ("arc") to heat a gas, typically oxygen or nitrogen, to temperatures potentially in excess of 3000 degrees Celsius. The gases heated by the plasma arc come into contact with the waste in a device called a plasma converter and vitrify or melt the inorganic fraction of the waste and gasify the organic and hydrocarbon (e.g., plastic, rubber, etc.) fraction. The extreme heat pulls apart the organic molecular structure of the material to produce a simpler gaseous structure, primarily CO, H2, and CO2 (Beck, 2003).

  Plasma arc gasification is intended to be a process for generating electricity, depending upon the composition of input wastes, and for reducing the volumes of waste being sent to landfill sites (R. W. Beck, 2003). Most plasma arc systems are cost effective at only very large scales (1,000,000 tons of feedstock per year or more). A number of companies are working on the development and deployment of this emerging technology.

- **Pyrolysis** also uses high temperatures and pressure in the absence of oxygen to decompose organic components in biomass into gas, liquid (bio-oil), and char products (bio-char) (U.S. DOE, 2003). The process occurs at lower temperatures than combustion or gasification. Controlling the temperature and reaction rate determines product composition (Southern States Energy Board, 2006).
  - Bio-oil is an acidic complex mixture of oxygenated hydrocarbons with high water content. Most data and research come from the pyrolysis of wood, although it is possible to convert any biomass feedstock into bio-oil through pyrolysis. Bio-oil's composition is influenced by several factors: feedstock properties, heat transfer rate, reaction time, temperature history of vapors, efficiency of char removal, condensation equipment, water content, and storage conditions. Bio-oil can be used for producing thermal energy (e.g., for heating buildings, water, and in industrial processes), for power generation using slow-speed diesel engines or combustion turbines, and for cofiring in utility-scale boilers. Bio-oil cannot be used as a transportation fuel without further refining (Easterly, 2002) (see Section 2.2.2 — Thermochemical and Biochemical Conversion, for a discussion of bio-oil and transportation fuels).

    The energy content of bio-oil ranges from 72,000 to 80,000 Btu per gallon whereas conventional heating oil (No. 2) has an energy content of about 138,500 Btu per gallon. Thus, bio-oil contains about 52 to 58 percent as much energy and almost twice as much bio-oil is required to produce the same amount of heat as No. 2 heating oil. In addition, bio-oil weighs about 40 percent more per gallon than heating oil (Easterly, 2002).

- A coproduct of producing bio-oil is char or bio-char (see Section 2.2.3 — Biochemical).

Anaerobic Digestion

Solid Fuels to Gaseous Fuels for Electricity, Heat, or CHP. Anaerobic digestion is the decomposition of biological wastes (i.e., wastewater treatment sludge or animal manure) by microorganisms in the absence of oxygen, which produces biogas. Digestion occurs under certain conditions (psychrophilic, mesophilic, and thermophilic), which differ mainly based on bacterial affinity for specific temperatures. This process produces a gas that consists of 60 to 70 percent methane, 30 to 40 percent CO_2, and trace amounts of other gases (EPA, 2002). The methane can be captured (and sometimes filtered or cleaned) and used to produce **electricity** and/or **heat**, directly used to offset fossil fuels, upgraded to pipeline quality gas, or used in the production of liquid fuels. Anaerobic digestion is commonly used at wastewater treatment facilities and animal feeding operations.

Anaerobic digestion at wastewater treatment facilities is used to process, stabilize, and reduce the volume of biosolids (sludge) and reduce odors. It is often a two-phase process: First, biosolids are heated and mixed in a closed tank for about 15 days as digestion occurs. The biosolids then go to a second tank for settling and storage. Temperature, acidity, and other characteristics must be monitored and controlled. Many wastewater treatment plants that use anaerobic digesters burn the gas for **heat** to maintain digester temperatures and heat building space. The biogas can also be used to produce **electricity** (e.g., in an engine-generator or fuel cell) or flared for disposal.

Anaerobic digesters at animal feeding operations are used to process, stabilize, and reduce the volume of manure, reduce odors and pathogens, separate solids and liquids for application to cropland as fertilizer or irrigation water, and produce biogas. Farm-based anaerobic digesters consist of four basic components: the digester, a gas-handling system, a gas-use device, and a manure storage tank or pond to hold the treated effluent prior to land application. The biogas can be used to generate **heat**, **hot water**, or **electricity**, directly used to offset fossil fuels, upgraded to pipeline quality gas, or used in the production of liquid fuels. The captured biogas is typically used to generate electrical power, with many farms recovering waste heat for on-farm use. These systems generate about 244,000 MWh of electricity per year in the United States. The biogas can also be used in boilers, upgraded for injection into the natural gas pipeline, or flared for odor control.

» **For more information about anaerobic digestion, see EPA's Guide to Anaerobic Digesters at *www.epa.gov/agstar/operational.html*.**

2.3.2 CONVERSION TECHNOLOGIES FOR BIOFUELS

Conversion of biomass into ethanol and biodiesel liquid fuels has been increasing steadily over the past decade. As of November 2008, there are 180 fuel ethanol production facilities in operation or expansion and another 23 under construction (Renewable Fuels Association [RFA], 2008). Total fuel ethanol production in 2008 was 9 billion gallons (RFA, 2009). In addition, as of January 2008, 171 companies have invested in development of biodiesel manufacturing plants and were actively marketing biodiesel. The annual production capacity from these biodiesel plants is 2.24 billion gallons per year (National Biodiesel Board, n.d.). This discussion focuses on ethanol and biodiesel production; however, other biofuels can also be produced, such as methanol, butanol, synfuels, and algal fuel. Additional details about current and developing technologies for converting solid biomass into liquid fuels are available from the Western Governors' 2008 Association Strategic Assessment of Bioenergy Development in the West, *Bioenergy Conversion Technology Characteristics* (Western Governors' Association, 2008).

Both ethanol and biodiesel can be produced using a variety of feedstocks and processes. Their feedstocks

ETHANOL AND BIODIESEL.

Both ethanol and biodiesel are registered as fuel and fuel additives with the U.S. EPA.

As initially required under the Energy Policy Act of 2005 and subsequently revised in the Energy Independence and Security Act (EISA) of 2007, Congress created a Renewable Fuel Standard (RFS) to ensure that transportation fuel sold in the United States contains minimum volumes of renewable fuel, such as ethanol or biodiesel. The current RFS program will increase the volume of renewable fuel required to be blended into gasoline to 36 billion gallons by 2022.

Source: U.S. EPA, 2009

and conversion technologies are shown in Figure 2-2 and described below.

Thermochemical and Biochemical Conversion

Solid Fuels to Cellulosic Ethanol. Ethanol can be made from cellulosic materials such as grasses, wood waste, and crop residues. Cellulosic ethanol is made from plant parts composed of *cellulose*, which makes up much of the cell walls of plants, and *hemicellulose*, also found in plant cell walls. *Lignin,* another plant part that surrounds cellulose, can also be used to make ethanol. Feedstocks that use both cellulose and lignin are sometimes referred to as "lignocellulosic" feedstocks; for simplicity, this section uses the term cellulosic to refer to both cellulosic and lignin-based ethanol production.

Breaking down the cellulose in cellulosic feedstocks to release the sugars for fermentation is more difficult than breaking down starch (e.g., in corn) to release sugars; thus, cellulosic ethanol production is more complex and more expensive than conventional ethanol production. Cellulosic biofuel production uses biochemical or thermochemical processes (NREL, 2007).

ETHANOL

A type of alcohol that is used as an alternative energy transportation fuel, can be made from crops such as corn, sugarcane, sorghum, and switchgrass, as well as opportunity/waste fuels such as agricultural and forest/wood residue.

- *Conventional ethanol* has been made from corn or sugarcane for decades using processes that have evolved over time, but are nonetheless considered "conventional" ethanol production.
- *Cellulosic ethanol* is created from cellulosic feedstocks using processes that have been developed more recently and are not yet commercially deployed. Cellulosic ethanol is considered "advanced" or "second generation," using more complex processes and potentially a wider variety of biomass feedstocks.

- **Biochemical conversion**. Biochemical conversion for ethanol production from cellulosic feedstocks involves:
  - Pretreatment of the feedstock using high-temperature, high-pressure acid; enzymes; or other methods to break down the lignin and hemicellulose that surround the cellulose.
  - Hydrolysis using enzymes and acids to break down the cellulose into sugars.
  - Fermentation to convert the sugars into ethanol (as in conventional production).
  - Distillation to produce purer ethanol (as in conventional production).
- **Thermochemical conversion**. Thermochemical conversion uses heat and chemicals to break down cellulosic feedstock into syngas. Depending upon the process being used, the gas can be converted to liquid fuels such as ethanol, bio-butanol, methanol, mixed alcohols, or bio-oil (through pyrolysis). Thermochemical conversion is particularly useful for lignin, which cannot be easily converted to ethanol using the biochemical process described above; up to one-third of cellulosic feedstock can be composed of lignin. Forest and mill residue feedstocks generally have high lignin contents, and thus would be more suitable for thermochemical ethanol conversion than biochemical conversion.

  The thermochemical conversion process involves:
  - Drying the cellulosic feedstock.
  - Gasification (using heat to convert the feedstock to a syngas) or pyrolysis (using heat and pressure to produce an oil).
  - Contaminant removal.
  - Conversion of the syngas to ethanol, bio-oil, or other products.
  - Distillation to separate ethanol from water (if producing ethanol).

» **A number of researchers and organizations are evaluating process changes and refinements to make cellulosic ethanol production more commercially viable and cost-competitive. For more information, see NREL's *Research Advances: NREL Leads the Way—Cellulosic Ethanol* at *www.nrel.gov/biomass/pdfs/40742.pdf*.**

» **For more information on cellulosic ethanol production, see *www.afdc.energy.gov/afdc/ethanol/production_cellulosic.html*.**

Solid Fuels to Bio-Oil. Bio-oil has limited market presence and does not yet enjoy the popularity of other biofuels such as ethanol and biodiesel. Current research and development in pyrolysis focuses on maximizing liquid (bio-oil) yields because of the ability to transport and store liquid fuels and the ability of bio-oil to be further refined in existing petroleum refineries into transportation fuels. In 2005, successful tests produced syngas through gasification of bio-oil, which can be further processed into syndiesel. Syndiesel can be used in all diesel end-use devices without modification (Dynamotive, 2005). Recent tests also show that it is possible to take bio-oil and refine it into a green diesel product using existing petroleum refineries. This technology pathway effectively takes advantage of the infrastructure associated with the existing petroleum industry (Holmgren et al., 2005). Beyond energy products, bio-oil can be further refined into a range of specialty chemicals, including flavor enhancers, and fuel additives.

Fermentation

Solid Fuels to Conventional Ethanol. In the United States, all commercially established ethanol production to date has been based on the biochemical process of fermentation, which involves conversion of sugars in starchy plants (such as corn or sugarcane) by microorganisms into alcohol. As of November 2008, 171 of the 180 operating ethanol biorefineries in the United States used corn as the primary feedstock (RFA, 2008).

Ethanol from corn is produced in either dry mills or wet mills. In dry mills, corn is ground into flour, water and enzymes are added, the mixture is "cooked," and yeast is added for fermentation. The mixture is then distilled and water is removed to produce ethanol. In wet mills, corn is soaked in hot water to separate starch and protein, the corn is ground and the germ is separated, the remaining slurry is ground, and some of the remaining starch is further processed to produce sugars. The material is then fermented and distilled to produce ethanol.

In recent years, most new ethanol production facilities have been dry mill plants. As of July 2008, approximately 95 percent of United States corn-ethanol facilities were dry mills, accounting for nearly 90 percent of gallons produced. Dry mills typically produce ethanol, animal feed, and sometimes CO_2 (U.S. EPA, 2008d).

For more information on conventional corn-based ethanol production, see *www.afdc.energy.gov/afdc/ethanol/production_starch_sugar.html*.

Transesterification

Oils to Biodiesel. Biodiesel production converts oils or fats into biodiesel, which can be used to fuel diesel vehicles (or stationary engines). In biodiesel production, fats and oils are converted into biodiesel through a process known as "transesterification." The oils and fats are filtered and pretreated to remove water and contaminants (e.g., free fatty acids), then mixed with an alcohol (often methanol) and a catalyst (e.g., sodium hydroxide) to produce compounds known as fatty acid methyl esters and glycerin (U.S. DOE, 2008). The esters are called biodiesel when they are intended for use as fuel. Glycerin is used in pharmaceuticals, cosmetics, and other markets. Often biodiesel and glycerin are produced as coproducts.

BIODIESEL

Biodiesel is usually blended with petroleum diesel to create either B20 (a 20 percent biodiesel blend) or B90 (a 90 percent biodiesel blend), which can be used in diesel engines with little or no modification and provides better engine performance and lubrication than petroleum fuel (U.S. EPA, 2008e).

In the United States, biodiesel is made primarily from soybeans/soy oil or recycled restaurant grease; in Europe, biodiesel is produced primarily from rapeseed (EERE, 2008). About half of current biodiesel production facilities can use any fats or oils as a feedstock, including waste cooking oil; the other production facilities require vegetable oil, often soy oil. Biodiesel production facilities are often located in rural areas, near biodiesel feedstock sources such as farms growing soybeans. Farmers often use biodiesel in their farm equipment.

Increased demand for biodiesel feedstocks from farms, as well as establishment of locally sited and/or owned biodiesel production facilities, can help boost rural economies.

For more information about biodiesel production, see the U.S. DOE Web site at *www.afdc.energy.gov/afdc/fuels/biodiesel_production.html* and the National Biodiesel Board's Web site at *www.biodiesel.org/pdf_files/fuelfactsheets/Production.PDF*.

2.3.3 CONVERSION TECHNOLOGIES FOR BIOPRODUCTS

Biomass feedstocks are made of carbohydrates, and thus contain the same basic elements—carbon and hydrogen—as petroleum and natural gas. Many products, such as adhesives, detergents, and some plastics, can be made from either petroleum or biomass feedstocks. Like biofuels, technologies for converting biomass feedstocks into bioproducts use three main processes: biochemical conversion, thermochemical conversion, or transesterification.

Biochemical conversion for bioproducts includes fermentation and plant extraction. Thermochemical conversion technologies, such as direct combustion, gasification, and pyrolysis, use heat, chemicals, catalysts, and pressure to break down biomass feedstocks. Transesterification uses alcohols to break down vegetable oils for use in bioproducts.

As of 2003, use of biomass feedstocks provided more than $400 billion of bioproducts annually in the United States (U.S. DOE, 2003). Production of chemicals and materials from bio-based products was approximately 12.5 billion pounds, or 5 percent of the current production of target U.S. chemical commodities (U.S. DOE, 2005).

BIOPRODUCTS

Many industrial and consumer products, such as soap, detergent, soy-based ink, solvents, and adhesives, are already produced totally or partially from biomass feedstocks, primarily corn, vegetable oils, and wood.

In addition, many products currently made from petroleum could instead be made, in whole or part, from biomass feedstocks. Also, new bioproducts and technologies are being developed with the potential to increase production and use of bioproducts.

Current Bioproduct Applications	
Acrylic fibers	Pharmaceuticals
Adhesives	Polymers
Cosmetics	Resins
Detergents	Soaps
Lubricants	Solvents
Paints	Textiles

Biochemical

Biochemical conversion for bioproducts includes fermentation and plant extraction.

Sugars and Starches to Bioproducts. Fermentation with microorganisms or enzymes is commonly used to convert starches and the sugar glucose into a variety of organic acids and ethanol that are then used to create bioproducts or intermediate materials used in manufacturing bioproducts. Food processing wastes are used as biomass feedstocks in the fermentation process for bioproducts (A.D. Little, Inc., 2001).

Specifically, fermentation can also be used to convert sugars into:

- Lactic acid derivatives such as acrylic acid, which can be used in coatings and adhesives;
- Ethyl lactate, which can replace many petroleum-based solvents; and
- Polylactide (PLA), a plastic that can be used in packaging and fiber applications, and can be melted and reused or composted when it reaches the end of its useful life.

Ongoing research and pilot-scale applications of bioproducts made from lactic acid derivatives show great promise. Advances in fermentation technology (e.g., new microorganisms and separation techniques) may allow other sugars (e.g., pentose sugars such as xylose) to be converted to bioproducts. These advances would open up use of cellulosic biomass feedstocks (e.g., corn stover, switchgrass, wheat straw) to make bioproducts. Such advances may allow additional bioproducts to be made through fermentation at costs competitive with conventional petroleum-based products (U.S. DOE, 2003).

Plant Components to Bioproducts. Lumber, paper, and cotton fiber are well-known examples of plants used to make bioproducts. Tocopherols and sterols are substances in plants that can be extracted and purified for use in vitamins and cholesterol-lowering products. A plant known as guayule produces nonallergenic rubber latex that can replace other types of rubber to which many people have developed allergies (U.S. DOE, 2003).

Thermochemical

Thermochemical conversion technologies—sugar conversion, gasification, and pyrolysis—use heat, chemicals, catalysts (such as acids, metals, or both), and pressure to break down biomass feedstocks, directly converting sugars into bioproducts or producing intermediate materials that can be converted into final bioproducts through other means.

Sugars to Bioproducts. Thermochemical conversion has been used for more than 50 years to convert the sugar glucose into sorbitol. Sorbitol derivatives—such as propylene glycol, ethylene glycol, and glycerin—are important commercial products used in solvents, coatings, pharmaceuticals, and other applications. Currently, propylene glycol and ethylene glycol are made from petroleum; thermochemical conversion uses biomass feedstocks (rather than petroleum) to produce these sorbitol derivatives.

Thermochemical conversion can also convert sugars other than glucose (e.g., xylose) to sorbitol. Thermochemical conversion is also used to convert sugar to levulinic acid, which is then used to produce a variety of bioproducts, such as methyl tetrahydrofuran (MTHF), used in primaquine, an antimalarial drug, and diphenoloic acid (DPA), used as an alternative to bisphenol A (BPA) in polymers.

New catalysts and thermochemical technologies are creating new opportunities for bioproducts, including use of cellulosic feedstocks to create sorbitol-related and other bioproducts (U.S. DOE, 2003).

Solid Fuels to Syngas. Gasification uses high temperatures and oxygen to convert solid carbonaceous material into syngas, which is a mixture of carbon monoxide (CO), hydrogen, and sometimes CO_2. Syngas can be converted into chemicals such as methanol, which is then converted into other chemicals such as formaldehyde and acetic acid. Syngas can also be converted into chemicals, such as paraffins and fatty acids, by using catalysts (cobalt or iron) and high temperature and pressure (known as the Fischer-Tropsch process) (U.S. DOE, 2003).

Solid Fuels to Bioproducts. Pyrolysis uses high temperatures and pressure in the absence of oxygen to decompose organic components in biomass into liquids, solids, and gases. The liquids, in particular, can contain chemicals that can be used in bioproduct manufacturing, but isolating these chemicals via separation technology can be difficult. The technology closest to commercialization is pyrolysis of cellulosic feedstocks containing high amounts of lignin. This technology can produce a replacement for the toxic chemical phenol in phenol-formaldehyde resins, used in plywood and other wood composites (U.S. DOE, 2003).

Bio-char is another potential product from the pyrolysis process, which has multiple uses. One option is to use the char as a soil amendment on agricultural lands. Bio-char has been shown to improve soil organic matter, reduce fertilizer and water requirements, improve nutrient delivery to the plant (through adsorption), and sequester carbon (Cornell University, 2009).

Densification

Solid Fuels to Pellets or Briquettes. A robust market exists for solid biomass fuels such as pellets or briquettes, which are a bioproduct formed from compressed wood or agricultural residue feedstocks that can be used as fuel for heating (see Section 2.2.1 — Direct Combustion).

Pellets are typically 1/4” or 5/16” diameter and are the most costly compressed biomass form. Bripells are the same shape as pellets but 1-1/2” in diameter. They are so named because they are between briquettes and pellets in size. Briquettes are compressed biomass forms larger than a pellet. Typically, briquettes are square or rectangular and can be the size of typical backyard barbeque fuel up to the size of a building brick (NREL, Unpublished).

Pellets are a refined product and require the most expensive processing. The higher cost of pellets as a fuel for heating is offset by the convenience of being able to use fuel burning equipment that can be automated and needs minimal attention (particularly when compared to bulk biomass systems). This convenience is important because pellets typically compete for market share against almost zero-maintenance natural gas, propane, or electric heat. Briquettes require less energy to produce and are processed through simpler production methods (NREL, Unpublished).

Transesterification

Oils to Bioproducts. Transesterification uses alcohols to break down vegetable oils for use in bioproducts. Vegetable oils are composed primarily of triglycerides, which can be broken down using an alcohol (such as methanol) into glycerin and fatty acids. The fatty acids are then modified into intermediate products used to make bioproducts. Vegetable oils from biomass feedstocks such as soybeans, sunflowers, and linseed are used to manufacture bioproducts such as lubricants, solvents, resins, plasticizers, inks, and adhesives (U.S. DOE, 2003).

» **For more information on conversion technologies used to manufacture bioproducts, see U.S. DOE’s report** *Industrial Bioproducts: Today and Tomorrow* **at** *www.brdisolutions.com/pdfs/BioProductsOpportunitiesReportFinal.pdf*.

2.4 RESOURCES FOR DETAILED INFORMATION

Resource	Description	URL
Bioenergy		
Woody Biomass Utilization, U.S. Forest Service and Bureau of Land Management.	This U.S. Forest Service and Bureau of Land Management Web site provides links to a variety of resources and reports on woody biomass utilization, including tools and references specifically targeted at state governments.	*www.forestsandrangelands.gov/Woody_Biomass/index.shtml*
BioWeb, Sun Grant Initiative.	An online catalog of a broad range of resources on bioenergy, including descriptions of biomass resources, biofuels, and bioproducts; explanations of conversion technologies; and summaries of relevant policies. The resources are searchable by both topic and level of detail of information provided. The catalog is a product of the Sun Grant Initiative, a national network of land-grant universities and federally funded laboratories working together to further establish a bio-based economy.	*http://bioweb.sungrant.org/*
Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply, U.S. DOE, USDA, 2005.	Describes issues associated with reaching the goal of 1 billion tons of annual biomass production (see especially pp. 34–37).	*www.osti.gov/bridge*
Biomass Energy Data Book, U.S. DOE, September 2006.	Provides a compilation of biomass-related statistical data.	*http://cta.ornl.gov/bedb/index.shtml*
Biomass Feedstock Composition and Property Database, U.S. DOE.	Provides results on chemical composition and physical properties from analyses of more than 150 samples of potential bioenergy feedstocks, including corn stover; wheat straw, bagasse, switchgrass, and other grasses; and poplars and other fast-growing trees.	*www1.eere.energy.gov/biomass/feedstock_databases.html*
A Geographic Perspective on the Current Biomass Resource Availability in the United States, Milbrandt, A., 2005.	Describes the availability of the various types of biomass on a county-by-county basis.	*www.nrel.gov/docs/fy06osti/39181.pdf*
Kent and Riegel's Handbook of Industrial Chemistry and Biotechnology, Kent, 2007.	Detailed, comprehensive, fairly technical explanation of the range of biomass conversion technologies.	
Biopower/Bioheat		
Biomass Combined Heat and Power Catalog of Technologies, U.S. EPA, September 2007.	Detailed technology characterization of biomass CHP systems, including technical and economic characterization of biomass resources, biomass preparation, energy conversion technologies, power production systems, and complete integrated systems. Includes extensive discussion of biomass feedstocks.	*www.epa.gov/chp/documents/biomass_chp_catalog.pdf*
Combined Heat and Power Market Potential for Opportunity Fuels, U.S. DOE, Resource Dynamics Corporation, August 2004.	Determines the best "opportunity fuels" for distributed energy sources and CHP applications.	*www.eere.energy.gov/de/pdfs/chp_opportunityfuels.pdf*

2.4 RESOURCES FOR DETAILED INFORMATION *(cont.)*

Resource	Description	URL
Biofuels/Bioproducts		
Bioenergy Conversion Technology Characteristics, Western Governors' Association, September 2008.	Investigates the biofuel conversion technologies that are currently available, as well as technologies currently under development that are developed enough to be potentially available on a commercial basis circa 2015.	*www.westgov.org/wga/initiatives/transfuels/Task%202.pdf*
A National Laboratory Market and Technology Assessment of the 30x30 Scenario, NREL, March 2007.	Draft assessment of the market drivers and technology needs to achieve the goal of supplying 30 percent of 2004 motor gasoline fuel demand with biofuels by 2030.	
From Biomass to BioFuels: NREL Leads the Way, NREL, August 2006.	Provides an overview of the world of biofuels, including the maturity levels of various biofuels, how they are produced, and the U.S. potential for biofuels.	*www.nrel.gov/biomass/pdfs/39436.pdf*
Research Advances Cellulosic Ethanol: NREL Leads the Way, NREL, March 2007.	Highlights some of NREL's most recent advances in cellulosic ethanol production.	*www.nrel.gov/biomass/pdfs/40742.pdf*

2.5 REFERENCES

- **A.D. Little, Inc.**, 2001. *Aggressive Use of Bioderived Products and Materials in the U.S. by 2010.* U.S. DOE. Washington, DC, 2001. *devafdc.nrel.gov/pdfs/6282.pdf*.

- **Antares Group**, Inc., 2003. *Assessment of Power Production at Rural Utilities Using Forest Thinnings and Commercially Available Biomass Power Technologies*. Prepared for the U.S. Department of Agriculture, U.S. DOE, and NREL. As cited in U.S. EPA, 2007.

- **Beck**, 2003, Beck, R. W. *City Of Honolulu Review of Plasma Arc Gasification and Vitrification Technology for Waste Disposal*. Honolulu, 2003. *www.opala.org/pdfs/solid_waste/arc/PlasmaArc.pdf*.

- **Biomass Energy Resource Center**, 2007. *Wood Pellet Heating: A Reference on Wood Pellet Fuels & Technology for Small Commercial & Institutional Systems*. Montpelier, VT, June, 2007. *www.biomasscenter.org/pdfs/DOER_Pellet_Guidebook.pdf*.

- **Biomass Research and Development Board**, 2008. *National Biofuels Action Plan.* Washington, DC, October 2008. *www1.eere.energy.gov/biomass/pdfs/nbap.pdf*.

- **Biomass Research and Development Initiative**, 2008. *Increasing Feedstock Production for Biofuels: Economic Drivers, Environmental Implications, and the Role of Research*. Washington, DC, 2008. *www1.eere.energy.gov/biomass/pdfs/brdi_feedstock_wg2008.pdf*.

- **City and County of San Francisco**, 2007. *Mayor Newsom Launches SFGreasecycle - The Nation's First Citywide Program That Collects Waste Grease to Create Biofuel for Municipal Fleet.* San Francisco, CA, November, 20, 2007. *www.sfgov.org/site/mayor_index.asp?id=71394*.

- **Commonwealth of Massachusetts**, 2008. *Advanced Biofuels Task Force Report*. Boston, 2008. *www.mass.gov/Eoeea/docs/eea/biofuels/biofuels_complete.pdf*.

- **Cornell University**, 2009. *Biochar Soil Management*. Ithaca, NY. *www.css.cornell.edu/faculty/lehmann/research/biochar/biocharmain.html*.

- **Dynamotive**, 2005. *Successful Conversion of Dynamotive's Bio Oil to Synthetic Gas Demonstrates Potential for Production of Synthetic Diesel and other Advanced Fuels*. Press Release, September 22, 2005. *www.thefreelibrary.com/Successful+Conversion+of+DynaMotive's+BioOil+to+Synthetic+Gas...-a0136505108*.

- **Easterly**, 2002. Easterly, J. *Assessment of Bio-Oil as a Replacement for Heating Oil. Northeast Regional Biomass Program*. Washington, DC, November, 2002. *www.mtholyoke.edu/courses/tmillett/course/geog_304B/pub34.pdf*.

- **EERE (Office of Energy Efficiency and Renewable Energy)**, 2008. *Biofuels.* U.S. DOE, Washington, DC, 2008. *www1.eere.energy.gov/biomass/*.

- **EIA (Energy Information Administration)**, 2008a. *Renewable Energy Trends in Consumption and Electricity 2006*. EIA, Washington, DC, July, 2008. *www.eia.doe.gov/cneaf/solar.renewables/page/trends/table1_5b.xls*.

- **EIA**, 2008b. *Table 6. Biomass Energy Consumption by Energy Source and Energy Use Sector 2001–2005*. Washington, DC, April 2008. *www.eia.doe.gov/cneaf/solar.renewables/page/rea_data/table6.html*.

- **EPRI (Electric Power Research Institute) and U.S. DOE**, 1997. *Renewable Energy Technology Characterizations*. EPRI TR-109496. Washington, DC, 1997. *www1.eere.energy.gov/ba/pba/tech_characterizations.html*.

- **Holmgren**, 2005. Holmgren, J., R. Marinangeli, T. Markera, M. McCall, J. Petri, S. Czernik, D. Elliott, D. Shonnard. *Opportunities for Biorenewables in Petroleum Refineries*. UOP, December 2005. *www.pyne.co.uk/Resources/user/PYNE%20Newsletters/001338_Pyne%20p4-7.pdf*.

- **Kent**, 2007. Kent, James A., ed. *Kent and Riegel's Handbook of Industrial Chemistry and Biotechnology*. 11th ed., pp. 1499–1548. New York: Springer, 2007.

- **Mayfield**, 2008. *Algal Model Systems*. The Scripps Research Institute. Presented at the National Renewable Energy Laboratory—Air Force Office of Scientific Research Workshop on Algal Oil for Jet Fuel Production. NREL, Golden, CO, February 2008. *www.nrel.gov/biomass/algal_oil_workshop.html*.

- **Milbrandt**, A., 2005. *Geographic Perspective on the Current Biomass Resource Availability in the United States*. NREL/TP-560-39181. NREL, Golden, CO, December 2005. *www.nrel.gov/docs/fy06osti/39181.pdf*.

- **National Biodiesel Board, n.d. Biodiesel Production**. National Biodiesel Board, Washington, DC, n.d. *www.biodiesel.org/pdf_files/fuelfactsheets/Production.pdf*.

- **NREL (National Renewable Energy Laboratory)**, 2006. *From Biomass to Biofuels: NREL Leads the Way*. August 2006. NREL/BR-510-39436. NREL, Golden, CO, August 2006. *www.nrel.gov/biomass/pdfs/39436.pdf*.

- **NREL**, 2007. *Research Advances—Cellulosic Ethanol: NREL Leads the Way*. NREL/BR-510-40742. NREL, Golden, CO, March 2007. *www.nrel.gov/biomass/pdfs/40742.pdf*.

- **NREL**, 2008. *Research Review 2007*. NREL/MP-840-42386. NREL, Golden, CO, August 2008. *www.nrel.gov/research_review/pdfs/2007/42386.pdf*.

- **NREL**, Unpublished. *Assessment of Biomass Pelletization Options for Greensburg, Kansas*. Draft Technical Report. NREL, Golden, CO.

- **RFA (Renewable Fuels Association)**, 2008. *Ethanol Biorefinery Locations*. Renewable Fuels Association, Washington, DC, 2008. *www.ethanolrfa.org/industry/locations*.

- **RFA**, 2009. Historic *U.S. Fuel Ethanol Production*. Renewable Fuels Association, Washington, DC, 2009. *www.ethanolrfa.org/industry/statistics/#A*.

- **Southern States Energy Board**, 2006. *American Energy Security: Building a Bridge to Energy Independence and to a Sustainable Energy Future*. Southern States Energy Board. Norcross, Georgia, 2006. *americanenergysecurity.org/wordpress/wp-content/uploads/2009/02/aes-report.pdf*.

- **Ugarte et al.**, 2006. Ugarte, D., B. English, K. Jensen, C. Hellwinckel, J. Menard, B. Wilson, 2006. *Economic and Agricultural Impacts of Ethanol and Biodiesel Expansion*. The University of Tennessee, Knoxville, TN, 2006. *beag.ag.utk.edu/pp/Ethanolagimpacts.pdf*.

- **U.S. DOE (Department of Energy)**, 2003. *Industrial Bioproducts: Today and Tomorrow*. U.S. DOE, Washington, DC, July 2003.

- **U.S. DOE**, 2004. *Combined Heat and Power Market Potential for Opportunity Fuels*. Resource Dynamics Corporation, Washington, DC, August 2004.

- **U.S. DOE**, 2005. *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply.* U.S. DOE, Washington, DC, April 2005. DOE/DO-102995-2135. *feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf*.

- **U.S. DOE**, 2007. *ABCs of Biopower*. U.S. DOE, Washington, DC, March 15, 2007. *www1.eere.energy.gov/biomass/abcs_biopower.html*.
- **U.S. DOE**, 2008. *Biodiesel Production*. U.S. DOE, Washington, DC, 2008. *www.afdc.energy.gov/afdc/fuels/biodiesel_production.html*.
- **U.S. DOE, n.d.** *The U.S. Dry-Mill Ethanol Industry*. U.S. DOE, Washington, DC, n.d. *www.brdisolutions.com/pdfs/drymill_ethanol_industry.pdf*.
- **U.S. EPA (Environmental Protection Agency)**, 2002. *Managing Manure With Biogas Recovery Systems: Improved Performance at Competitive Costs*. U.S. EPA, Washington, DC, 2002. *www.epa.gov/agstar/pdf/manage.pdf*.
- **U.S. EPA**, 2007a. *Biomass Combined Heat and Power Catalog of Technologies*. U.S. EPA, Washington, DC, 2007. *www.epa.gov/chp/documents/biomass_chp_catalog.pdf*.
- **U.S. EPA**, 2007b. *Utility-Ethanol Partnerships: Emerging trend in district energy/CHP*. U.S. EPA, Washington, DC, 2007. *www.epa.gov/chp/documents/district_energy_article.pdf*.
- **U.S. EPA**, 2008a. *Landfill Methane Outreach Program (LMOP)*. U.S. EPA, Washington, DC, 2008. *www.epa.gov/lmop/overview.htm*.
- **U.S. EPA**, 2008b. *Combustion*. U.S. EPA, Washington, DC, July 2008. *www.epa.gov/osw/nonhaz/municipal/combustion.htm*.
- **U.S. EPA**, 2008c. *Municipal Solid Waste (MSW) in the United States*. U.S. EPA, Washington, DC, 2008. *www.epa.gov/epawaste/nonhaz/municipal/msw99.htm*.
- **U.S. EPA**, 2008d, *Ethanol Production Facilities Database. Combined Heat and Power Partnership*. U.S. EPA, Washington, DC, July 2008.
- **U.S. EPA**, 2008e. *Biodiesel*. U.S. EPA, Washington, DC, 2008. *www.epa.gov/smartway/growandgo/documents/factsheet-biodiesel.htm*.
- **U.S. EPA**, 2009a. *Renewable Fuel Standard Program*. U.S. EPA, Washington, DC, March 12, 2009. *www.epa.gov/OMS/renewablefuels/*
- **U.S. EPA**, 2009b. *Guide to Anaerobic Digesters*. U.S. EPA, Washington, DC, 2009. *www.epa.gov/agstar/operational.html*.
- **U.S. EPA**, 2009c. *Energy Projects and Candidate Landfills*. U.S. EPA, Washington, DC, 2009. *www.epa.gov/lmop/proj/index.htm*.
- **Western Governors' Association**, 2008. *Strategic Assessment of Bioenergy Development in the West, Bioenergy Conversion Technology Characteristics*. Antares Group, Inc. 2008. *www.westgov.org/wga/initiatives/transfuels/Task%202.pdf*.