Bioenergy Products and Processes of Particular Interest in the Mid-south Region

Prepared by **BioEnergy Systems LLC**
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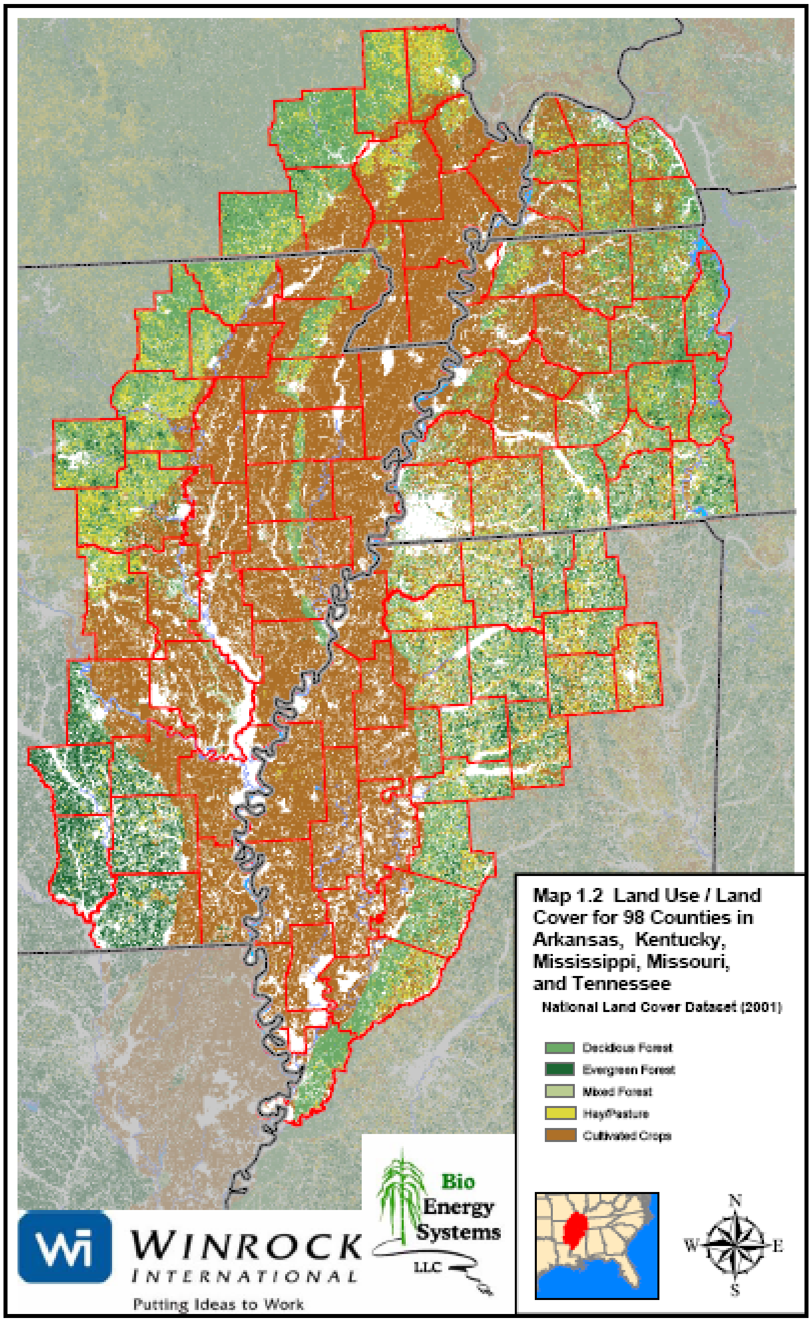
Map 1.2 Land Use / Land Cover for 98 Counties in Arkansas, Kentucky, Mississippi, Missouri, and Tennessee

National Land Cover Dataset (2001)

Executive Summary

Any overview of bioenergy products and markets should focus on the three primary components of a bioenergy enterprise: products, feedstocks, and conversion technologies. Many combinations of these components are possible, but not necessarily feasible. The right combination of feedstock(s), conversion process(s), and products, as well attention to logistical and pre-processing considerations, can result in a technically viable and profitable bioenergy enterprise.

The 5-state, 98-county study region is rich in biomass feedstocks. While this report focuses on bioenergy products and processes (and pre-conversion considerations), feedstocks are covered extensively in the 2009 *Assessment of Agricultural and Forest Biomass Resources in the Mid Portion of the Mississippi River Alluvial Valley*.

Conversion technologies are classified as thermochemical or biochemical processes. Thermochemical processes take place at higher temperatures and are typically able to utilize higher fractions of the feedstock, particularly cellulosic feedstocks whose lignin can only be broken down thermochemically. Biochemical processes are anaerobic and can, generally speaking, utilize higher-moisture or liquid feedstocks (e.g., animal manure and food wastes).

Pre-processing considerations—e.g., transportation, sizing, and drying—are often underestimated and misunderstood aspects of a bioenergy enterprise. These items can constitute significant cost; this is especially true of drying. In addition to evaluating the costs of feedstocks delivered to the processing facility, an economic analysis of any bioenergy enterprise should also consider pre-processing activities in order to determine the full cost of material ready for conversion into bioenergy products.

More specifically, this overview discusses the following bioenergy products, processes, and pre-conversion considerations:

Bioenergy Products

- Electricity
- Thermal energy
- Solid fuels
- Gaseous fuels
- Liquid fuels

Thermochemical Processes

- Combustion
- Gasification
- Pyrolysis
- Fischer-Tropsch
- Torrefaction
- Gasification + Fermentation

Biochemical Processes

- Fermentation
- Transesterification
- Anaerobic digestion

Pre-Processing Considerations

- Transportation
- Sizing
- Drying

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Foreword

This report was prepared by BioEnergy Systems LLC under subcontract to Winrock International Institute for Agricultural Development, with funding support from the Arkansas Energy Office, in coordination with a regional study of bioenergy and bioproduct opportunities initiated by Memphis-based BioDimensions. The report was authored by Jim Wimberly, president of BioEnergy Systems LLC, with assistance from Nicole Lynch with imanage LLC. The objective of this report is to provide the reader with an overview of bioenergy products and processes. However, the author wishes to stress the overview nature of the information presented in this report; there are many informational resources (including entire books) available on each topic and sub-topic discussed, and readers are encouraged to refer to the links provided in this report's end notes as starting points for obtaining additional information about the various topics discussed.

A. Introduction

A variety of energy products can be made from a variety of biomass feedstocks using a variety of conversion processes.[1] According to the U.S. Department of Energy (DOE):[2]

> *"Bioenergy technologies use renewable biomass resources to produce an array of energy related products including electricity, liquid, solid, and gaseous fuels, heat, chemicals, and other materials. Bioenergy ranks second (to hydropower) in renewable U.S. primary energy production and accounts for three percent of the primary energy production in the United States.*
>
> *"The term 'biomass' means any plant derived organic matter available on a renewable basis, including dedicated energy crops and trees, agricultural food and feed crops, agricultural crop wastes and residues, wood wastes and residues, aquatic plants, animal wastes, municipal wastes, and other waste materials."*

The term "biofuel" is typically used by DOE and others to refer to refined liquid fuels made from biomass resources (e.g., ethanol, biodiesel, renewable gasoline, etc), although other feedstocks (e.g., sawdust) used for other bioenergy products (e.g., electricity) could also be considered "biofuels." In recent years, DOE support for bioenergy has focused heavily on liquid biofuels,[3] although the scope of support for other bioenergy products (and non-energy biobased products) appears to be expanding somewhat under the Obama administration.

The term "biopower" is generally used by DOE and others to refer to electricity generated from biomass resources (the term "bioelectricity" is also encountered, but less frequently).[4] "Cogeneration" refers to simultaneous production of thermal and electrical energy from biomass; numerous cogeneration systems exist within the study area, primarily at larger forest products manufacturing facilities that use woody residues generated on-site or nearby.

This report provides an overview of bioenergy products and, to a limited extent, potential markets for these products in the 5-state study region. This report also discusses processing technologies used to convert biomass feedstocks into these products, as well as pre-processing considerations that can affect the technical viability and/or economic feasibility of a bioenergy enterprise.

Matching the proper technology(s) to the proper feedstock(s) to make the target product(s)—based on existing or anticipated demand for the target bioenergy product(s)—and utilizing effective pre-processing techniques and logistical management practices, are key to developing a bioenergy enterprise and deploying a regional bioenergy industry which can compete with conventional energy sources.

B. Electricity

1. Strategies for converting biomass into electricity

There are three basic strategies for producing electricity from biomass resources:

- Dedicated ("stand-alone") power generation – in which the powerplant is a separate facility dedicated to electricity generation (often owned by a third party, selling the power at wholesale rates to a utility under a long-term contract).
- Cogeneration (sometimes referred to as combined heat and power, or CHP) – in which the facility generates both heat (thermal energy) and electricity; such systems are often used at forest products and agricultural processing facilities, where biomass residues are generated on-site and used as fuel for on-site thermal and electrical needs. Additional information regarding cogeneration is available from the International Energy Agency at: www.iea.org/Textbase/techno/essentials3.pdf
- Co-firing – in which a coal-fired powerplant substitutes a fraction of the coal fuel with biomass (typically in the 5% - 20% range, on an energy basis). According to the National Renewable Energy Laboratory, co-firing at 15% reduces greenhouse gas emissions by 18%.[5]

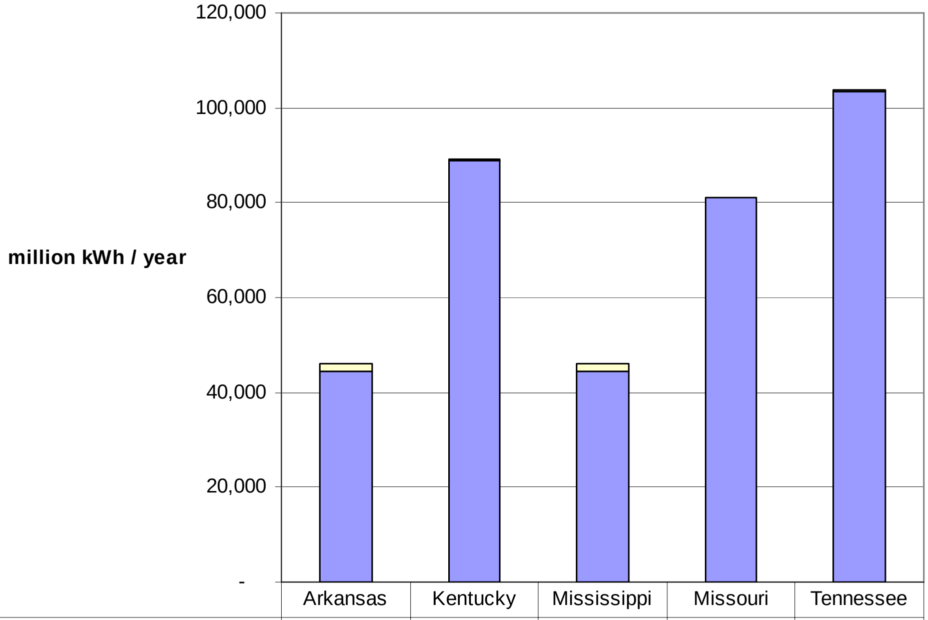
2. Demand for electricity

Demand for electricity in the United States continues to increase, although the rate of increase has slowed in recent years.[6] Public policy is moving towards increasing portions of power generation from renewables – refer to Figure 1. According to the Database of State Incentives for Renewables & Efficiency,[7] 28 states (one of which is Missouri) have some type of Renewable Portfolio Standard (RPS) as of May 2009.[8] At the federal level, HR 2454 (the American Clean Energy and Security Act, also known as the Waxman-Markey bill) calls for a national RPS, increasing from 6% in 2012 to 20% in 2020 (although up to 40% of the requirement may be met through energy efficiency).[9]

Figure 1. Grid-connected electricity generation from renewable energy sources, 1990-2030 (billion kilowatt-hours).
Source: U.S. Energy Information Administration

3. Power generation and market potential

Total power generation in the 5-state study region was approximately 360,000 million kilowatt-hours (kWh) in 2006 – refer to Figures 2 and 3.[10] Of this amount, 4,100 million kWh (i.e., 1.1% of the total) was generated from biomass resources; production from biomass by state ranged from 3.7% (Arkansas) to 0.01% (Missouri).[11] In 2007, the average capacity of coal-fired powerplants in the United States was 229 megawatts (MW), whereas the average capacity of biomass-fired powerplants was 7.5 MW.[12]



	Arkansas	Kentucky	Mississippi	Missouri	Tennessee
□ electricity generation from biomass in 2006	1,715	433	1,541	9	429
■ electricity generation from other non-hydro renewables in 2006	-	-	-	-	22
🟦 electricity generation from other sources	44,450	88,918	44,360	80,931	103,454

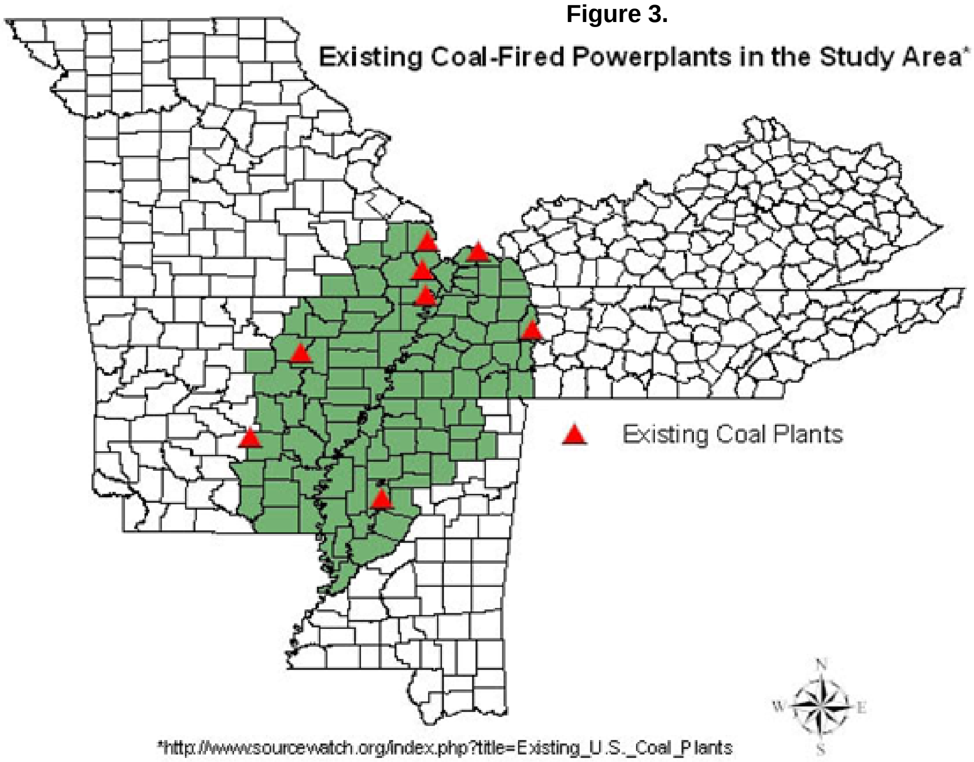
Figure 2. Power generation in the study region (2006).
Source: derived from U.S. Energy Information Administration data.

Generating 12% of the power in the 5-state region from renewable resources would mean production of 44,000 million kWh per year. If, say, 80% of that amount is to be met using biomass resources, then total potential production from biomass would be 35,200 million kWh/year, or 850 times the region's 2006 biomass-to-electricity production levels.

If, say, 80% of the electrical generation from biomass is produced using dedicated cellulosic energy crops, then the total required quantity of feedstock would be 18,200,000 tons per year.[13] If the average agronomic yield for the cellulosic biomass is 15 tons per acre per year, then total production land area required to meet this electricity production level would be 1,200,000 acres.

If the biomass feedstock could be produced and sold for $40 per ton (farmgate price), then total farmgate revenues for the 5-state region from production of dedicated feedstocks for power production would be $730,000,000/year, with resulting total net revenues of $109,000,000 per year, assuming a 15% margin.

Figure 3.



Existing Coal-Fired Powerplants in the Study Area*

*http://www.sourcewatch.org/index.php?title=Existing_U.S._Coal_Plants

4. Biomass to electricity conversion technologies

Most electricity produced from biomass is generated using a basic steam cycle in which a solid biomass fuel is combusted–refer to Figure 4. Combustion of the biomass in the boiler releases heat which is used to make steam. The steam is used to drive a steam turbine, which in turn drives a generator to produce electricity. Such steam-based systems are well established and are widely used.[14]

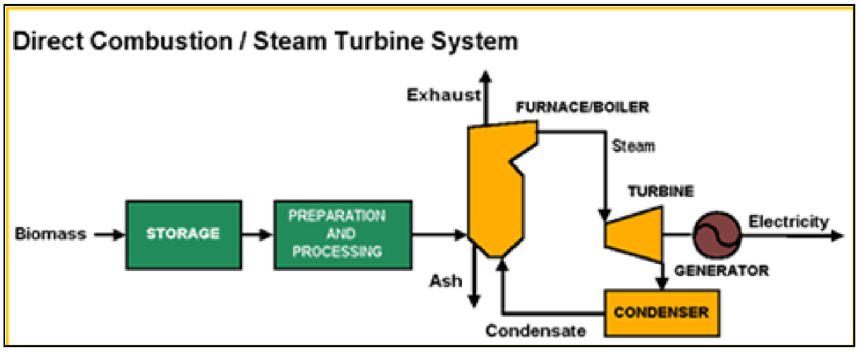


Figure 4: In a direct combustion system, processed biomass is the boiler fuel that produces steam to operate a steam turbine and generator to make electricity.

source: U.S. Department of Energy

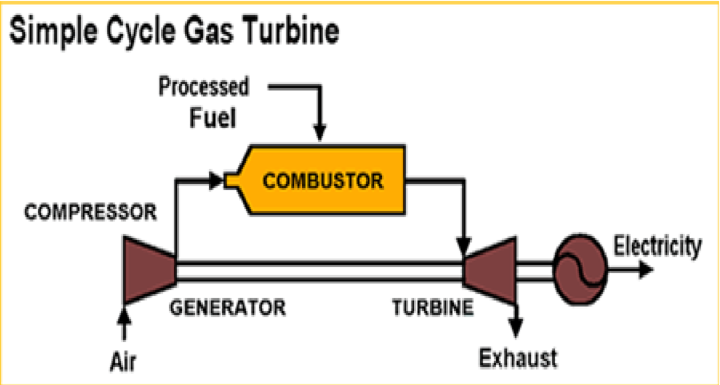


Figure 5: In a simple-cycle gas turbine, both pressurized fuel gas and hot combustion product gases operate a gas turbine and generator, producing electricity .
source: U.S. Department of Energy

Combustion turbines can also be used, although such systems are more complex and have not yet been widely commercialized. Such systems require the solid biomass to be converted first into a gaseous or liquid fuel, which is subsequently used as fuel for the combustion turbine. Refer to Figure 5. A combustion turbine can be combined with a steam turbine, known as a combined-cycle system. The hot exhaust gases from the gas turbine are used to make steam, which is then used to drive a steam turbine. Refer to Figure 6. A combined cycle system has higher system efficiency than a single cycle system, i.e., more kilowatt-hours generated per ton of feedstock used. However, disadvantages (relative to traditional single cycle powerplants) include higher capital and operating costs; in addition, the technology risks associated with these pre-commercial technologies increase project financing challenges.

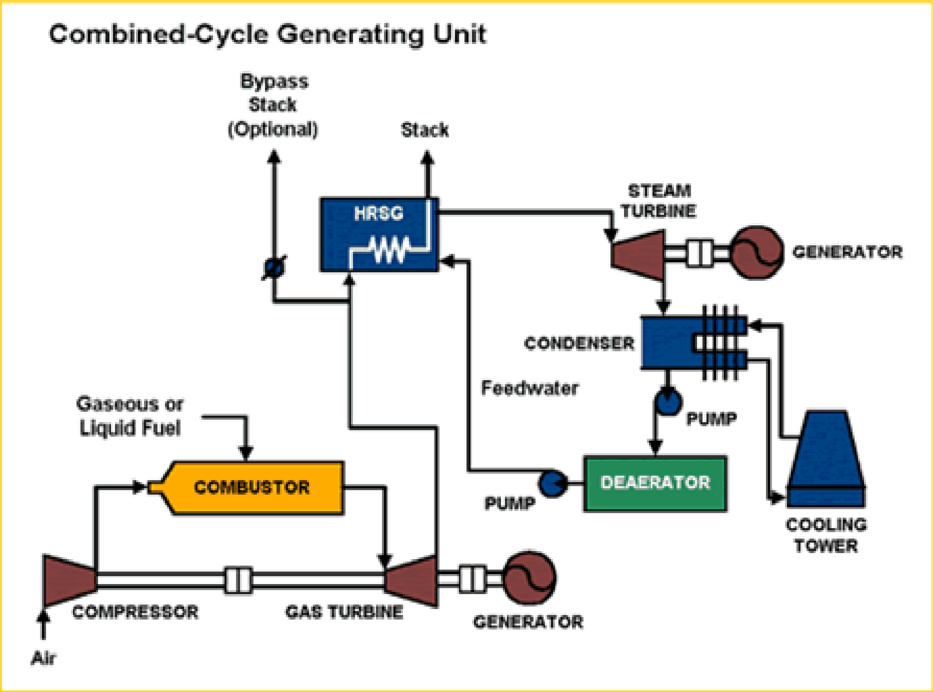


Figure 6: In a combined-cycle generating system, hot turbine exhaust gases are used to produce steam to run a steam turbine and generator.
source: U.S. Department of Energy

In some instances, gasified biomass can be used as a fuel for an internal combustion engine used to drive a generator for power production. Such systems are commonly used in small-scale installations using biogas from anaerobic digesters to generate power.

An overview of biomass-to-electricity conversion technologies is available from DOE at www.eere.energy.gov/de/biomass_power.html.

5. Closed loop v. Open-loop

The term "closed-loop" or "carbon-neutral" refers to production of power from dedicated energy crops, in which all of the carbon emitted during electricity production is offset through utilization of atmospheric carbon for subsequent plant growth via photosynthesis. Closed-loop power generation is eligible for a 2.1¢ per kilowatt-hour federal tax credit.[15]

Open-loop refers to production of power from biomass residues. Such systems are considered to have less greenhouse gas benefits because the biomass was not produced specifically and exclusively for power generation. Open-loop power generation is eligible for a reduced federal tax credit of 1.1¢ per kilowatt-hour.[16]

For new installations the American Recovery and Reinvestment Act of 2009 provides taxpayers eligible for the federal renewable electricity production tax credit (PTC) with an option to take a federal business energy investment tax credit (ITC), or to receive a grant from the U.S. Treasury Department instead of taking the PTC.[17]

The potential tax benefits from closed-loop biopower production in the Delta region are substantial. A 100 megawatt powerplant utilizing 100% dedicated energy crops (i.e., closed-loop biomass) as fuel could earn over $150,000,000 in production tax credits over the 10-year eligibility period.[18]

C. Thermal energy

Direct combustion of solid biomass fuel is the traditional method used to produce thermal energy, although both gasified and liquefied biomass can be burned to produce heat. There are two primary markets for thermal energy: process heat and space heating.

1. Process heat

Process heat is required for almost all manufacturing processes, ranging from agricultural crop drying to paper production to food processing. Due to its widespread availability and convenience (and historically low cost), natural gas is the most commonly used fuel for process heat.[19] Biomass can be used to supplement or displace natural gas at many facilities, although additional materials handling, storage, and combustion equipment will be required to accommodate the biomass fuel.

Process heat from biomass is usually via hot air or, more commonly, via hot water or steam (i.e., the combustion furnace will be coupled to an air-to-air or air-to-water heat exchanger). Although lists of thermal energy users could not be located for the study region, lists of manufacturing facilities are maintained by most of the states.[20]

2. Space heating

Natural gas is also the most commonly used fuel for space heating in the mid-south region, for both residential and commercial applications.[21] Again, biomass could be used to supplement or displace natural gas in many situations. Of particular interest, wood pellets can be used—in pellet-fired stoves and furnaces—for residential/commercial space heating.

Due to price volatility of natural gas and other heating fuels (e.g., propane and fuel oil) during the past five years, demand in North America and Europe for pellet fuels has grown significantly (refer to the discussion of pellet fuels in §D.2). For more information regarding wood pellets and pellet-fired heating systems refer to the Pellet Fuels Institute, the industry’s trade association.[22]

Numerous factors affect the quantity of fuel consumed for heating a residence or light-commercial facility, including the efficiency of the heating unit. For natural gas-fired residential heating systems, efficiency is measured in Annual Fuel Utilization Efficiency, or AFUE.[23] The AFUE for natural gas-fired residential furnaces is typically in the range of 78%-84% whereas the estimated fuel efficiency of pellet-fired residential furnaces is typically in the range of 80%-85%.[24]

The potential demand for space heating using wood pellets can be illustrated as follows:

- **Residential**: there are 8,480,000 households in the 5-state region (AR, KY, MS, MO, and TN);[25] assuming that demand for pellet fuel increases to 5% of the region’s households and assuming an average consumption rate of 1.75 tons per household per year, the total consumption of wood pellets would be about 740,000 tons/year.
- **Poultry houses**: During the ’06-’07 and ’07-’08 heating seasons, interest in pellet-fired furnaces for heating poultry houses increased substantially. There are approximately 25,700 poultry houses in the 5-state region.[26] The average poultry house consumes 3,000-6,000 gallons/house/year of propane;[27] pellet-fired furnaces can be used to offset most of this fossil fuel (approximately 85%).[28] Assuming that demand for pellet fuel increases to 25% of the region’s poultry houses and assuming an average consumption rate of 42 tons per poultry house per year, the total consumption of wood pellets would be about 229,000 tons/year.

D. Solid fuels

Solid fuels are typically combusted for thermal energy production and/or electricity generation (usually via a single-cycle system using a boiler followed by a steam turbine—refer to Figure 5). Examples of solid biomass fueled systems used in the mid-south region include:

- Using densified fuels for spacing heating in poultry houses (thereby displacing propane) – refer to §C.2.
- Using wood pellets for residential space heating (thereby displacing natural gas, propane, fuel oil, or electricity) – refer to section §C.2.
- Using loose woody residues to generate both electricity and process heat (i.e., cogeneration) at a paper mill, thereby displacing power from the grid and natural gas for process heat.
- Using rice hulls to generate electricity and/or process heat for agricultural crop processing, using biomass gasifiers.

A wide variety of solid biomass feedstocks are available, reflecting a wide variety of physical and chemical properties. Solid biomass fuels are available in two primary physical forms: unprocessed (or “loose” or “raw”) form, and densified biomass.

1. Non-densified or loose biomass

“Loose” biomass is the most commonly used form of solid biomass fuel and is typically combusted to produce thermal energy (or, indirectly, electricity, via a steam cycle). Examples of loose biomass include forest residues (e.g., harvesting slash), woody processing residues (e.g., sawdust), agricultural field residues (e.g., corn stover), agricultural processing residues (e.g., rice hulls), dewatered algae biomass, and harvested energy crops.

2. Densified biomass

Compared to loose biomass, the advantages of densified biomass include uniformity, easier handling and storage (lower bridging potential), lower transport costs (due to increased energy density and materials handling), and more effective combustion (due to fuel homogeneity and more accurate in-feed capabilities). The only real disadvantage is cost—the cost of densification, a process which typically requires additional feedstock drying and grinding, in addition to the densification process itself—ranges from $35-$90 per ton (excluding feedstock costs), depending on the physical characteristics of the feedstock (and the extent of variation in the said characteristics).

There are two primary forms of densified solid biomass: pellets and briquettes. For both pelletizing and briquetting equipment the feedstock must first be dried to 10 to 12% moisture content,[29] and particle size reduced to accommodate the specific equipment and target product.[30] There are several existing densification enterprises in the five-state study region;[31] a list of facilities and more information regarding target markets can be obtained from the Pellet Fuels Institute (PFI), the pelletizing industry's trade association.[32]

Pellets are made primarily from the woody biomass, although there is increasing interest in pellets made from a variety of biomass feedstocks, including perennial grasses.[33] Pellets are typically 1/4 inch in diameter and approximately 1 inch long, although various other sizes are also available. See Figure 7. The PFI has established product quality specifications for premium grade and standard grade pellets, with premium grade pellets having less than 1% ash.[34] The 2009 economic stimulus legislation includes a consumer tax credit for the purchase of pellet stoves (up to $1,500).[35]


Figure 7: wood pellets.
source: Verstegen B.V.

The primary markets for wood pellets are for residential space heating[36] and, to a lesser extent, light industrial space heating (refer to the discussion in §C.2.). For residential markets pellets are typically sold in 40 pound bags (i.e. 50 bags per ton). With approximately 800,000 residential pellet stoves installed in the U.S.,[37] pellet fuel can now be purchased at retail outlets throughout the study region.

For light commercial markets such as poultry house heating, a growing number of pellet manufacturers are selling products in bulk (either in super-sacks or by the truckload). In the past few years new markets have emerged in Europe for pelletized biomass for large-scale energy applications including power generation. For example, the Drax power plant in the UK will use 1.5 million tons of pelletized biomass for co-firing with coal,[38] with much of that supply coming from North America.

Briquettes come in many shapes and sizes utilizing a variety of densification techniques,[39] with some manufacturers now moving towards higher energy-content briquettes made by blending biomass with other high-energy materials such as coal or charcoal. Examples of some briquettes are shown in Figure 8.


Figure 8: biomass briquettes.
source: Wichita Burner Inc.

Historically, briquetting machines have had lower capacity or throughput compared to pelletizing equipment.[40] However, increasing interest in biomass briquetting may lead to development of briquetting equipment with commercial-scale production capacities (i.e., greater than 1-2 tons per hour per unit).[41]

E. Gaseous fuels

Gasified biomass can be used for space heating, process heat, and/or power production. There are two basic biomass-derived gaseous fuels: synthetic gas ("syngas"), made via gasification (a thermochemical process), and biogas, made via anaerobic digestion (a biochemical process).

1. Syngas

Syngas is a mixture of mostly hydrogen, carbon monoxide and carbon dioxide, and has less than half the energy density of natural gas.[42] Syngas is primarily used as a feedstock to produce other products such as hydrogen, ammonia, ethanol and methanol. Refer to Figure 9. Unfortunately, most syngas requires extensive cleanup to remove carbonyl sulfide and other acid gas compounds before it can be used as a fuel. Numerous technologies are in development and use for syngas cleaning. Gas cleanup is the key enabling technology for wide-spread application of integrated gasification combined-cycle technology for power generation and conversion of syngas to transportation fuel, fuel additives, chemicals, and hydrogen.[43] To this end, GTI, the Gas Technology Institute, is currently working on two projects for the U.S. Department of Energy's Energy Efficiency and Renewable Energy Office. These projects will improve existing syngas conditioning technologies, as well as develop additional syngas cleanup technologies.[44]

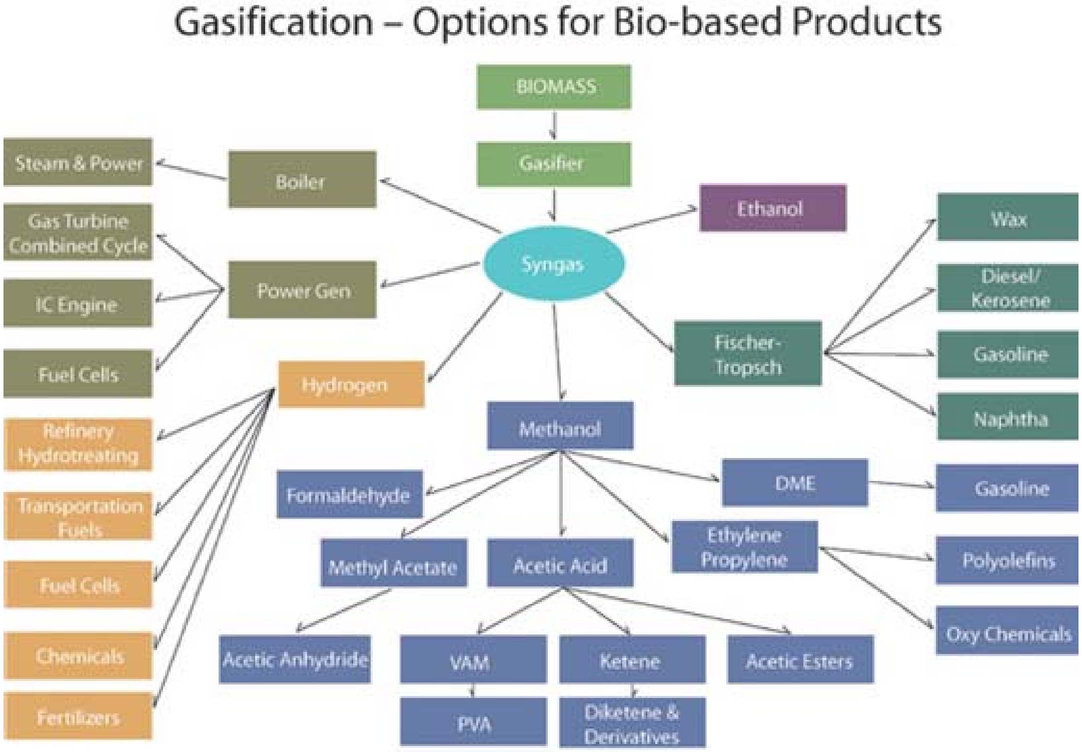


Figure 9: Syngas utilization options.
source: Biomass Magazine, January 2008

2. Biogas

Biogas, created through anaerobic digestion of high-moisture materials (e.g., manure, agricultural processing effluent), is commonly used for space heating and/or to generate electricity. Biogas can also be refined to pipeline quality and inserted into an existing natural gas pipeline.

Biogas produced in anaerobic digesters consists of methane (50%–80%), carbon dioxide (20%–50%), and trace levels of other gases. The relative percentage of these gases in biogas depends on the feedstock, the process design, and how the process is managed. When burned, a cubic foot of biogas yields about 10 Btu of heat energy per percentage of methane composition. For example, biogas composed of 65% methane yields approximately 650 Btu per cubic foot.

Anaerobic digestion with biogas recovery and utilization is not a new technology. Heavily studied in the 1930s and utilized during World War II, anaerobic digestion has experienced a world-wide resurgence. Germany has over 3000 agricultural digesters producing electricity today, with new ones are being built at a rate of about 1000 a year; anaerobic digestion is one the fastest growing renewable energy technologies in that country.[45] By contrast, the U.S. has only 113.[46] Small-scale digesters are also widely used in China, where over 15 million households were using biogas by the end of 2004.[47]

While there are disadvantages to the anaerobic digestion process, namely the process is time- and labor-intensive and requires careful monitoring of operating conditions, interest in large-scale anaerobic digestion and biogas utilization facilities has increased significantly in the United States during the past two decades. One such system is the Huckabay Ridge facility built by Microgy, Inc., in Stephenville, Texas (see Figures 10 and 11). This facility utilizes eight 916,000-gallon digester tanks to process manure from 10,000 dairy cows. The first of its kind, and with an on-site gas conditioning facility, Huckabay Ridge produces 1 billion cubic feet of biogas per year with an energy output of 650,000 million BTU.[48]

Figure 10: Mircogy Inc biogas production and conditioning facility in Texas.
source: Microgy Inc.

Figure 11: Mircogy Inc biogas production and conditioning facility in Texas.
source: Microgy Inc.

F. Liquid fuels

There are three primary forms of liquid fuels from biomass: alcohol fuels such as ethanol and methanol, vegetable oils such as biodiesel, and biocrude such as pyrolysis oil or Fisher-Tropsch liquids. Some biomass-to-liquids fuels (BTL) are used to replace or extend petroleum-derived fuels such as gasoline, diesel, and jet fuel; other liquefied biomass products can be used to make various high-value chemicals or to make more refined biofuels, including fuels that are molecularly equivalent to fuels derived from crude oil or other fossil fuels.

1. Alcohol fuels

Ethanol is the most widely known and used alcohol fuel. It is produced through fermentation of sugars by yeast, fungi, or bacteria. Ethanol production from grain and sugar crops is a well-established technology. Figure 12 depicts locations of ethanol production facilities in the United States (2008) using corn and sorghum feedstocks. Ethanol made from grain/sugar crops (along with biodiesel made from oilseed crops—refer to §F.2) are commonly referred to as first-generation biofuels.

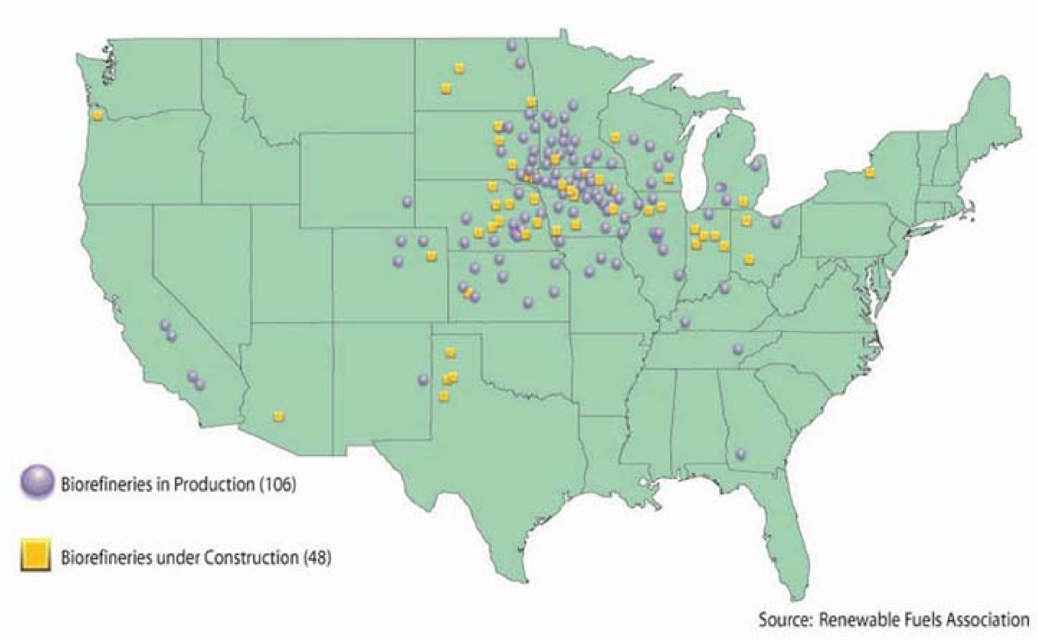
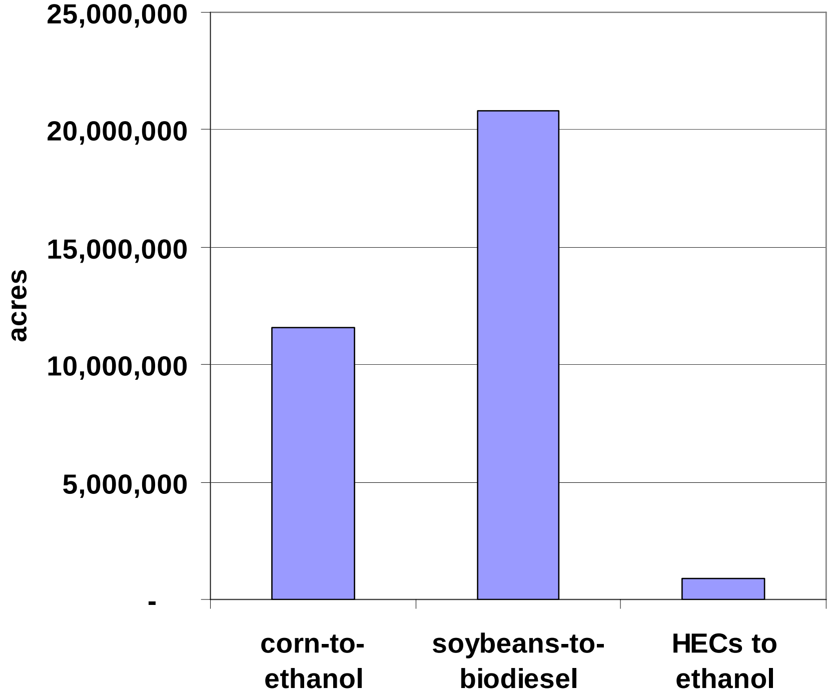


Figure 12: Ethanol production facilities in the United States (2008).
source: Renewable Fuels Association.

Ethanol made from lignocellulosic biomass—commonly referred to as cellulosic ethanol (also known as bioethanol)—is considered a second-generation biofuel. Whether from grain or cellulosic feedstocks, the ethanol fuel product is identical. However, cellulosic ethanol requires pretreatment of the cellulosic feedstocks to extract fermentable sugars from the cellulose and hemi-cellulose components.

Compared to processing of sugar/grain crops, the pretreatment process for cellulosic feedstocks adds difficulty and cost. In contrast, the primary advantage of cellulosic ethanol production is that lignocellulosic feedstocks are abundant and relatively inexpensive. Cellulosic feedstocks offer significant environmental benefits as well: “Perennial energy crops provide a better environment for more-diverse wildlife habitation. Their extensive root systems increase nutrient capture, improve soil quality, sequester carbon, and reduce erosion.”[49] In addition, higher yields of cellulosic crops compared to grain (or oil seed) crops result in lower ecological footprints, i.e., fewer acres required for feedstock production for a given amount of energy. Figure 13 compares the acres required for production of one billion gallons of first- and second-generation biofuels under Delta conditions.[50] HECs refers to herbaceous energy crops (e.g., *miscanthus giganteus*).

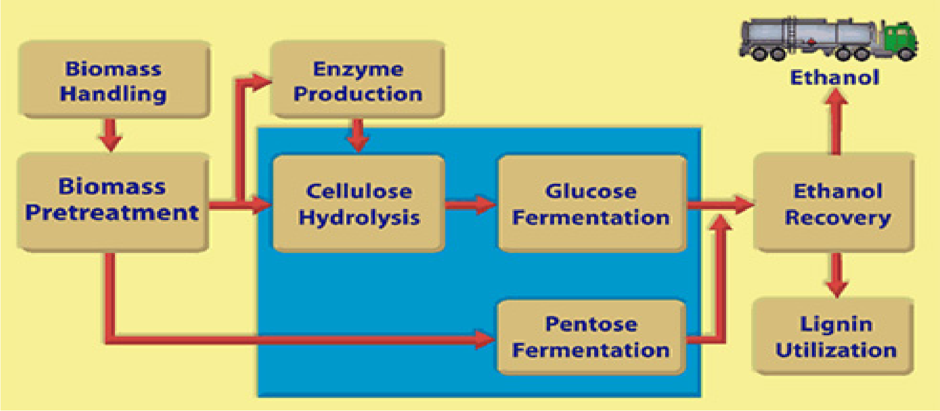
Figure 13. Land area required to produce 1.0 billion gallons of ethanol equivalents for 3 biofuels scenarios under Delta conditions



Cellulose to ethanol production was first attempted in the late 1800s, was heavily researched and used during World War II, and is on the rise again as more cost-effective processes are emerging and the benefits of cellulosic feedstocks are being proved.

There are two categories of pretreatment technologies used for converting cellulosic biomass to ethanol: hydrolysis (a biochemical process), and gasification (a thermochemical process); both pretreatment processes are followed by fermentation. There are three common types of biochemical pretreatment processes: acid hydrolysis, dilute acid hydrolysis, and enzymatic hydrolysis. A simplified process flow diagram of an enzymatic hydrolysis + fermentation process is shown in Figure 14.[51]

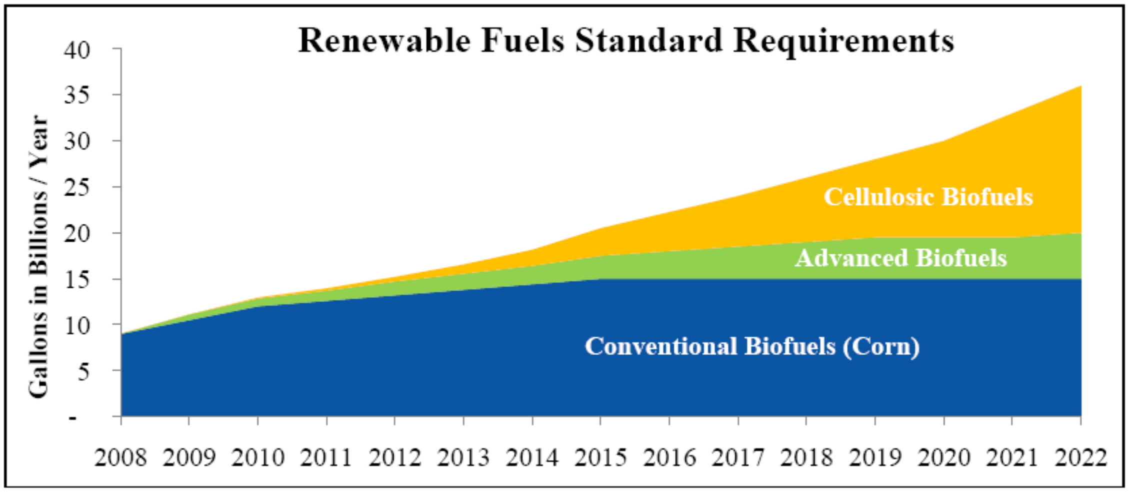
Figure 14. Simplified Process Flow Diagram for Cellulosic Ethanol Production
Source: U.S. Department of Energy



Substantial efforts and investments are underway worldwide to develop and commercialize processing technologies for converting cellulosic feedstocks into ethanol. Efforts in the U.S. are being stimulated and supported primarily through public policies and through DOE's cellulosic biorefinery program.[52]

Figure 15 illustrates the amount of liquid biofuels that must be produced in the U.S. to comply with the Renewable Fuels Standard (RFS) established in the 2007 Energy Independence and Security Act (HR 6).[53] The RFS entails increased production of conventional biofuels (e.g., corn-derived ethanol) up to 15 billion gallons per year (BGY) by 2015; total production of first-generation ethanol in 2008 was 9 BGY.[54] In contrast, the requirement for cellulosic ethanol will increase from 0.1 BGY in 2010 to 16 GBY in 2022; another 5 GPY of "advanced biofuel" is required by 2022.

Figure 15: Projected Requirements for various Biofuels based on the '07 RFS
Source: ClearFuels Technology Inc.



Source: H.R. 6 – Energy Independence and Security Act of 2007

Figure 16 illustrates the fractions of motor gasoline and diesel fuels that will be provided from biofuels through 2030, based on the projected production levels required by the RFS and DOE's projected demands for liquid transportation fuels.

As a transportation fuel, ethanol—whether derived from corn or lignocellulosic feedstocks—can be used to extend/displace gasoline. Ethanol can be splash-blended with gasoline up to at least ten percent and used in existing gasoline engines without any modifications to the engines (the ethanol industry claims that the upper limit is closer to 15%, and efforts are underway in both the public and private sectors to determine maximum allowable ethanol blend levels).

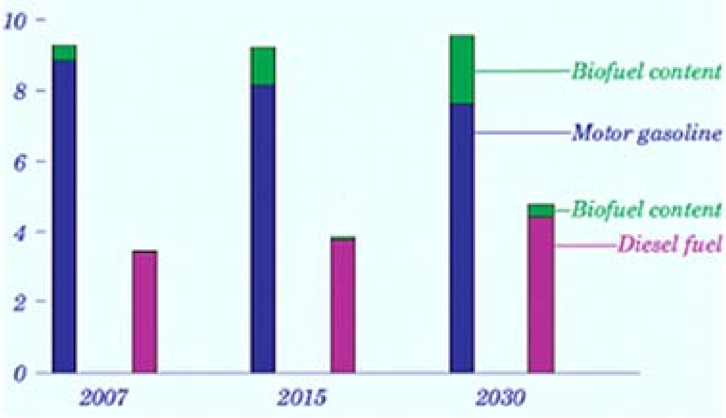


Figure 16: Projected Consumption of Primary Transportation Fuels by Source (Petroleum vs. Biomass), in millions of barrels per day.
source: U.S. Department of Energy

Some vehicles, known as Flexible Fuel Vehicles or FFVs, come equipped with gasoline engines that can accommodate up to 85% ethanol blend. The ethanol industry claims that, in many cases, FFVs do not cost more than similar gasoline-fueled engines. Almost eight million FFVs are on the road in the U.S. today.[55]

The theoretical demand for ethanol is significant: total gasoline and ethanol consumption in the U.S. in 2008 was 137 billion gallons and 9.6 billion gallons, respectively. Since ethanol can be blended with gasoline at 10% by volume without any modifications required to the engine, the potential demand for ethanol for use as a blend with gasoline is approximately 13.7 BGY. If the country were to switch completely to E85, then demand for ethanol would exceed 116 billion gallons – more than 12 times current consumption of ethanol. One DOE projection of annual demand for ethanol in the United States is nearly 35 billion gallons by 2030.[56]

Ethanol is also processed into ETBE[57], an oxygenate used with gasoline (instead of MTBE, a petroleum-derived oxygenate historically used with gasoline, the use of which has declined in the United States due to environmental and health concerns).[58]

2. Biodiesel

Like ethanol, biodiesel fuel has its origin in the late nineteenth century. Vegetable oil was one of the fuels originally tested in Rudolph Diesel's compression-ignition engine. The French government demonstrated the first biodiesel engine at the 1900 World's Fair; the engine ran on peanut oil. In the 1920s, the widespread availability and low cost of petroleum-based diesel made biodiesel almost obsolete, with the exception of a brief resurgence in Belgium in the 1930s. Not until the 1980s did biodiesel return to favor in Europe and the United States. Since that time biodiesel processing technology has become well-established and can utilize a variety of oil feedstocks, including virgin oils (e.g., soybean-derived oil, cotton seed-derived oil), animal fats, and waste vegetable oils.

Biodiesel is made from oils or fats through transesterification, which separates the feedstock into methyl esters (biodiesel) and glycerin. Almost all biodiesel is made from virgin vegetable oils (primarily soybean oil in the United States, canola or rapeseed oil in Europe); at some facilities in the U.S., waste vegetable oil (or “WVO”, such as restaurant grease) and/or fatty byproducts from animal processing facilities are used as feedstocks.[59] Transesterification requires a catalyst (typically methanol), with a volumetric yield of biodiesel relative to the oil feedstock of approximately 98%.

According to the *Report on US Biodiesel Market Analysis and Forecasts to 2013*, strong federal policy support, including the Energy Policy Act of 1992, the biodiesel tax credit enacted in 2004, the USDA Commodity Corporation Credit (CCC) program, the Energy Policy Act of 2005, and most recently, the Energy Independence and Security Act of 2007, has created a strong market for biodiesel in the US. Production increased from around 6.3 million gallons in 2001 to 731 million gallons in 2008, with some projections showing increased demand to around 1,463 million gallons by 2013.

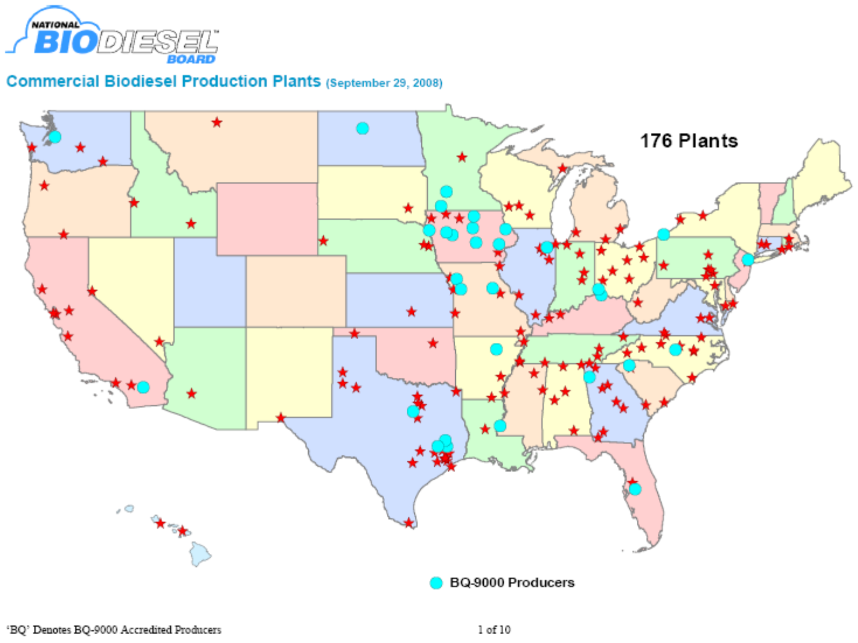


Figure 17: Biodiesel production facilities.
source: National Biodiesel Board

However, growth in demand for biodiesel has slowed due to a combination of the current financial crisis, the decline in petroleum product prices, and biodiesel’s reduced efficiency compared to gasoline.[60] In fact, the high cost (and volatility) of virgin oil prices, combined with the drop in fossil energy prices in mid-2008 have profoundly impacted the economics of biodiesel production in the region. As a result, most of the biodiesel production facilities in the 5-state study area have, at least temporarily, reduced or suspended biodiesel production and sales,[61] and biodiesel production at the national level has fallen to 2006 levels.[62]

3. Biocrude

A third BTL category consists of biocrude, a term commonly used for the unrefined biomass-derived liquid made via pyrolysis or the Fischer-Tropsch process. Biocrude is essentially a mixture of hydrocarbons, with a higher viscosity, higher specific gravity, and lower energy content compared to petroleum crude oil.

Pyrolysis oil (or “bio-oil” or “biocrude”) is the primary-product of pyrolysis (refer to §G.1 for a discussion of the pyrolysis process). Biocrude from pyrolysis can be used to make electricity, either as fuel for a single-cycle combustion system (including co-firing with coal) or as fuel for a combustion turbine (either in a simple- or combined-cycle system, with the latter referred to as an integrated-pyrolysis-combined-cycle system or IPCC). In addition, research results indicate that bio-oil can be blended directly with diesel (i.e., without further refining) to displace a fraction of the fossil-based fuel with the biomass-derived renewable fuel, although such use needs to be commercially validated.

Fischer-Tropsch liquids (“FT-liquids”) are the primary-products of the Fischer-Tropsch gasification + catalysis process (refer to §G.1 for a discussion of the process). Like pyrolysis oil, FT-liquids are a mixture of hydrocarbons that can be used directly for thermal energy production and/or electrical power generation.

Biocrude, including both pyrolysis oil and FT-liquids, can also be further refined into a wide spectrum of hydrocarbon products (e.g., gasoline, diesel, jet fuel),[63] in which case the bio-oil essentially serves as a substitute for petroleum crude. Although both pyrolysis and the Fischer-Tropsch process are well understood and have been commercialized by the fossil fuel industry for decades, refining of biomass-derived pyrolysis oils and FT-liquids is still in the pre-commercial stage. The quantity of refined liquid hydrocarbon fuels that can be produced from biocrude depends on numerous factors, with reported yields varying from 12% to over 60% on a volumetric basis.[64] The refined liquid fuel products made from bio-oil are molecularly equivalent to the same products made from petroleum crude, and therefore could be used within the existing liquid fuels distribution and utilization infrastructure without modifications to said infrastructure.[65]

In recent years the oil extracted from **algae** has been increasingly referred to as biocrude. Algae contains 2% - 40% oil by weight, depending on the type/strain.[66] As with biodiesel from oilseed crops, algae-derived oil can be refined via transesterification into a diesel-like liquid fuel, or harvested algae can serve as a cellulosic feedstock, with subsequent conversion into power and/or liquid fuels (e.g., via combustion or pyrolysis).

Interest in production of algae as a renewable energy feedstock has increased rapidly in the past few years, in large part because of claims regarding extremely high feedstock yields (some as high as 20,000 gallons per acre per year; for comparison, gross production of biodiesel from soybeans under Delta conditions is approximately 60 gallons per acre per year). However, even assuming more humble yields for algae-derived oil, algae constitutes a crop of significant interest and potential for the 5-state study region, particularly since algae can be produced on degraded or non-agricultural lands.[67]

G. Conversion technologies

Biomass can essentially be considered a "solar battery" in which sunlight is converted into potential energy via photosynthesis and stored in the form of biomass until converted into usable energy. Various thermochemical[68] and biochemical[69] technologies can be used to convert solid biomass into the various energy products discussed in this report.

1. Thermochemical conversion processes

Examples of thermochemical conversion technologies include:

- **Combustion**: Burning biomass to produce thermal energy or, indirectly, electricity (via a steam cycle – refer to Figure 5) is the most commonly used conversion technology. Co-firing of biomass with coal generally entails combustion.
- **Gasification**: The solid biomass is converted into a gaseous phase (syngas) in an oxygen-deprived reactor at high temperature;[70] the syngas is subsequently burned in a combustion turbine[71] (refer to Figure 6) or further processed into additional fuels (including pipeline-quality gas – refer to §E.2) or high-value chemicals.[72] A bioenergy system consisting of gasification followed by combined-cycle power generation is referred to as an integrated-gasification-combined-cycle system (IGCC).[73] A simple schematic of an IGCC system is shown in Figure 18 (except that this schematic shows fossil fuels being used as the feedstocks).[74]

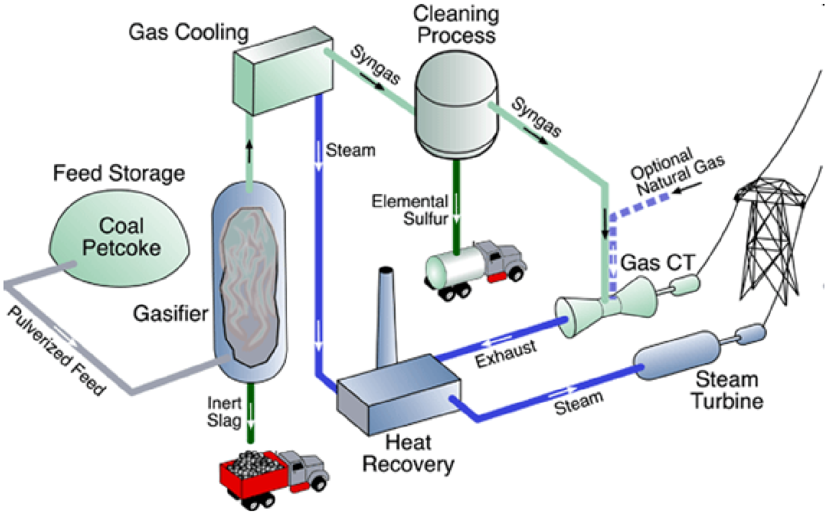


Figure 18. Integrated Gasification—Combined Cycle System.
source: Energy Northwest

- **Pyrolysis**: Pyrolysis is a 2-step process, consisting of thermal decomposition of biomass in the absence of oxygen (similar to gasification) followed by condensation of the vapors.[75] Refer to Figure 19. In "fast pyrolysis" these subsequent phase changes occur in less than two seconds. Products include pyrolysis oil or "bio-oil" or "biocrude" (a mixture of hydrocarbons[76]—essentially liquefied biomass), non-condensable vapors (which are used to drive the pyrolysis process) and char (a dry, powdery, high energy content, carbonaceous material that also contains the mineral ash from the feedstock).[77] Depending on the design and operation of a specific system, yields of pyrolysis oil range from about 50%-70% of feedstock by weight,[78] while yields of pyrolysis char range from 10%-30%.[79] At a process yield of 60% and a specific gravity of 1.2, a ton of biomass produces approximately 1,200 gallons of bio-oil.

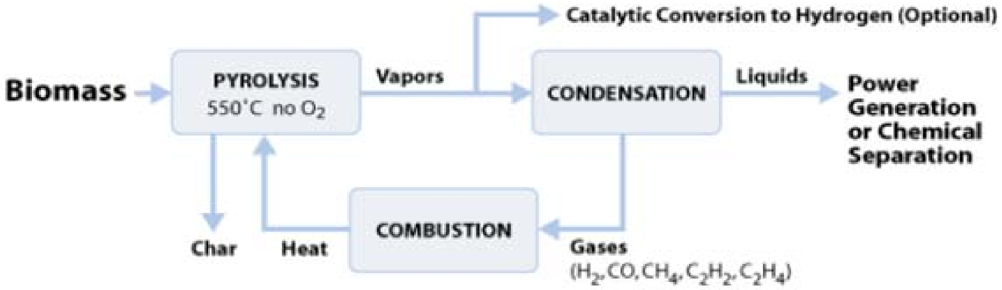


Figure 19. Biomass Liquefaction via Pyrolysis.
source: REPP

One of the benefits of pyrolysis is that the mineral constituents of the char (e.g., potassium and phosphorus that were contained within the biomass feedstocks) have fertilization value for crop production.[80] In addition, the use of biomass-derived pyrolysis char (biochar) as a soil amendment has been shown to improve plant growth.[81] The carbon within the biochar appears to have a long residence time when incorporated into soils (i.e., in hundreds or thousands of years),[82] thereby creating significant potential opportunities for carbon sequestration.[83] Each ton of biochar is equivalent to about 3 to 3.7 tons of CO_2.[84] At 25% char yield and 3.4 tons CO_2 per ton of char, pyrolysis of one million dry tons of biomass could result in the sequestration of 850,000 tons of CO_2. Refer to Figure 20.

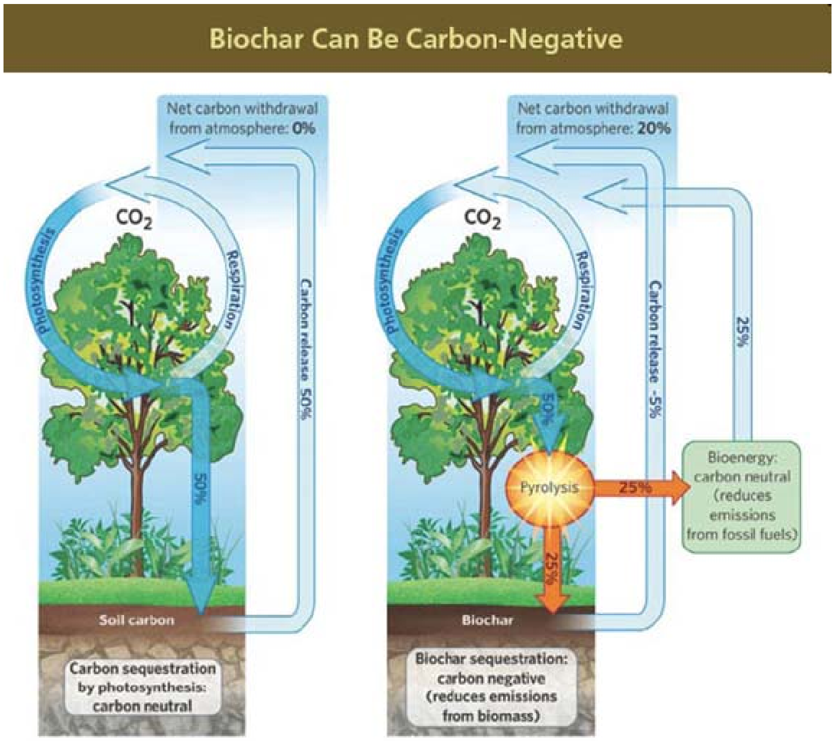


Figure 20. Biochar from Pyrolysis.
source: International Biochar Initiative

- **Fischer-Tropsch**: The Fischer-Tropsch (F-T) process entails gasification of the biomass feedstock followed by conversion of the syngas into a mixture of liquid hydrocarbons ("biocrude") through a catalytic process.[85] The F-T process was originally developed in Germany in the 1920s for converting coal into liquid fuel;[86] the technology was expanded to commercial scale in the 1950s in South Africa.

  As with biocrude from pyrolysis, the F-T products can be further refined into a full spectrum of transportation fuels.[87] Also referred to as gas-to-liquid or GTL products, GTL fuels have superior properties; for example, F-T diesel "has near zero sulfur and aromatic content and very high cetane numbers."[88]

  According to the Princeton Environmental Institute (October 2008), "Fischer-Tropsch liquids from biomass…offers as advantages over cellulosic ethanol the prospects that: (i) no significant transportation fuel infrastructure changes would be required for widespread use, (ii) the technology could plausibly come into widespread use more quickly than cellulosic ethanol, which needs considerably more development before it can be widely deployed, (iii) it can probably accommodate more easily the wide range of biomass feedstocks that are likely to characterize the lignocellulosic biomass supply—because gasification-based processes tend to be more tolerant of feedstock heterogeneity than biochemical processes."[89] (Note: These advantages also apply to biomass-to-liquid fuels made via pyrolysis.)

  As of May 2009 there are no known commercial operations using Fischer-Tropsch-based biomass-to-liquids technologies, although several projects are in various planning stages. Although the process is well-known at commercial scale for use with coal and natural gas feedstocks, there are still technical risks associated with production of FT-liquids from biomass.

- **Torrefaction**: A process akin to charcoal production in which biomass is "roasted" in the absence of oxygen, torrefaction produces an intermediate solid fuel with superior properties compared to untreated biomass: it has higher energy density, is hydrophobic, homogeneous, friable, and less fibrous.[90] Torrefied biomass contains approximately 70% by weight of the original material, but has 30% higher energy density. The properties of torrefied biomass make it particularly suitable for co-firing with coal.

  As of May 2009 several commercialization efforts are underway using torrefaction.[91] The economics of a torrefaction-based enterprise will depend primarily on the cost of production, the economics of co-firing with coal, and the economics of carbon offsets (if the torrefied biomass is used as a fuel) and/or sequestration (if the torrefied biomass is used as a soil amendment).

- **Gasification + fermentation**: A hybrid thermochemical-biochemical process, the feedstock is gasified, with the resulting syngas fermented into ethanol. A pilot-scale facility using this technology is located in Fayetteville, Arkansas; the hybrid process was developed by Bioengineering Resources, Inc., which was purchased by Ineos Bio in July 2008.[92] A key benefit of this technology is the ability to accommodate a wide range of feedstock types and quality.

2. Biochemical conversion processes

There are three primary processes for biochemical conversion of biomass: fermentation, transesterification, and anaerobic digestion. All three conversion processes are anaerobic. Biochemical conversion processes occur at lower temperatures and have lower reaction rates than thermochemical processes. Generally speaking, biochemical processes can utilize higher-moisture feedstocks (including animal manure and food wastes).

- **Fermentation** is used with first-generation feedstocks such as corn, sorghum, or cane juice. Hydrolysis—a process in which the cell walls are broken down into soluble sugars—is required as a pretreatment for cellulosic feedstocks.

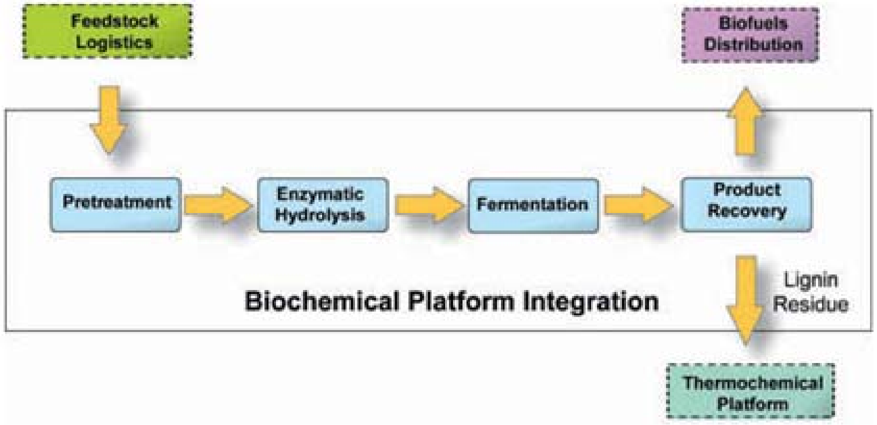


Figure 21. A simple schematic of the biochemical process.
source: U.S. Department of Energy

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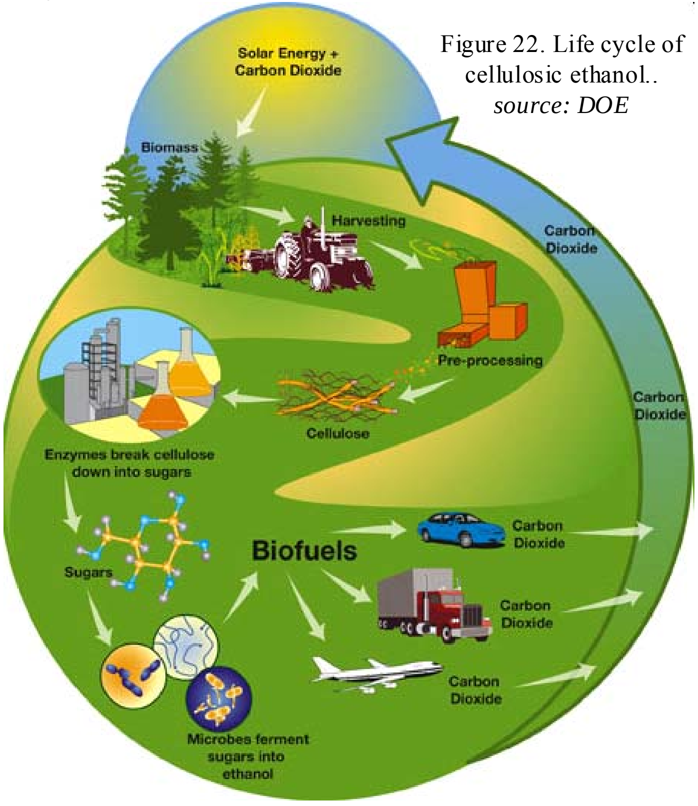

Figure 22. Life cycle of cellulosic ethanol..
source: DOE

- Hydrolysis techniques include dilute acid hydrolysis, concentrated acid hydrolysis, and enzymatic hydrolysis, as well as gasification (the only thermochemical pretreatment option – see “gasification + fermentation” above). A simple process flow diagram of a biochemical conversion process utilizing enzymatic hydrolysis is shown in Figure 21. Cellulosic ethanol is generally regarded as being more environmentally beneficial than corn ethanol – refer to Figure 22.

Transesterification is the process by which biodiesel is made (as distinct from, and generally inferior to, renewable diesel made from upgraded pyrolysis oil or FT-liquids). In transesterification an alcohol reacts with the triglyceride oils contained in vegetable oils, animal fats, or recycled greases, forming fatty acid alkyl esters (bio-diesel) and glycerin. The reaction requires heat and a strong base catalyst such as potassium hydroxide or methanol.

Some feedstocks require pre-processing such as acid esterification before they can undergo transesterification. Refer to Figure 23. Biodiesel production systems using transesterification are available in both batch and continuous flow options, with batch systems typically used for smaller-scale operations.

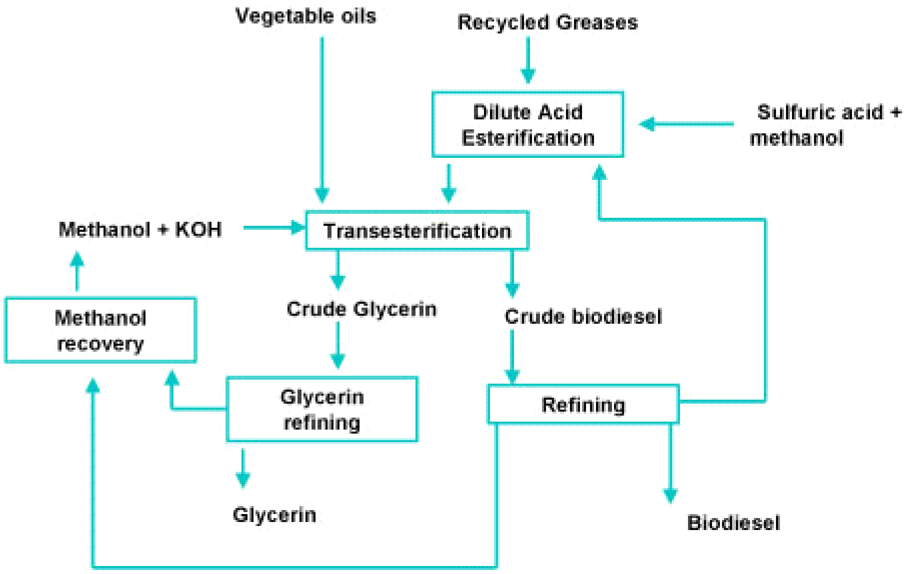

Figure 23. A simple schematic of the transesterification process.
source: U.S. Department of Energy

- **Anaerobic digestion** is a series of processes in which microorganisms break down biomass in the absence of oxygen (anaerobic). The bacteria convert the matter into biogas, which consists of methane (50%–80%), carbon dioxide (20%–50%), and trace levels of other gases such as hydrogen, carbon monoxide, nitrogen, oxygen, and hydrogen sulfide. The relative percentage of these gases in biogas depends on the feedstock and management of the process.[93]

  Anaerobic processes can be managed in a "digester" (an airtight tank) or a covered lagoon (a pond used to store manure) for waste treatment. The primary benefits of anaerobic digestion are nutrient recycling, waste treatment, and odor control. Except in very large systems, biogas production is a highly useful but secondary benefit.

H. Pre-conversion considerations

Biomass feedstocks are collected/harvested and transported to a processing facility, where pre-processing and storage activities are usually required prior to the material being fed into the energy conversion system. This section discusses the transport of green feedstock to the processing facility, as well as the two most important pre-processing functions associated with most bioenergy operations: sizing and drying. (Note that at least some of the particle size reduction typically occurs during harvesting or prior to loading—refer to §H.2 below).

1. Transport of green biomass

Many factors affect feedstock transportation, and the costs and logistics should be determined only on a project-specific basis. Nonetheless, the following principles are universally applicable:

- Minimizing the average haul distance reduces feedstock transport cost per ton.
    - *Higher crop yield reduces haul distance, which reduces transport cost.*
- Maximizing the bulk density increases the quantity hauled per load.
    - *Which decreases the transportation cost per ton.*
- Minimizing moisture content of harvested/collected biomass reduces feedstock cost.
    - *Hauling water (contained in the biomass) increases transport cost.*
    - *Higher moisture content increases the subsequent cost of moisture removal.*

Numerous overviews of biomass transportation logistics are available for reference.[94] A companion report to this document entitled ***Assessment of Agricultural and Forest Biomass Resources in the Mid Portion of the Mississippi River Alluvial Valley*** includes an economic analysis of feedstock transportation.[95] For any commercial-scale bioenergy project, transportation costs should be analyzed on a project-specific basis, and detailed analytical tools are available to assist with these logistical and economic analyses.[96]

2. Sizing

Most of the processing technologies discussed in this report require small feedstock particle sizes. Size reduction typically occurs at one or more points in the supply chain:

- At the time of harvesting in order to increase bulk density and transport efficiency (e.g., chipping of tree branches, or chopping of energy crops by a chopper harvester).
- At the processing facility, before the conversion process (and generally prior to any drying that may be required).

Some combustion systems can accommodate 2-inch chip size, whereas most pyrolysis reactors need the biomass particles to be less than 0.1-inch in the longest dimension. Accordingly, grinders and other size reduction equipment are typically an integral part of any biomass-to-energy processing facility.

3. **Drying**

Moisture reduction of biomass is a critical but often under-appreciated function. The amount of drying required depends on numerous factors such as the type of feedstock, moisture content at the time of harvest, required storage conditions and duration, materials handling equipment used, transport considerations, and the type of conversion process used. While some processes such as combustion can tolerate relatively high feedstock moisture levels (up to about 60% wet basis), other processes such as densification or pyrolysis require the material to be dried to 10% (wet basis) or less.

Many biomass materials have significantly high moisture content at the time of harvest. Woody biomass, for example, averages about 50% wet basis (i.e., approximately half of the weight of a tree is water), and some herbaceous energy crops can exceed 60% wet basis if harvested green. Such materials must be dried before they can be utilized by most of the conversion processes discussed herein. Equally important, feedstocks cannot be stored for any significant length of time without first removing most of the moisture in the material; otherwise, the material can rot (and the quality will degrade), obnoxious odors can result from anaerobic storage conditions, and there are risks of spontaneous combustion in the storage piles…all of which could be costly to the enterprise.

Not only is removing the moisture from biomass feedstocks a critical step, but the cost of moisture removal can be significant…drying is often the second most expensive component of a bioenergy enterprise’s budget (second only to the cost of the feedstock). For example, a feedstock having 45% moisture content (m.c.) wet basis may be delivered to the processing facility for, say, $22 per green ton (the delivered cost is determined by the acquisition cost plus the transport cost). Factoring out the water, the cost of the material is calculated to cost $40 per ton dry matter basis (dmb). This dmb method enables us to accurately compare the costs of various feedstocks that have different moisture contents on an “apples-to-apples” basis.

But, although the feedstock is reported to have a cost of, say, $40 per ton dmb, it is essential to understand that the material is still wet, and that most of the water must be removed prior to storage and/or conversion into energy products. To obtain a true comparison of the “full cost” of feedstocks for a given facility, one must include the cost of feedstock drying (and other preprocessing functions that may be applicable such as sizing and/or storage).

For example, a comparison of the total costs of the two illustrative feedstocks is shown in Figure 24. Although the cost of each feedstock delivered to the processing facility (from the forest or field) is the same, the total cost after drying is significantly different, due to the feedstocks’ different moisture contents and associated costs of moisture removal.

Figure 24: cost comparison of two illustrative feedstocks after drying

	Feedstock A	Feedstock B	
total weight of feedstock	1.00	1.00	green tons
moisture content (m.c.)	45%	20%	
acquisition cost	$17.00	$27.00	per green ton
transport cost	$5.00	$5.00	per green ton
delivered cost (to the processing facility)	$22.00	$32.00	per green ton
delivered cost (to the processing facility)	$40.00	$40.00	per ton dmb
weight of feedstock - dry matter only	0.55	0.80	tons, dmb
required m.c. for energy conversion	10%	10%	
weight of feedstock after drying	0.61	0.89	tons, as dried
amount of water to be removed	0.39	0.11	tons - water
cost of drying	$9.80	$2.80	
total cost of dried biomass as delivered to the conversion system	$49.80	$42.80	
relative cost of drying compared to the cost of biomass delivered to the processing facility	24.5%	7.0%	

As shown, full cost accounting is needed (on a project-specific basis) to understand the net cost of biomass feedstocks delivered to the conversion system. Note that the simple analyses presented in Figure 24 do not include other costs that may be applicable such as storage, other pre-treatment processes such as those described in other sections of this report, or transport of the processed biomass from the processing facility to the energy conversion facility if the latter is at a different location.

I. End Notes

[1] Non-energy products or bioproducts can also be made from biomass feedstocks. Depending on the extent of value-added processing undertaken, the value of biobased products ranges from relatively low-value products such as mulch or compost to relatively high-value products such as pharmaceuticals or plastics. Discussions regarding non-energy bioproducts are beyond the scope of this sub-report, although additional information regarding bioproducts can be obtained from various sources, e.g.: http://www.nrel.gov/learning/re_bioproducts.html, http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf

[2] http://www.energy.gov/energysources/bioenergy.htm

[3] The Federal emphasis on liquid biofuels has been evidenced by:

- Subsidies for first-generation ethanol production (primarily from corn); federal subsidies for ethanol production trace back to the Energy Tax Act of 1978 (http://www.eia.doe.gov/kids/history/timelines/ethanol.html)
- Subsidies for first-generation biodiesel production (primarily from virgin oils such as soybean oil) trace back to the American Jobs Creation Act of 2004 (http://www.ampc.montana.edu/policypaper/policy16.pdf)
- The establishment of a Renewable Fuels Standard (refer to the Energy Policy Act of 2005 http://www.ethanolrfa.org/policy/regulations/federal/standard/ and the Energy Independence and Security Act of 2007 http://www.epa.gov/OMS/renewablefuels/)
- The National Biofuels Action Plan (October 2008); http://www1.eere.energy.gov/biomass/pdfs/nbap.pdf
- Substantial funding and support for biorefinery research, development, demonstration, and deployment (including, most recently, support from the American Recovery and Reinvestment Act of 2009 http://www07.grants.gov/search/search.do;jsessionid=GSmrKDGG1RJPk40HMKL8s20KBcpvRQqQJqTLcvHNV9vJrhztnPGp!-1521724462?oppId=47227&flag2006=false&mode=VIEW).

[4] http://www.eere.energy.gov/de/biomass_power.html

[5] www.nrel.gov/docs/fy00osti/28009.pdf

[6] According to the U.S. Department of Energy: "Electricity demand fluctuates in the short term in response to business cycles, weather conditions, and prices. Over the long term, however, electricity demand growth has slowed progressively by decade since 1950, from 9 percent per year in the 1950s to less than 2.5 percent per year in the 1990s. From 2000 to 2007, increases in electricity demand averaged 1.1 percent per year. The slowdown in demand growth is projected to continue over the next 23 years (Figure 54), as a result of efficiency gains in response to rising energy prices and new efficiency standards for lighting, heating and cooling, and other appliances.

In the reference case, electricity demand increases by 26 percent from 2007 to 2030, or by an average of 1.0 percent per year. The largest increase is in the commercial sector (38 percent), where service industries continue to lead demand growth, followed by the residential sector (20 percent) and the industrial sector (7 percent). Population growth and rising disposable incomes increase the demand for products, services, and floor space, and ongoing population shifts to warmer regions increase the use of electricity for space cooling.

From 2007 levels, electricity demand increases by 36 percent in the high growth case, to 5,323 billion kilowatthours in 2030, compared with an increase of 16 percent in the low growth case, to 4,518 billion kilowatthours in 2030. Plug-in electric hybrid vehicles are not expected to reverse the trend of slowing growth in electricity demand, which increases by only 0.1 percent for every 1 million PHEV-40 vehicles in operation."

Source: http://www.eia.doe.gov/oiaf/aeo/electricity.html

[7] Refer to www.dsireusa.org/documents/Summary**Maps/RPS_map**.ppt

[8] A Renewable Portfolio Standard or RPS (sometimes referred to as a Renewable Electricity Standard or RES) is a requirement that a certain amount of electricity generation be from renewable sources. RPS standards vary widely by state; some states have mandatory requirements, whereas some states have renewable goals. Refer to: http://www.pewclimate.org/what_s_being_done/in_the_states/rps.cfm

[9] http://energycommerce.house.gov/index.php?option=com_content&view=article&id=1629&catid=141&Itemid=85

[10] http://www.eia.doe.gov/oiaf/aeo/electricity.html

[11] State-by-state energy demand and production data is available from DOE at:

Arkansas	http://apps1.eere.energy.gov/states/state_specific_information.cfm/state=AR
Kentucky	http://apps1.eere.energy.gov/states/state_specific_information.cfm/state=KY
Mississippi	http://apps1.eere.energy.gov/states/state_specific_information.cfm/state=MS
Missouri	http://apps1.eere.energy.gov/states/state_specific_information.cfm/state=MO
Tennessee	http://apps1.eere.energy.gov/states/electricity.cfm/state=tn

[12] http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html

[13] All stated quantities of biomass are in tons dry matter basis (i.e., calculated at 0% moisture content); this calculation assumes an average of 8,100 Btu/pound of biomass.

[14] In addition to being the most common type of technology used for generating electricity from biomass, direct combustion steam-cycle systems are also the primary type of technology used for generating power from coal.

[15] The "Section 45" Production Tax Credits (PTCs) were established in the 1992 Energy Policy Act; eligible facilities can use the tax credit for ten years after the facility is placed in service. The American Recovery and Reinvestment Act of 2009 extended the eligibility dates for the PTCs to December 31, 2013.
(http://www.irs.gov/newsroom/article/0,,id=208318,00.html)

[16] http://www.epa.gov/chp/funding/funding/usopenloopbiomassenergyproduct.html
http://www.irs.gov/irb/2006-42_IRB/ar07.html

[17] http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=US13F

[18] This assumes an 83% capacity factor.

[19] For a map of the natural gas pipeline network in the continental United States, refer to:
http://www.eia.doe.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/ngpipelines_map.html

[20] For Arkansas, a list of manufacturing facilities is maintained by the Arkansas Economic Development Commission: http://arkansasedc.com/data-center/reports-and-publications/industry-data.aspx

For Kentucky, a "Directory of Manufacturers" is compiled by the Kentucky Cabinet for Economic Development:
http://www.thinkkentucky.com/kyedc/kpdf/Facilities_by_Location.pdf

For Mississippi, a "Mississippi Manufacturers Cross Match Database" is maintained by the Mississippi Development Authority's Existing Industry and Business Division: http://crossmatch.mississippi.org/manufacturers/

For Missouri, a central list of manufacturing facilities was not located.

For Tennessee, profiles of manufacturing companies are available by industry category (e.g., chemicals, lumber, paper) from the Depart of Economic & Community Development: http://www.tnecd.gov/ER_key_labor.html

[21] Propane (or Liquefied Petroleum Gas, or LPG) is commonly used for space heating in rural areas where natural gas lines are not available. Notably, propane is the primary fuel used for heating the 25,700 rural-based poultry houses located in the 5-state region.

[22] For more information regarding pellet fuels and appliances, refer to: www.pelletheat.org (the Pellet Fuels Institute) ; http://hearth.com/what/pellet/pellet1.html ; and

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[23] From Wikipedia, the free encyclopedia:
"The annual fuel utilization efficiency (AFUE; pronounced 'A'-'Few') is a thermal efficiency measure of combustion equipment like furnaces, boilers, and water heaters. The AFUE differs from the true 'thermal efficiency' in that it is not a steady-state, peak measure of conversion efficiency, but instead attempts to represent the actual, season-long, average efficiency of that piece of equipment, including the operating transients.[1]

The method for determining the AFUE for residential furnaces is the subject of ASHRAE Standard 103. A furnace with a thermal efficiency (ηth) of 78% may yield an AFUE of only 64% or so, for example, under the Standard's test conditions. When estimating annual or seasonal energy used by combustion devices, the AFUE is the better efficiency measure to use in the calculations.[2] But for an instantaneous fuel consumption rate, the thermal efficiency may be better."
http://en.wikipedia.org/wiki/Annual_fuel_utilization_efficiency

[24] http://en.wikipedia.org/wiki/Annual_fuel_utilization_efficiency

[25] www.energystar.gov/ia/partners/promotions/change_light/downloads/State_Households_and_energy_prices.xls

[26] Based on poultry inventory data from the USDA National Agricultural Statistics Service (www.nass.usda.gov) and assuming 22,000 birds/house (broilers) and 5,400 birds/house (turkeys).

[27] http://www.biomass2.com/furnaces/CVP%20final%20report.pdf

[28] http://www.biomass2.com/furnaces/Biomass%20furnaces%20for%20heating%20poultry%20houses%20final%20report.pdf

[29] Some briquetting systems claim to be able to accommodate biomass with up to 15% moisture content (wet basis), and some pellet producers require feedstock moisture content levels below 10%.

[30] *www.*pubs.cas.psu.edu/FreePubs/pdfs/uc203.pdf

[31] http://www.pelletheat.org/3/residential/fuelAvailability.cfm#south

[32] www.pelletheat.org

[33] http://grassbioenergy.org/res/pellet_stove_demo.asp

[34] http://www.pelletheat.org/2/quality.html

[35] http://www.pelletheat.org/3/residential/taxCredit.html

[36] http://www.pellethead.com/product_line.htm
http://www.treehugger.com/files/2008/10/buying-wood-burning-pellet-stove-guide-review-information.php

[37] http://www.pelletheat.org/3/residential/index.html

[38] http://www.biomassmagazine.com/article.jsp?article_id=2408&q=&page=all

[39] http://www.stjosephky.com/biomass%20briquette%20systems.htm; http://www.cfnielsen.com/; http://www.warrenbaerg.com/index.php?n=1&id=1; http://www.biomassbriquettesystems.com/

[40] http://www.edc-cu.org/briquettes.htm; http://www.biomassmagazine.com/article.jsp?article_id=1524

[41] Refer to this website for additional photos of biomass briquettes:
http://www.renewenergysystems.com/index.php?option=com_content&task=view&id=19

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[42] http://en.wikipedia.org/wiki/Syngas

[43] http://www.southernresearch.org/environmental/hot-gas-cleanup.html

[44] http://www.gastechnology.org/webroot/app/xn/xd.aspx?it=enweb&xd=1researchcap\1_8gasificationandgasprocessing\1_8_3_majcurrentproj\biomassgasification.xml

[45] http://www.greenpeace.org.uk/blog/climate/the-weekly-geek-anaerobic-digestion-20080220

[46] http://www.epa.gov/agstar/operational.html

[47] http://www.snvworld.org/en/Documents/20060209%20Article%20on%20Biogas%20Asia%20in%20Renewable%20Energy.pdf

[48] http://www.environmentalpower.com/

[49] http://genomicsgtl.energy.gov/biofuels/benefits.shtml

[50] The graph reflects agronomic yields of 3.0, 0.8, and 15.0 dry tons per acre per year for corn, soybeans, and herbaceous energy crops, respectively, as well as net energy balance figures of 1.3, 3.2, and 5.5 respectively.

[51] http://www.ethanolrfa.org/resource/made/

[52] In February 2007, DOE announced six awards totaling $385M in Federal funding for cellulosic ethanol plants: http://www.energy.gov/news/4827.htm. In January 2008, DOE announced four awards totaling $114M in Federal funding for "small-scale" cellulosic ethanol plants: http://www1.eere.energy.gov/biomass/news_detail.html?news_id=11549

[53] http://www.ethanolrfa.org/resource/standard/

[54] http://www.ethanolrfa.org/resource/standard/

[55] http://www.afdc.energy.gov/afdc/vehicles/flexible_fuel.html

[56] http://www.eia.doe.gov/oiaf/aeo/gas.html

[57] http://en.wikipedia.org/wiki/ETBE

[58] http://en.wikipedia.org/wiki/MTBE

[59] WVO or fats can be used exclusively or as a blend with virgin oil stocks; in most instances, initial purification steps are required to deal with the various types and levels of impurities contained in these feedstocks.

[60] http://www.free-press-release.com/news/200903/1237364590.html

[61] "*Biofuel industry path seen getting bumpier*", Arkansas Democrat-Gazette, May 25, 2009.

[62] http://nbb.grassroots.com/09Releases/Production09/

[63] http://www1.eere.energy.gov/biomass/fy04/pyrolysis_oil_upgrad.pdf

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[64] Based on the author's analyses of available data. The volumetric yields are higher than weight-based yields due to addition of hydrogen during the upgrading process and the lower specific gravity of refined fuels compared to biocrude.

[65] http://dynamotive.com/2009/04/22/renewable-gasoline-and-diesel-from-ligno-cellulose-biomass-produced-at-dynamotives-research-facility-in-ontario-canada/

[66] http://www.oilgae.com/

[67] Some links of interest regarding algae include:
National Algae Association http://www.nationalalgaeassociation.com/
Algal Biomass Organization http://www.algalbiomass.org/
A Sober Look at Biofuels From Algae by Biodiesel Magazine,
http://biodieselmagazine.com/article.jsp?article_id=3313
Oil from algae by Journey to Forever: http://journeytoforever.org/biodiesel_yield.html#alg

[68] http://www1.eere.energy.gov/biomass/thermochemical_conversion.html

[69] http://www1.eere.energy.gov/biomass/biochemical_conversion.html

[70] http://www.nrel.gov/biomass/pdfs/overview_biomass_gasification.pdf
http://www.scribd.com/doc/7141717/Biomass-Gasification-Overview-Presentation

[71] The combustion turbine drives an electricity generator. In some instances, the exhaust gases from the combustion turbine are captured and used to make steam, with subsequent additional power generation using a steam-driven turbine – such systems are referred to as combined cycle systems; the combination of power generated from the combined turbine-generators results in increased overall system efficiency (i.e., units of electricity produced per ton of biomass consumed) relative to a single cycle system.

[72] http://www.woodgas.com/gasification.htm;
http://www.gastechnology.org/webroot/app/xn/xd.aspx?it=enweb&xd=iea/homepage.xml;
http://www.nrel.gov/biomass/proj_thermochemical_conversion.html

[73] http://en.wikipedia.org/wiki/Integrated_Gasification_Combined_Cycle

[74] http://www.energy-northwest.com/generation/igcc/technical.php

[75] http://www.pyne.co.uk/?_id=76; http://www1.eere.energy.gov/biomass/printable_versions/pyrolysis.html;
http://www.btgworld.com/index.php?id=22&rid=8&r=rd

[76] http://www.cset.iastate.edu/research-projects/product-distribution-from-fast-pyrolysis-of-biomass.html

[77] *Fast Pyrolysis of Biomass: A Handbook*, by A Bridgwater, S Czernik, J Diebold; 1999 Elsevier Science Ltd

[78] http://www.uop.com/renewables/UOP_Ensyn_Final.pdf

[79] http://www.fao.org/docrep/t4470e/t4470e0a.htm#7.3.%20products%20and%20their%20characteristics

[80] http://dynamotive.com.c9.previewyoursite.com/wp-content/themes/dynamotive/pdf/BlueLeaf_Biochar_Field_Trial_2008.pdf

[81] http://www.carbonchar.com/carbon-sequestration

[82] http://www.eprida.com/presentations/lerdwgcom.pdf

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[83] http://www.eprida.com/hydro/

[84] http://www.popularmechanics.com/science/research/4297513.html

[85] http://en.wikipedia.org/wiki/Fischer-Tropsch_process

[86] http://www.fischer-tropsch.org/primary_documents/presentations/present_pdfs/FT_Fuels_and_Lubricants_History.pdf

[87] http://www.ecn.nl/docs/library/report/2004/rx04119.pdf

[88] http://www.nrel.gov/vehiclesandfuels/npbf/gas_liquid.html

[89] www.**princeton**.edu/pei/energy/publications/texts/Kreutz-et-al-PCC-2008-10-7-08.pdf

[90] http://www.thermalnet.co.uk/docs/ECN_%20Torrefaction%20of%20Biomass%20as%20pretreatmentLille.pdf

[91] http://torrefication.blogspot.com/;http://www.integrofuels.com/; http://www.pelletheat.org/3/institute/2008summerConf/JoeJames.pdf

[92] http://www.ineosbio.com/57-Welcome_to_INEOS_Bio.htm

[93] http://www.energysavers.gov/your_workplace/farms_ranches/index.cfm/mytopic=30003

[94] Overviews of preprocessing economics and technologies are available from Purdue University at http://www.jgpress.com/bcre07/t10.pdf, from DOE's Idaho National Laboratory at http://www.inl.gov/technicalpublications/Documents/3374900.pdf, and from the University of British Columbia at http://www.biocap.ca/rif/report/Sokhansanj_S.pdf.

[95] BioEnergy Systems LLC; March 2009. www.biomass2.com

[96] For example, refer to comprehensive BioFeedstAT analysis, a Biomass Feedstock Assessment Tool, a description of which is available at: www.biofeedstat.com