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Biomass Conversion: Emerging Technologies, Feedstocks, and Products

Research and Development
Sustainability Program

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Credits and Notes

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Cover photos (from left): Switchgrass plants in Oklahoma, 210 cm. in height; ethanol plant in York, Nebraska; and bus in Nebraska that runs on soybean biodiesel. All photographs are courtesy of the National Renewable Energy Laboratory Photographic Information Exchange (www.nrel.gov/data/pix/searchpix.html).

All Internet references in the report were current as of November 9, 2007.

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Frequently Used Terms

Biobased Chemical Feedstock: an industrial chemical produced from biomass.

Biobased Fuel (or "Biofuel"): any fuel used for transportation or other purposes produced from biomass.[1] Biobased fuels are a type of bioenergy.

Biobased Product (or "Bioproduct"): an industrial product produced from biomass, or a commercial or industrial product (including animal feed and electric power) derived through the process of converting biomass to fuel.[2]

Biomass Energy (or "Bioenergy"): any useful, renewable energy produced from organic matter as complex carbohydrates in organic matter are converted to energy. Organic matter may be used directly as a fuel, may be processed into liquids and gases, or may be a residual of processing and conversion.[3]

Biomass: any organic matter that is available on a renewable or recurring basis, including agricultural crops and trees, wood and wood wastes and residues, plants (including aquatic plants), grasses, residues, fibers, and animal, municipal, and other waste materials.[4]

Biopower: electric power or heat derived from direct combustion of biomass feedstock through gasification and then combustion of the resultant gas or through other thermal conversion processes. Power is generated with engines, turbines, fuel cells, or other equipment.[5] Biopower is a type of bioenergy.

Biorefinery: a facility that processes and converts biomass into value-added products, which can range from biomaterials to fuels such as ethanol or important feedstocks for producing chemicals and other materials. Biorefineries can be based on several processing platforms using mechanical, thermal, chemical, and biochemical processes.[6]

Feedstock: a material that is converted to another form or product.[7]

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1 Biomass Research and Development Act, Revised by the Energy Policy Act of 2005, Sec. 303. [7 U.S.C. 7624 note] Definitions, <http://www.brdisolutions.com/initiative/hidden%20pages/1/Developmentaspx>.
2 Ibid.
3 "Bioenergy Feedstock Information Network" (BFIN), <http://bioenergy.ornl.gov>.
4 Biomass Research and Development Act, op. cit..
5 "Bioenergy Feedstock Information Network" (BFIN), <http://bioenergy.ornl.gov>.
6 Ibid.
7 Iowa State University, Office of Renewable Programs, "Glossary of Biorenewable Terms," <http://www.biorenew.iastate.edu/resources/glossary-of-biorenewables-terms.html>.

Abstract

The Biotechnology Matrix and the Biomass System

The centerpiece of this report is a comprehensive matrix (in Appendix C and as an insert in larger format) that presents eight technologies now being developed to convert biomass feed stocks to energy. The matrix displays the biomass system from feedstock through conversion to sugars and other intermediate products, to fuel and energy, and to final products. A variety of products may be created from a given feedstock; similarly, a particular final product may be derived from different feedstocks and conversion technologies. The matrix shows that different energy sources are driving the technologies that convert plant matter into fuel and energy.

This report describes the principal steps in the biomass system: (1) growing and harvesting (or collecting), (2) processing into feedstock, (3) conversion into sugar and other intermediate products, (4) conversion into energy and other final products, (5) distribution of these products, and (6) their use as biofuels, power, and other biobased products. The technical and economic viability of this complex system relies on a reliable feedstock supply, efficient conversion technologies and distribution systems, and effective demand and markets for the byproducts and final energy products.

Introduction

Human Labor, Fossil Energy, Biomass

For millennia humans have supplemented their own labor with energy from draft animals, sun and wind, and burning wood and whale oil – ancient sources of bioenergy. Fossil fuels have supplied energy for specialized purposes for many centuries, but the industrial revolution greatly expanded their extraction and use. Fossil fuels have provided immense quantities of inexpensive and high-density energy, they are finite in quantity, are often buried in inconvenient locations, and release large amounts of carbon dioxide into the atmosphere. In recent years, rising petroleum prices linked to higher drilling costs and an inevitable decline of production – as well as concerns for the environment, rural prosperity, and national security – have heightened interest in biomass (renewable organic matter) as a source of fuel and other forms of energy.

Using biological material for transportation fuel is not new. Seeking a viable alternative to the coal-fired steam engine, Rudolph Diesel used peanut oil in his compression engine in 1898. Vegetable oils were used in diesel engines until the 1920s, when alterations enabled the engines to use a residue of petroleum – what we now call “No. 2 Diesel.” Beginning with the 1908 Model T, Henry Ford designed his automobiles to use ethanol. Convinced that renewable resources were crucial for the success of his business, Ford built an ethanol refinery in Kansas and formed a partnership to sell the biofuel in Standard Oil stations; 25-percent-ethanol fuel became widely used in the Midwest. Despite

Ford's continued promotion of ethanol, biofuels were replaced in the 1940s by lower-priced, aggressively marketed petroleum products.

The Corn Ethanol Boom

From providing just one percent U.S. of the nation's transportation fuel supply in 2000, ethanol production roughly quadrupled by 2007 to an expected 7 million tons, about 3 percent of the nation's vehicle fuels. Ethanol production is likely to soar in the next several years as refineries now under construction or expanding will nearly double current capacity. The Department of Energy expects ethanol to greatly exceed the goal of 7.5 billion gallons of annual domestic renewable fuel production by 2012 set by the 2005 Energy Policy Act. Nearly all of this will be from corn ethanol, which now uses about 18 percent of U.S. corn production. President Bush has set a goal that cellulosic ethanol – refined from the woody plant matter in the rigid cell wall material that makes up the greater part of plants – will be cost-competitive with corn ethanol by 2012. With the further development of cellulosic conversion technologies like those described in this report, the White House goal of producing 35 billion gallons a year of ethanol by 2017 could be attained with less reliance on corn ethanol.

The Promise and Challenge of Cellulosic Biomass

Cellulosic ethanol differs from corn- and other grain-based ethanol in that it may be distilled from the fermentation of sugars from the entire plant, not just from the grains. Cellulosic biomass feedstocks include agricultural plant wastes (corn stover, cereal straws, and sugarcane bagasse), wastes from industrial processes (sawdust and paper pulp) and municipal waste (grass clippings, table scraps), and crops grown expressly for fuel production (switchgrass, sugarcane, and fast-growing trees like poplar and willow). The sugars in cellulose are locked in complex carbohydrates (consisting of long chains of simple sugars) that are generally more recalcitrant to the action of enzymes to separate these complex structures into fermentable sugars. Some of the new and emerging technologies for breaking down forms of cellulosic biomass to sugars for energy production described in this report will likely become key drivers in diversifying ethanol production to meet the wide expectation that cellulosic material will become the dominant ethanol feedstock in coming decades.

I. The Emerging Bioenergy Industry

Since the first major federal funding for renewable biomass-derived energy began in the 1970s,[8] the bioenergy industry has shown economic and technological advances, and political support for the industry continues to grow. This growth is especially notable in more recent years because of a timely convergence of policy, legislation, technology, and investment interest, which has ensured that the industry will be a major consideration in energy and agricultural policies. The National Energy Act (2005) provided guidance for promoting biomass-derived energy. The President's 2006 Advanced Energy Initiative called for improved and alternative 1) transportation fuel, and 2) domestic and workplace power sources;[9] both recommendations feature bioenergy prominently. The President's "Twenty in Ten" energy goal called in 2007 for reducing U.S. gasoline consumption by 20 percent by 2017.[10] Steps toward achieving this goal include (1) increasing the supply of renewable and alternative fuels through a mandatory fuels standard requiring use of 35 billion gallons of renewable and alternative fuels in 2017 and (2) reforming and modernizing corporate average fuel economy (CAFE) standards for cars and light trucks.

The Role of EPA

The 2005 National Energy Act charged the EPA with helping to support diverse research and development as well as the purposes and objectives of the Biomass Act of 2000. The goals and objectives include these:

- Developing technologies for abundant production of competitively priced biobased fuels
- Developing biobased products
- Developing a diverse and sustainable domestic supply of biomass feedstock
- Increasing energy security
- Increasing rural development
- Enhancing environmental and public health, and
- Diversifying markets for raw agricultural and forestry products

Since the passage of these acts, the Office of Research and Development (ORD) has focused on applying sustainability principles to the biomass system, as well as pursuing research and development in areas relevant to the biomass system. EPA's Office of Air and Radiation (OAR) has

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[8] Helena Chum, "Biofuels in the Energy Mix," slide presentation at "The Promise of Energy Independence: Examining National Policy and Regional Action Forum" (University of Maine, October 5, 2005), <http://www.library.umaine.edu/cohen/forum/chum.pdf>.

[9] U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy, "Biomass FAQs," <http://www1.eere.energy.gov/biomass/biomass_basics_faqs.html>.

[10] The White House, "Energy Security for the 21st Century," <http://www.whitehouse.gov/infocus/energy>.

significant responsibilities under the Clean Air Act related to clean fuels, as well as responsibilities under the Energy Policy Act related to renewable fuel standards. Several voluntary OAR programs aim at achieving clean air and reducing greenhouse gas. EPA's Region 7 (Nebraska, Kansas, Iowa, and Missouri) has significant interest in ensuring sustainable biomass production and agricultural practices and biomass production. Region 7 and other EPA Regions are also interested in shifts in land use and other environmental impacts from agricultural practices and biofuel facilities.

Significant research is needed to ensure sustainable biomass production, including research to quantify any potential effluents, emissions, wastes, and net energy use from current and future biomass conversion systems, along with energy and water efficiencies. The impacts of integrated options for feedstock, technology, and distribution on land, water, and energy use ought to be considered in order to sustain the value of long-term investments in certain geographic regions.

Differences among EPA regions will help advance understanding of biomass conversion systems. Because of geographic variations among biomass systems, some regions are more "biomass-rich" in particular categories of biomass, as illustrated by Region 7's abundance of agricultural crops suitable for biofuels. Figure 1 depicts the total national biomass resources available per square kilometer by county in each EPA region. This total biomass estimate includes crop residues; methane emissions from manure management, landfills, and wastewater treatment facilities; forest residues; primary and secondary mill residues; urban wood waste; and dedicated energy crops.[11] All EPA regions, however, have biomass conversion potential that should be understood.

One way of furthering balanced biomass development is to ensure that policymakers, permit writers, and loan grant program directors understand the diverse options of biomass conversion technologies. This report gives context and information about many bioenergy technologies with a particular focus on emerging technologies that are not presently common in commercial applications. It does not

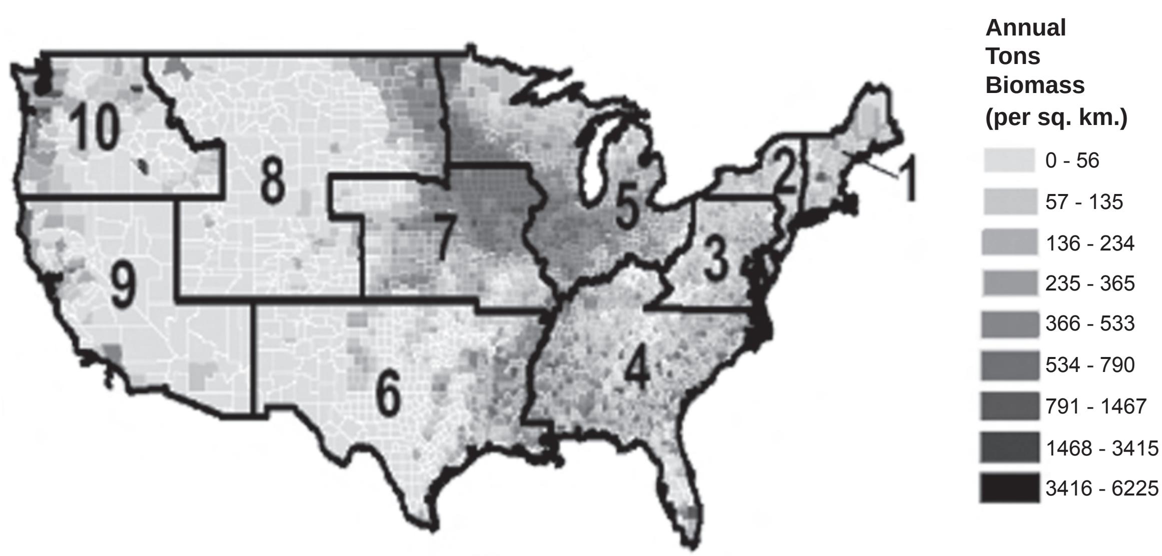

Figure 1. Total Biomass Density in the Continental U.S.
(Data: National Renewable Energy. http://www.nrel.gov/gis/data_analysis.html)

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[11] National Renewable Energy Laboratory, "Dynamic Maps, GIS Data, and Analysis Tools," <http://www.nrel.gov/gis/data_analysis.html>.

cover, for example, the combustion technologies are already playing a large role in the production of biomass power, heat, and combined heat and power (CHP).

The Bioenergy Industry

Political, economic, and technologic circumstances have reshaped the bioenergy industry as a significant contributor to national renewable energy in recent years. Since 2003, energy from biomass has been the leading source of renewable energy production by source in the United States,[12] and 3 percent of the nation's total energy consumption is derived from biomass.[13] Furthermore, biomass use in the industrial sector is expected to increase at a rate of 2 percent annually in the industrial sector and to double every ten years in the electric utility sector.[14]

Collaboration among federal agencies has supported the recent momentum contributing to this increased interest in bioenergy. The Biomass Research and Development Act of 2000 charged federal agencies with the task of coordinating and accelerating "all Federal biobased products and bioenergy research and development."[15] This Act created the Biomass Research and Development Board (BRDB), with representation from the Environmental Protection Agency, the Departments of Agriculture, Energy, Interior, and Transportation, National Science Foundation, Office of Science and Technology Policy, and the Office of the Federal Environmental Executive.[16]

Biofuels

The bioenergy industry has gained momentum in recent years due in part to focused funding and research for ethanol production. Current commercialized technologies for ethanol production are limited in using feedstocks from grains and other carbohydrates. Still, ethanol production in recent decades has increased since the 1980s (Figure 2). Efforts by groups such as the President's Advanced Energy Initiative, the Biomass Research and Development Board, DOE, USDA and the EPA are accelerating research, development, and commercialization of cellulosic ethanol. Proponents of cellulosic ethanol suggest that it will have many benefits over carbohydrate-based ethanol production, including many environmental and economic advantages. (See Appendix B.) Scientists have suggested that further research can make cellulosic ethanol cost-competitive by 2012, offering the potential to displace up to 30 percent of current U.S. fuel use.[17]

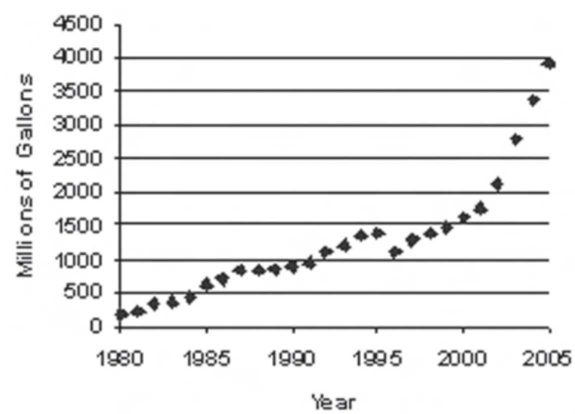

Figure 2. Historic National Ethanol Production
(Data: Renewable Fuel Association)

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12 U.S. Dept. of Energy, Energy Information Agency, Monthly Energy Review, Table 1.2 Energy Production by Source (March 2007), <http://www.eia.doe.gov/emeu/mer/pdf/pages/sec1_5.pdf>.

13 U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program, "Information Resources for Consumers," <http://www1.eere.energy.gov/biomass/for_consumers.html>.

14 U.S. Depts. of Agriculture and Energy, "Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply," (2006), <http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf>.

15 Biomass Research and Development Initiative <http://www.brdisolutions.com >.

16 Ibid.

17 The White House, "State of the Union: Advanced Energy Initiative" (January 31, 2006), <http://www.whitehouse.gov/news/releases/2006/01/20060131-6.html>.

Within the U.S., much of the biofuel emphasis is poised to shift to cellulosic ethanol. Replacing 30 percent of the fuel supply with biofuels will necessitate a dramatic increase of biomass availability. Besides higher yields of grains and seeds, conversion of cellulosic biomass from such non-food sources as fibrous, woody, and inedible portions of plant matter will be required, likely leading to cellulosic biomass eventually replacing corn-based ethanol. Cellulosic feedstocks will use feedstocks such as crop residues, woody biomass, and switchgrass. Driving this shift is the President's commitment to making cellulosic ethanol cost-competitive with corn-based ethanol by 2012.

This transition will call for large supplies of sustainable feedstock, major feedstock and conversion technology advances, large-scale integrated bio-refinery demonstrations, and massive new infrastructure development that will affect land use and ecosystems. Policy and market-based incentives and extensive permitting of new facilities will be needed to facilitate this transition, which is expected to cover the next 25 years. Current corn-based biofuels will dominate commercial use at least until 2012 when the first commercial cellulosic biofuels plants are likely to become operational.[18]

There are many types of biofuels. Though ethanol is today by far the dominant biofuel in production in the U.S., many different types of biofuels are available including biodiesel, methanol, biocrude, and methane.[19] A variety of national policies and goals are supporting all biofuels, not just ethanol. In 2001, just 0.5 percent of total U.S. transportation fuels consumed were biofuels.[20] However, in support of the President's Advanced Energy Initiative, the Department of Energy's National Biofuels Initiative has set a goal that biofuels will provide by 2030 an amount equal to 30 percent of today's U.S. gasoline consumption.[21] In fact, U.S. biodiesel production has greatly increased in recent years (Figure 3). As discussed above, ethanol production also has a large national significance.

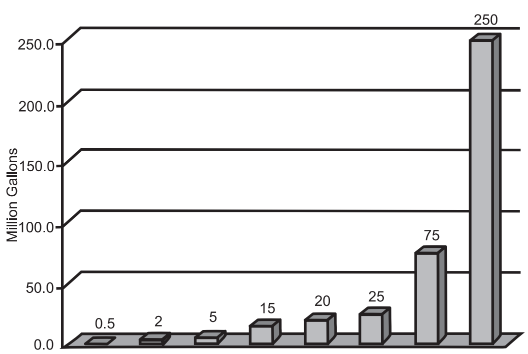

Figure 3. Estimated U.S. Biodiesel Sales
(Data: National Biodiesel Board)

Biofuel production has a global significance. From 2004 to 2005, the total million gallons of ethanol produced worldwide increased by 13 percent, from 10,770 to 12,150 million gallons.[22] Interest in and production of biodiesel production has also increased worldwide. From 2000 to 2005, global biodiesel production has increased fourfold, due in part to huge interest in the EU, where biodiesel accounts for 80 percent of the region's total biofuels production.[23] In March 2007, the United States and Brazil signed a memorandum of understanding to advance cooperation on biofuels", both biodiesel and

[18] U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program, "Biofuels Initiative," <http://www1.eere.energy.gov/biomass/biofuels_initiative.html>.

[19] U.S. Dept. of Energy, National Renewable Energy Laboratory, "Biofuels for Sustainable Transportation" (June 2000), <http://www.nrel.gov/docs/fy00osti/25876.pdf>.

[20] Oak Ridge National Laboratory, "Growth in Biomass Could Put U.S. on Road to Energy Independence" (April 21, 2005), <http://www.ornl.gov/info/press_releases/get_press_release.cfm?ReleaseNumber=mr20050421-01>.

[21] U.S. Dept. of Energy, National Renewable Energy Laboratory, "Biofuels for Sustainable Transportation" (June 2000), <http://www.nrel.gov/docs/fy00osti/25876.pdf>.

[22] Renewable Fuels Association, "Industry Statistics," <http://www.ethanolrfa.org/industry/statistics>.

[23] World Watch Institute, "Biofuels for Transportation: Selected Trends and Facts" (June 7, 2006), http://www.worldwatch.org/node/4081>.

ethanol.[24] Although Brazil is recognized for its leadership in ethanol production, other countries have also significantly increased their biofuel production; Germany, for example, raised its biodiesel production fivefold from 1995 to 2001.[25]

Various crops are grown worldwide for both food and energy uses--corn and soybean in the U.S., flaxseed and rapeseed in Europe, sugar cane in Brazil and palm oil in Southeast Asia. Corn and sugarcane are the predominant feedstocks used to produce ethanol fuels worldwide, while soybeans and rapeseed oils are used to produce biodiesel. The dual use as both food and energy for many of these crops has led to rising market prices for many goods. Most recently, corn prices in the U.S. have risen in response to ethanol-related demand for the crop.[26]

Biomass Conversion Uses Three Types of Technology. Three basic categories of technologies can convert biomass into inert gases and organic oils, gases, and fuels that can be further used to yield desired energy products.

- **Thermochemical technologies** use high temperatures to convert biomass feedstocks to energy, typically in the form of electricity and heat. However, the technologies have the potential to produce electricity, heat, bioproducts, and fuels.
- **Biochemical technologies** use biological agents to convert biomass feedstocks to energy, typically in the form of liquid and gaseous fuels. However, the technologies have the potential to produce electricity, heat, bioproducts, and fuels.
- **Chemical technologies** use chemical agents to convert biomass feedstocks to energy, typically in the form of liquid fuels.

These three biomass conversion technologies are not limited to producing only bioenergy: they may also produce byproducts that, if efficiently managed, can be valuable biobased products.

Biobased Products

Biomass can be converted into products such as chemicals, polymers, animal feed, and construction material, rendering lower-value biomass materials and waste products into higher value products. These biobased products are created from low-value biomass feedstocks, which are often waste products from bioenergy production. Biobased chemical products can be a particularly profitable sector in biobased products. Biobased chemical products are valued as some of the most common and essential chemical feedstocks required in chemical manufacturing. As biomass conversion becomes increasingly popular and the necessary linkages between bioenergy production and bioproduct production are formed, this sector has the potential to grow rapidly.

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24 U.S. Dept. of State, Office of the Spokesman, Fact Sheet, “Advancing Cooperation with Brazil on Biofuels” (March 9, 2007), <http://www.state.gov/r/pa/prs/ps/2007/mar/81589.htm>.

25 U.S. Dept. of Agriculture, Foreign Agricultural Service GAIN Report, “Germany, Oilseeds and Products, Biodiesel in Germany – An Overview” (October 24, 2002), <http://www.fas.usda.gov/gainfiles/200210/145784397.pdf>.

26 U.S. Dept. of Agriculture, Foreign Agricultural Service Circular Series, “Grain: World Markets and Trade, Tightening 2006/7 Global Grain Supplies to Boost Prices” (May 2006), <http://www.fas.usda.gov/grain/circular/2006/05-06/graintoc.htm>.

The Biomass System

Biomass as an energy source is a system of interdependent components. Economic and technical viability of this system relies on a guaranteed feedstock supply, effective and efficient conversion technologies, guaranteed markets for the energy products, and cost-effective distribution systems. (1) The system begins with biomass harvesting (or biomass collection of non-agricultural waste); (2) this biomass is then prepared as feedstock, (3) which is converted to intermediate products. (4) These intermediate products are converted to final energy and other biobased products; (5) which are finally distributed and (6) used for biofuels, biopower, and biobased products. This system is illustrated in Figure 4 and detailed further in the following paragraphs.

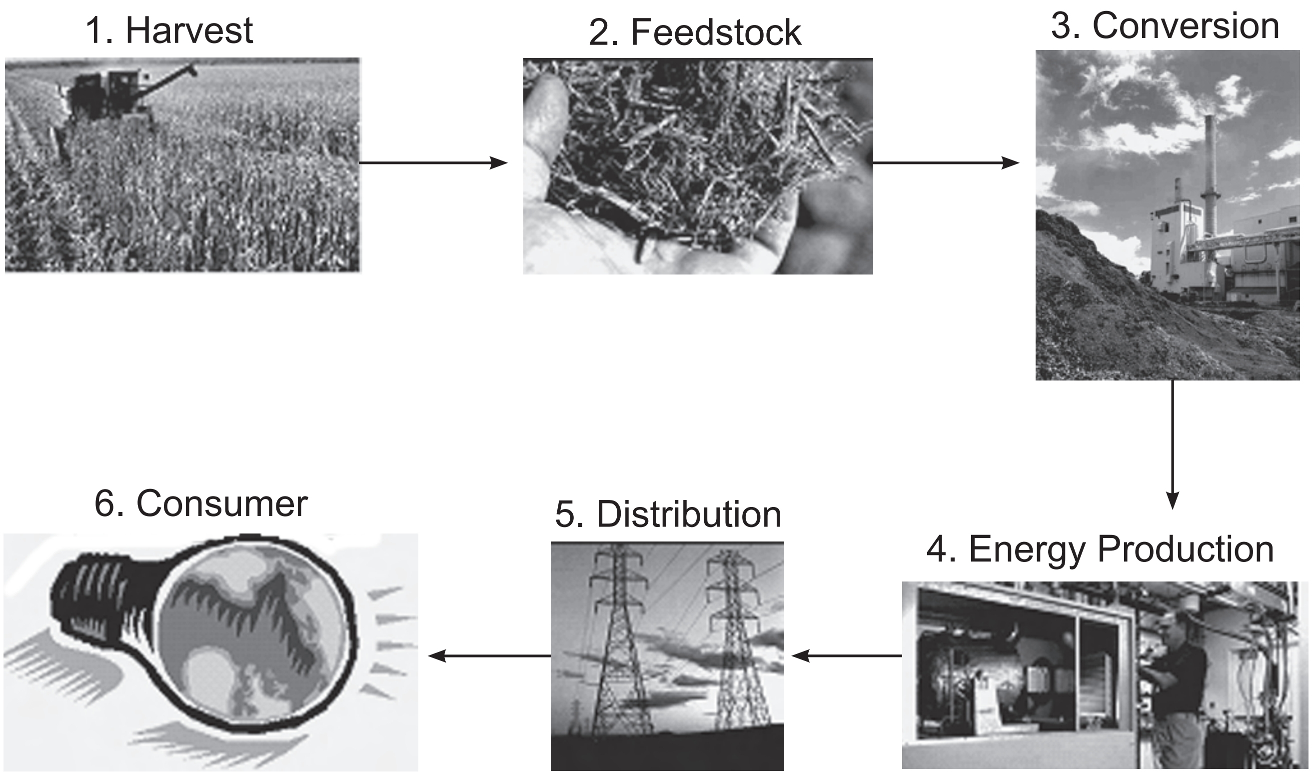

Figure 4. The System of Biomass as an Energy Source

Biomass can be harvested or collected for use as energy (Figure 4.1). Agricultural biomass is harvested and can be used for food and energy, while waste biomass is collected but can be used solely for energy. The synapses between food and energy create special concerns for agricultural biomass. Agricultural crop and forestry systems depend on the inputs of water, nutrients, and seed so that grain and crop residues can be produced. Typically, crop and forestry system products are used for the production of food and lumber, and the subsequent development, harvesting, and dispersal may present environmental challenges. Agricultural energy systems extend this traditional system, and some potential environmental issues are subsequently heightened. Such changes that may accompany this increased production include depletion of water supply and declines in water and soil quality, as well as increases in pesticide concentrations, migration of plantings of genetically modified organisms (GMO), and nutrient overloads.

Feedstocks can be derived from agricultural, forest, or waste products (Figure 4.2). Biomass can come in almost any form. Typical feedstocks include forest residues, agricultural crops and residues, wood and wood residues, aquatic plants, and fast-growing trees and plants. Typical waste feedstocks include municipal solid waste, construction waste, agricultural waste, animal manure, meatpacking waste, food processing waste, spent pulping liquor, cooking oil, paper mill residue, and wastewater treatment sludge. The process through which the biomass is converted to energy is dependent on the chemical composition, homogeneity, size, amount, and water content of the feedstock. Also, geographic location is a consideration, as biomass must be transported from farm to biorefinery. (See the Feedstocks column in Appendix C. Biomass Conversion Matrix.)

Technologies convert feedstock to intermediate products (Figure 4.3). Conversion processes, which include several technologies that decompose biomass into intermediate products, also come in many different forms and configurations. Depending on the feedstock, different methods are needed for conversion into intermediate products. A given feedstock may be appropriate for several different conversion pathways into intermediate products. Conversion technologies may be classified at several levels. At the highest level, feedstock decomposition processes are carried out principally through biochemical, thermochemical, or chemical means. The classification is quite specific and is based on engineering specifications, such as bed placement in a gasifier. Pre-processing techniques can also be used to prepare a feedstock for more efficient conversion. (See Column 1 in Appendix C.)

Intermediate products are converted to final products (Figure 4.4). A primary intermediate product results from each of the feedstock conversion processes. These products are of four principal types: an inert gas, a combustible gas, an oil/tar, and a combustible fuel. Further processing of intermediate products can produce end products, such as electricity, heat, fuels, and chemicals. Many options for converting an intermediate product to high-value end product are commercially available. Such options include: turbines, combustion, distillation, and Fischer-Tropsch catalytic conversion processes. (See Column 3 in Appendix C.)

Final products may face distribution issues (Figure 4.5). Final products such as transportation fuels, electric power, heat, and chemicals often face distribution problems. A closed biorefinery system uses the final products within the facility that supplied the feedstock, such as a cattle farm powered by an anaerobic digester-combustion facility. For an open biorefinery system, by contract, distribution issues must be considered and resolved: for example, the need to meet state and federal regulations for distributed energy in order to resell bioenergy to the grid.[27] In the case of corn-derived biofuel, fuels must be transported, sometimes at great distances, from ethanol production plants to gasoline blending facilities. Some material incompatibilities are associated with product distribution; for example, ethanol can be corrosive to such major infrastructure as storage tanks and pipelines.

Products are delivered to energy consumers (Figure 4.6). In the final step of the biomass to energy process, consumers receive biofuel, biopower, and bioproducts.

The Biorefinery Concept

Biorefineries can integrate preprocessing, conversion, and production processes within a single facility. Like petroleum refineries which process crude petroleum into higher-value products, a

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[27] U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy Distributed Energy Program, “Deployment: Grid Interconnection,” <http://www.eere.energy.gov/de/grid_interconnection.html>

biorefinery is a facility which converts biomass to higher-value products such as electricity, fuels, heat, and chemicals. The biorefinery concept of the National Renewable Energy Laboratory (NREL) builds on two distinct "platforms" that promote distinct groups of products. The sugar platform uses biochemical conversion and focuses on fermenting sugars extracted from biomass feedstocks. The syngas platform uses thermochemical conversion and focuses on gasification of biomass feedstocks and byproducts from conversion processes.[28]

NREL and many other government agencies consider the biorefinery as a viable option through which national security concerns, energy supplies, rural development, sustainability, and conservation efforts may all be addressed. This biorefinery scheme allows for both input and output flexibility according to feedstock supplies and market demands.

[28] National Renewable Energy Laboratory, "Biomass Research: What Is a Biorefinery?" <http://www.nrel.gov/biomass/biorefinery.html>

II. A Biomass Conversion Matrix

The Matrix

This section describes and explains the Biomass Conversion Matrix in Appendix C, providing a framework for understanding the potential for different biomass conversion technologies within a more comprehensive biorefinery infrastructure.

This matrix displays, through stages of their specific energy-conversion processes, many of the most promising among the wide assortment of bioconversion technologies that are not now widely used in commercial applications. Portions if the matrix are presented in the text and the entire matrix is presented in large format in Appendix C – which serves as a map to simultaneously display important features of the previously discussed system of using biomass as an energy source. The matrix displays the system from feedstock through conversion technology, intermediate product, and product-to-energy conversion method, to energy product. Each feedstock may be used to create a large variety of products, and likewise, a single product may be derived from many different feedstocks and conversion technologies. Thus, it is important to understand the matrix as a system.

The matrix is reproduced in a smaller format in Figure 5, which shows the major matrix features. It is a two-dimension table, with one axis corresponding to levels and sub-levels of conversion technology classification. The other axis specifies the feedstock, intermediate products, product-to-energy conversion method, and energy products of each conversion technology.

Eight Biomass Conversion Technologies

The eight conversion technologies examined in this report have been selected because of their relatively advanced state of development and expected future contribution to bioenergy. These emerging technologies all have solid promise, with some already well established. (This list omits combustion technologies such as stoker boilers and fluidized bed boilers that are already widely used in commercial applications.[29])

Gasification is a thermochemical decomposition process through which biomass or other organic matter is converted to a gaseous state in the limited presence of oxygen.[30]

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[29] For detailed technical information on commercial conversion technologies for biomass power and hear, see U.S.EPA, Combined Heat and Power (CHP) Program, “Catalog of CHP Technologies” (2007) <http://www.epa.gov/chp/basic/catalog.html>.

[30] U.S. Dept of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program, Technologies, “Biomass Gasification” <http://www1.eere.energy.gov/biomass/gasification.html>.

Conversion technologies platforms are classified according to decomposition process, and engineering specifications.

Appropriate feedstocks correspond to each conversion technology.

Resulting products correspond to each conversion technology.

			1. Biomass Conversion Technology	2. Feedstocks	3. Products
Thermochemical	Gasification	Fixed Bed	Downdraft Co-Current Fixed Bed Updraft Co-Current Fixed Bed Cross-Draft Fixed Bed Open Core Fixed Bed	**Any Organic Material** Examples: Agricultural wastes, hazardous organic wastes, industrial wastes. **Pretreatment:** Waste typically segregated. **Qualifications:** Dry MSW is favorable. Coal size distribution must be controlled to ensure good bed permeability. **Final Conversion Technology (Optional):** Fischer-Tropsch Catalytic Conversion	**Intermediate Products:** Combustible gases, liquids, tars, and inert fluidizing gases. **Final Products:** Electricity, Thermal Energy, Hydrogen, Ethanol and other alcohols, Diesel type fuels, Gasoline. **Co-products:** Charcoal, Ash, Carbon Dioxide.
		Fluidized Bed	Pressurized Circulating Fluidized Bed Atmospheric Circulating Fluidized Bed		
		Novel Design	Plasma Arc Gasifier 2-stage Gasifier Open Top Aqueous Phase Reforming		
	Pyrolysis	Fast Pyrolysis	Ablative Fast Pyrolysis Cyclonic Fast Pyrolysis Rotating Core Fast Pyrolysis Open Core Fast Pyrolysis	**Any Organic Material** **Pretreatment:** Sorting **Qualifications:** None	**Intermediate products:** Syngas and Charcoal **Final Products:** Bio-Oil and Charcoal **Co-products:** Electricity and Thermal Energy
		Slow Pyrolysis	Vacuum Pyrolysis Flash Pyrolysis	**Any Organic Material** **Pretreatment:** Sorting. **Qualifications:** Waste must be pre-sorted and processed to <6 mm (1 to 2 mm. preferred) and <10% moisture content to assure high heat transfer rate.	
Biochemical	Ethanol Production		Wet-Mill Fermentation	**Grains** Mostly: Corn **Pretreatment:** Separation of the oil, protein, fiber and the bulk of the nutrients from the starch	**Intermediate Products:** Mash, Sugar **Final Products:** Ethanol **Co-products:** Distillers grains plus solubles, Carbon Dioxide
			Dry-Mill Fermentation	**Grains, Sugars and Waste , Starches and Sugars** Examples: Grains (corn, sorghum, barley), Sugars (Sugarcane and beets), Beer, and other waste sugars and starches. **Pretreatment:** Grinding, cooking and fermentation	**Intermediate Products:** Starch, Sugar **Final Products:** Ethanol **Co-products:** Corn oil, corn gluten meal, corn gluten feed, carbon dioxide, liquid bio-fertilizers
			Lignocellulosic Biomass Fermentation	**Cellulosic/Woody Biomass** **Pretreatment:** Hydrolysis (Dilute Acid, Concentrated Acid, Enzymatic, Steam explosion)	**Intermediate Products:** Cellulose, hemicellulose. lignin **Final Products:** Ethanol **Co-products:** Carbon Dioxide, residual cellulose and lignin, electricity and thermal energy
	Anaerobic Digesters	Mesophilic Process or Thermophilic Process	Anaerobic activated sludge process Anaerobic clarigester Anaerobic contact process Anaerobic expanded-bed reactor Anaerobic filter Anaerobic fluidized bed Anaerobic lagoon Anaerobic migrating blanket reactor Batch system anaerobic digester Expanded granular sludge bed digestion Hybrid reactor Imhoff tank One-stage anaerobic digester Submerged media anaerobic reactor Two-stage anaerobic digester Upflow anaerobic sludge blanket digestion Upflow and down-flow anaerobic attached growth	Almost any organic material: paper, grass clippings, leftover food, sewages, animal wastes; and other forms of biomass such as distillers grains. **Pretreatment:** Sorting or screening to remove inorganic material. **Qualifications:** The material may need to be pre-processed and water added. . .	**Intermediate products:** N/A. **Final Products: Biogas,** Thermal Energy, Digestate. Co-products: Liquid and Solid Biofertilizers. .
	Landfill		Bioreactor vessel	**Organic Wastes** **Pretreatment:** Sorting pre-treatment **Qualifications:** The waste must be contained, compacted and covered in a vessel	**Intermediate products:** Biogas composed of Methane, Carbon Dioxide, Nitrogen, Hydrogen, Hydrogen Sulfide and Oxygen. **Final Products:** Electricity, thermal energy, methane. CNG or LNG for vehicle fuel. **Co-products:** Carbon Dioxide for possible use in greenhouse operations, and Biofertilizers.
			Landfill Site	**Organic Wastes** **Pretreatment:** None **Qualifications:** None	
	Aerobic		Static Pile Enclosed Compost Turned Window In-Vessel Compost Transesterification	**Practically any Organic Waste** **Pretreatment:** Sorting **Qualifications:** A separation between organic and contaminants is necessary.	**Intermediate products:** None **Final Products:** Valuable Compost **Co-products:** Heat and Carbon Dioxide. (May be useful in a greenhouse environment or for heating)
Chemical	Biodiesel Production			**Oils, fats, used cooking oils, greases, methanol or ethanol and a catalyst** **Pretreatment:** Used cooking oils, yellow greases, and some tree oils are taken through an esterification process to remove fatty acid that should, preferably, be reduced to less than 1% (at least below 4%). **Qualifications:** Essentially any bio-oil, animal fat or tallow, used cooking oil, yellow/trap grease, plant or tree oil can be converted into biodiesel if the fatty acid content is low enough.	**Intermediate Products:** Oils fats or greases taken through transesterfication **Final Products:** Biodiesel **Co-products:** Glycerin, Soaps

Figure 5. Biomass Conversion Matrix
(See Appendix C. for enlargement of this matrix.)

Pyrolysis (as used in this report) is a thermochemical decomposition process through which biomass or other organic matter is converted to a mixture of oil, gases, and carbon residues in the complete absence of oxygen.[31]

Starch and sugar fermentation is a direct biochemical decomposition process through which glucose-containing material is chemically decomposed in the presence of oxygen using enzymes to form ethanol and carbon dioxide[32]. The method requires no or minimal preprocessing.

Lignocellulosic biomass fermentation is a biochemical decomposition process through which biomass containing lignin, cellulose, and/or hemicellulose is pretreated to break into component sugars, and then is chemically decomposed to form ethanol and carbon dioxide[33]. The method includes the use of a saccharification step, in which calcitrous feedstock is preprocessed into fermentable sugars. Once preprocessed, this type of biomass is fermented as in "3, Starch and Sugar Fermentation" in preceding paragraph. (Appendix A illustrates how the process of starch and sugar fermentation differs from lignocellulosic biomass fermentation.).

Transesterification is a chemical reaction through which alcohol groups from an alcohol catalyst bond to fatty acids from oils, fats, and greases. This process both reduces the viscosity of the fatty acids and converts them to a combustible form. Esterification is a pretreatment process sometimes necessary to prepare the fatty acids for transesterification.[34]

Anaerobic digestion is a biochemical process through which biomass or other organic matter is consumed by bacteria and subsequently released in a gaseous state. This process occurs in the absence of oxygen.[35] Different types of bacteria can be used for this process: psychrophilic, mesophilic or thermophilic processes, depending on bacterial affinity for cool, intermediate or warm temperatures, respectively.

Landfill gas collection is a process through which gaseous effluent is collected from decomposing organic material at a waste disposal site. The waste decomposes under naturally anaerobic or manipulated aerobic conditions, and produces primarily methane and carbon dioxide. Gas is then collected from landfills.[36]

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31 U.S. Dept of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program, Technologies, "Pyrolysis and Other Thermal Processing" <http://www1.eere.energy.gov/biomass/pyrolysis.html>. Some technical literature refers to the first step in biomass gasification as "pyrolysis," but this is not the same process as the pyrolization of biomass discussed in this report. See Anthony V. Bridgwater, "Biomass Fast Pyrolysis," Thermal Science 8 (2004), 21-49, <http://thermalscience.vin.bg.ac.yu/pdfs/2004-2/TS22004Cl2.pdf>.

32 State of Oregon, Biomass Energy Home Page, "Biofuels Technologies," <http://www.oregon.gov/ENERGY/RENEW/Biomass/biofuels.shtml>.

33 Ibid.

34 U.S. Dept of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program, Other Platforms (2006), <http://www1.eere.energy.gov/biomass/other_platforms.html>; National Biodiesel Board, "Biodiesel Production," <http://www.biodiesel.org/pdf_files/fuelfactsheets/production.pdf>., Hideki Fukuda et al, "Biodiesel Fuel Production from Transesterification of Oils," Journal of Bioscience and Bioengineering, 92/5 (2001), 405-416, <http://www.jstage.jst.go.jp/article/jbb/92/5/405/_pdf>.

35 U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program, Other Platforms (2006), < www1.eere.energy.gov/biomass/other_platforms.html >.

36 U.S. Environmental Protection Agency, "Landfill Methane Outreach Program," <http://www.epa.gov/lmop>.

Aerobic digestion is a biochemical process through which organic matter is converted to thermal energy and fertilizer in the presence of oxygen.[37] Aerobic digestion is also called composting.

Classifying Biomass Conversion Technologies

This report presents a classification system that is intended to aid in clarifying future discussions of biomass conversion technologies. There are three main levels of classification used to catalogue conversion technologies in this report. First technologies are classified by method of decomposition, then by process specifications, and finally, by engineering design specifications. This cataloguing system is illustrated in Figure 6 and is detailed in the following section.

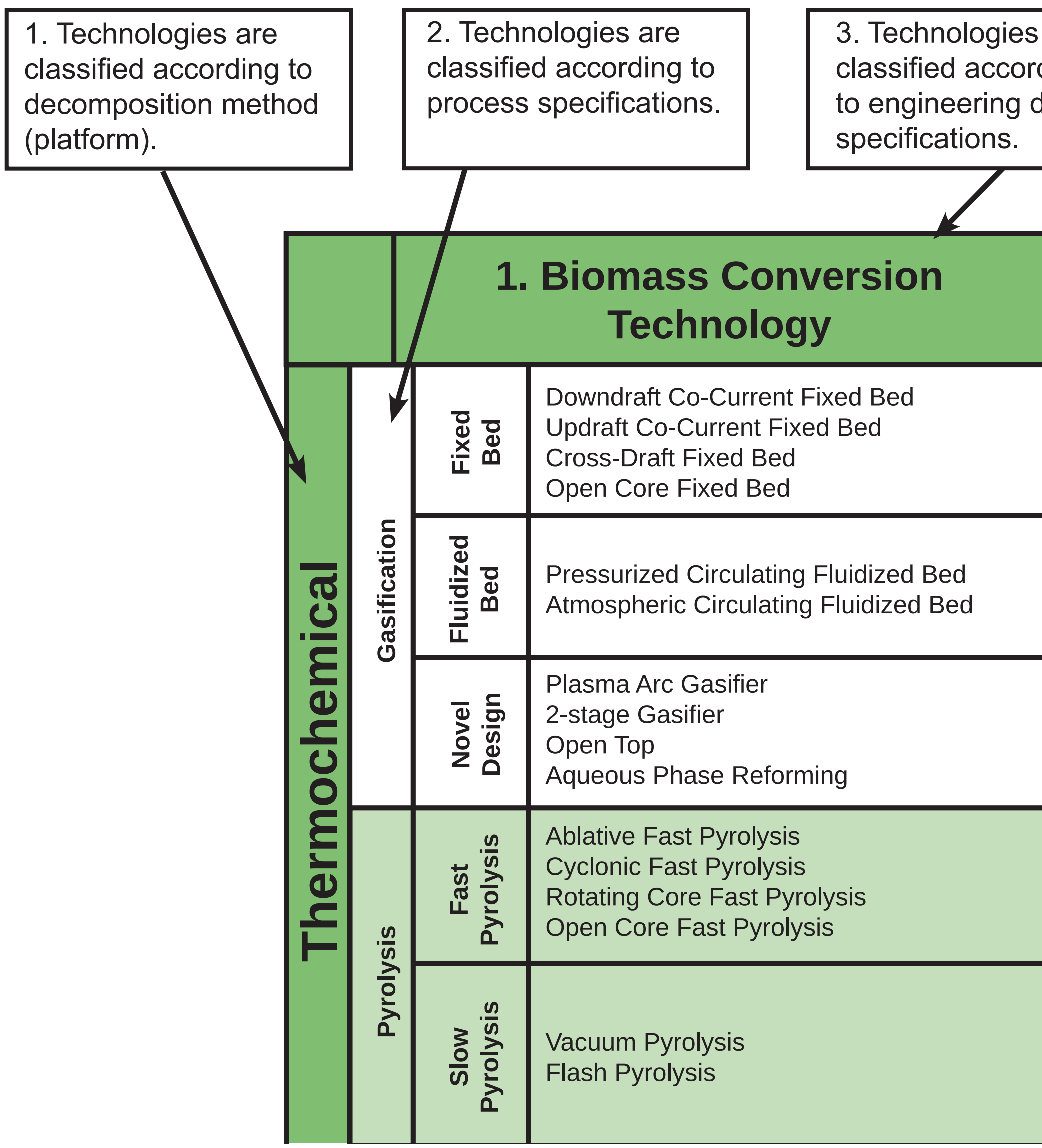

Figure 6. Biomass Conversion Technologies

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[37] Ohio State University, Extension Bulletin, Bulletin 604-06, Chapter 4, Treatment and Utilization Options for Livestock Manure," Ohio Livestock Manure Management Guide , <http://ohioline.osu.edu/b604/0005.html>; U.S. Environmental Protection Agency, "Composting," <http://www.epa.gov/epaoswer/non-hw/composting/basic.htm>.

First Classification Level: Method of Decomposition. On the highest level, the matrix classifies technologies according to the principal methods of decomposition.[38] This classification is illustrated in Table 1 below.

Table 1. Technologies and Methods of Decomposition

Technology	Method of Decomposition
Thermochemical	Uses heat to decompose feedstock into intermediate products. Thermochemical conversion technologies include gasification and pyrolysis.[39]
Biochemical	Uses enzymes and bacteria to decompose feedstock into intermediate products. Biochemical conversion technologies include starch and sugar fermentation, lignocellulosic fermentation, anaerobic digestion, landfill gas collection, and aerobic digestion.[40]
Chemical	Uses chemical reactions to decompose feedstock into intermediate products. The principal chemical conversion technology is transesterification.[41]

Physical processes, such as sorting, shredding, and drying, may sometimes also be necessary to prepare feedstock for the main thermochemical or biochemical conversion process.[42]

Second Classification Level: Process Specification. Conversion technologies are also classified according to process-specific conditions such as presence of oxygen, type of feedstock, and type of chemical reaction. This is the level of nomenclature that is most commonly used for policy and management publications. In some cases, several different technical classifications could have been

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[38] U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program, Biomass Basics (2006), <http://www1.eere.energy.gov/biomass/biomass_basics.html>; U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program, Other Platforms (2006), <http://www1.eere.energy.gov/biomass/other_plat forms.html; Oregon State Department of Energy, Biomass Energy Program Biomass Technology Chart, <http://www.oregon.gov/ENERGY/RENEW/Biomass/BiomassHome.shtml#chart>.

[39] U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program, Biomass Basics (2006), <http://www1.eere.energy.gov/biomass/biomass_basics.html>.

[40] Ibid.

[41] U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program, Other Platforms (2006), <http://www1.eere.energy.gov/biomass/other_platforms.html>.

[42] Phillip C. Badger, Processing Cost Analysis for Biomass Feedstocks (U.S. Dept. of Energy, Oak Ridge National Laboratory, 2002), <http://bioenergy.ornl.gov/pdfs/ornltm-2002199.pdf>.

made, however, one was chosen for the purpose of simplicity and consistency with policy publications. This classification is illustrated in Table 2 below.

Table 2. Technologies and Process Specifications

Technology	Process Specification
Thermochemical	Distinguished by the presence or absence of oxygen in the system.[43] • The presence of oxygen indicates gasification • The absence of oxygen indicates pyrolysis
Biochemical	Distinguished by the type of feedstock.[44] • Starch and sugar feedstock indicates starch and sugar fermentation • Lignocellulosic biomass indicates lignocellulosic fermentation • Wet feedstocks (typically animal manure) indicate anaerobic digestion • Drier organic feedstocks indicate aerobic digestion • Municipal solid wastes indicate landfill gas collection.
Chemical	Distinguished by the specific type of chemical reaction which occurs[45] • e.g., transesterification

Third Classification Level: Engineering Specifications. Conversion technologies may also be distinguished according to engineering design specifications—a level of technical detail not covered by most policy and management publications.

Gasification processes can be loosely categorized as fixed bed, fluidized bed, or "novel" designs. These process designs can be modular in nature, facilitating their use in small businesses, rural areas, developing countries, and biorefineries.[46] These modular designs would also facilitate integration

[43] U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program, Biomass Basics (2006), <http://www1.eere.energy.gov/biomass/biomass_basics.html>.
[44] U.S. Dept. of Energy, Oak Ridge National Laboratory, Bioenergy Feedstock Development Program Bioenergy Feedstock Characteristics, <http://bioenergy.ornl.gov/papers/misc/biochar_factsheet.html>; Oregon State Department of Energy, Biomass Energy Program Biomass Technology Chart, Oregon: Biomass Energy Program, <http://www.oregon.gov/ENERGY/RENEW/Biomass/BiomassHome.shtml#chart>.
[45] Oregon State Department of Energy, Biomass Energy Program, Biomass Technology Chart, <http://www.oregon.gov/ENERGY/RENEW/Biomass/BiomassHome.shtml#chart>.
[46] .S. Dept. of Energy, National Renewable Energy Laboratory, Biomass Factsheet: Small Modular Biomass Systems (2002), <http://www.nrel.gov/docs/fy03osti/33257.pdf>.

with other types of technologies in biorefineries. This classification of gasifier engineering design specifications is illustrated in Table 3 below.

Table 3. Gasification Types and Engineering Designs

Gasification Type	Engineering Design
Fixed Bed	Feedstock is placed on a static grate and heated while a gasification agent, such as nitrogen, is circulated through the gasifier. Variations of fixed bed gasification technologies employ different configurations of pressure and gas-flow direction.[47] Examples include downdraft co-current fixed bed gasifier, updraft co-current fixed bed gasifier, updraft counter-current fixed bed gasifier, cross-draft fixed bed gasifier, and open core fixed bed gasifier.
Fluidized Bed	Feedstock is heated and suspended directly in the gasification agent, without a static grate. Fluidized bed gasification technologies may employ different configurations of pressure and gas flow.[48] Examples include pressurized circulating fluidized bed gasifier and atmospheric circulating fluidized bed gasifier.
Novel Designs	A category of miscellaneous gasifiers, including the following processes: plasma arc gasification, 2-stage gasification, open-top gasification, and aqueous phase reforming gasification.

Pyrolysis processes can be categorized as slow pyrolysis or fast pyrolysis. Fast pyrolysis is currently the most widely used pyrolysis system. This classification of pyrolysis system engineering design specifications is illustrated in Table 4 below.

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[47] Biomass Technology Group (2004), Biomass Gasification, <http://www.btgworld.com/technologies/gasification.html>; U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program (2005) Biomass Gasification, <http://www1.eere.energy.gov/biomass/gasification.html>; International Energy Agency, Gasification Network, Technology (2005), <http://www.gasnet.uk.net/index.php?name=VGVjaG5vbG9neQ==&open=VGVjaG5vbG9neQ== >; Alexander Klein. Gasification: an Alternative Process for Energy Recovery and Disposal of Municipal Solid Wastes (Unpublished M.S. thesis, Columbia University, 2002), <http://www.seas.columbia.edu/earth/kleinthesis.pdf>.

[48] International Energy Agency, Gasification Network, Technology (2005), <http://www.gasnet.uk.net/index.php?name=VGVjaG5vbG9neQ==&open=VGVjaG5vbG9neQ== >; Klein, ibid.

Table 4. Pyrolysis Types and Engineering Designs

Pyrolysis Type	Engineering Design
Slow Pyrolysis	Converts organic material slowly to tar in the complete absence of oxygen. Compared to fast pyrolysis, slow pyrolysis is very time-consuming and produces low yields of tar-derived products.[49]
Fast Pyrolysis	Converts organic material rapidly to the gaseous state in the absence of oxygen, and then condenses the gas into either bio-oil or hydrogen.[50] Fast pyrolysis processes include open-core fixed bed pyrolysis, ablative fast pyrolysis, cyclonic fast pyrolysis, and rotating core fast pyrolysis systems.

Starch and sugar fermentation is a biochemical decomposition process through which glucose-containing material is chemically decomposed to form ethanol and carbon dioxide. This fermentation process can be categorized as either wet-mill or dry-mill fermentation processes. This classification of starch and sugar fermentation design specifications is illustrated in Table 5 below.

Table 5. Starch and Sugar Fermentation Types and Engineering Designs

Starch and Sugar Fermentation Type	Engineering Design
Wet Mill	The corn is soaked in water or dilute acid to separate the grain into its component parts (e.g., starch, protein, germ, oil, kernel fibers) before converting the starch to sugars that are then fermented to ethanol.[51]
Dry Mill	The kernels are ground into a fine powder and processed without fractionating the grain into its component parts. Most ethanol comes from dry milling.[52]

Lignocellulosic biomass fermentation is a biochemical decomposition process through which lignin-, cellulose-, and/or hemicellulose-containing biomass is chemically decomposed to form ethanol and carbon dioxide. Lignocellulosic biomass fermentation processes are similar enough that

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49 Wisconsin Biorefining Development Initiative, Biorefining Process: Fast Pyrolysis (2007), <http://www.wisbiorefine.org/proc/fastpyro.pdf>.

50 International Energy Agency, Pyrolysis Network Overall Fast Pyrolysis Process, <http://www.pyne.co.uk/?_id=71>; International Energy Agency, Pyrolysis Network Reactors: Bubbling Fluid Beds, <http://www.pyne.co.uk/?_id=69>; U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program, Pyrolysis and Other Thermal Processing (2005), <http://www1.eere.energy.gov/biomass/pyrolysis.html>.

51 Wisconsin Biorefining Development Initiative, Biorefining Process: Wet Mill Corn Processing (2007), <http://www.wisbiorefine.org/proc/wetcorn.pdf>.

52 Wisconsin Biorefining Development Initiative, Biorefining Process: Dry Mill Corn Processing (2007), <http://www.wisbiorefine.org/proc/drycorn.pdf>.

they are rarely divided into subtypes. There are several different pretreatment options available for lignocellulosic biomass, which are described in greater detail in Appendix C.

Transesterification is a chemical conversion process through which oils and fats are converted to methyl ester, also known as biodiesel. Transesterification is rarely subdivided into further classifications.

Anaerobic digestion processes can be categorized as psychrophilic, mesophilic or thermophilic, according to the affinity of bacteria for cool, intermediate or warm temperatures, respectively. This classification of anaerobic digester engineering design specifications is illustrated in Table 6 below.

Table 6. Anaerobic Digestion Types and Engineering Designs

Anaerobic Digestion Type	Engineering Design[53]
Psychrophilic or "low-temperature digestion"	The natural decomposition path for manures at temperatures found in lagoons. These temperatures vary from about 38 to 85°F (3 to 29°C). Biogas production will vary seasonally with variations in lagoon temperature. Uncovered lagoons in the U.S. typically operate in the psychrophillic range.
Thermophilic	Uses digesters to promote bacteria that grow at temperatures between 135 and 155°F (57 to 68°C). These digesters are heated and biogas production will not vary seasonally. This type of digestion is unusual due to the high cost to maintain temperatures in this range.
Mesophilic	Cultivates bacteria that have peak activity between 90 and 105°F (32 to 40°C). These digesters are heated and biogas production will not vary seasonally. Most United States energy-recovery digesters operate in the mesophilic range.

Landfill gas can be collected from sites categorized as bioreactor vessels or landfill sites. These sites release methane as a product of the natural or artificial decomposition of landfill material. This classification of the engineering design specifications of landfill gas collection sites is illustrated in Table 7 below.

[53] Energy and Environmental Analysis, Inc. and Eastern Research Group, Inc. Biomass Combined Heat and Power Catalog of Technologies. Washington: U.S. Environmental Protection Agency Office of Air and Radiation, Combined Heat and Power Partnership, 2007 (unpublished draft)

Table 7. Landfill Gas Collection Types and Engineering Designs

Landfill Gas Collection Type	Engineering Design
Bioreactor Vessels	A landfill that is manipulated with the addition of liquid or air, so as to facilitate rapid decomposition[54] This optimization of the natural decomposition process results in rapid gas formation.
Landfill Sites	Traditional locations of solid waste disposal in the United States. These sites can include sanitary landfills and sanitary landfills re-circulating leachate.[55]

Aerobic digestion processes can be categorized as static pile, enclosed compost, in-vessel compost, and turned wind-roll composting systems. Some designs can also be modular, for easy application to small business operations, rural areas, developing countries, and biorefineries. These methods can be used in conjunction with many facilities, including aerobic digestion of biosolids from wastewater treatment plants.[56] This classification of aerobic digestion engineering design specifications is illustrated in Table 8 below.

Table 8. Landfill Gas Collection Types and Engineering Designs

Aerobic Digestion Type	Engineering Design[57]
Static pile (passive windrow)	A low-tech and labor-efficient approach to making compost. However, the process is time-intensive, as compost is produced by natural aeration.
Enclosed compost vessel (bin compost)	A low-tech, moderately labor-efficient approach to making compost. The compost is formed through natural aeration and turning.
In-vessel compost system	Produces compost in drums or other vessels. The system is a high-tech and labor efficient approach, as the vessels are aerated automatically with machines.
Turned windrow compost system	Produces compost in piles. The piles are mechanically aerated and are thus a low-tech and medium-labor option.

54 U.S. Environmental Protection Agency, Office of Solid Waste, Municipal Solid Waste: Bioreactors (2006), <http://www.epa.gov/epaoswer/non-hw/muncpl/landfill/bioreactors.htm>.

55 Energy and Environmental Analysis, Inc. and Eastern Research Group, Inc., op. cit.

56 U.S. Environmental Protection Agency, Biosolids Generation, Use, and Disposal in the United States (1999), <http://www.epa.gov/epaoswer/non-hw/compost/biosolid.pdf>.

57 British Columbia (Canada) Ministry of Agriculture, Food, and Fisheries, Composting Factsheet: Composting Methods (1996), <http://www.agf.gov.bc.ca/resmgmt/publist/300series/382500-5.pdf>.

Feedstock and Pretreatment

Conversion technologies are designed to accept specific types of feedstock for optimal processing. Feedstocks can include oils, fats, greases, sludge, sugars, starches, lignocellulosic biomass, biosolids, municipal solid waste, and woody biomass. These feedstocks are included in the Appendix C matrix, as illustrated below in Figure 7.

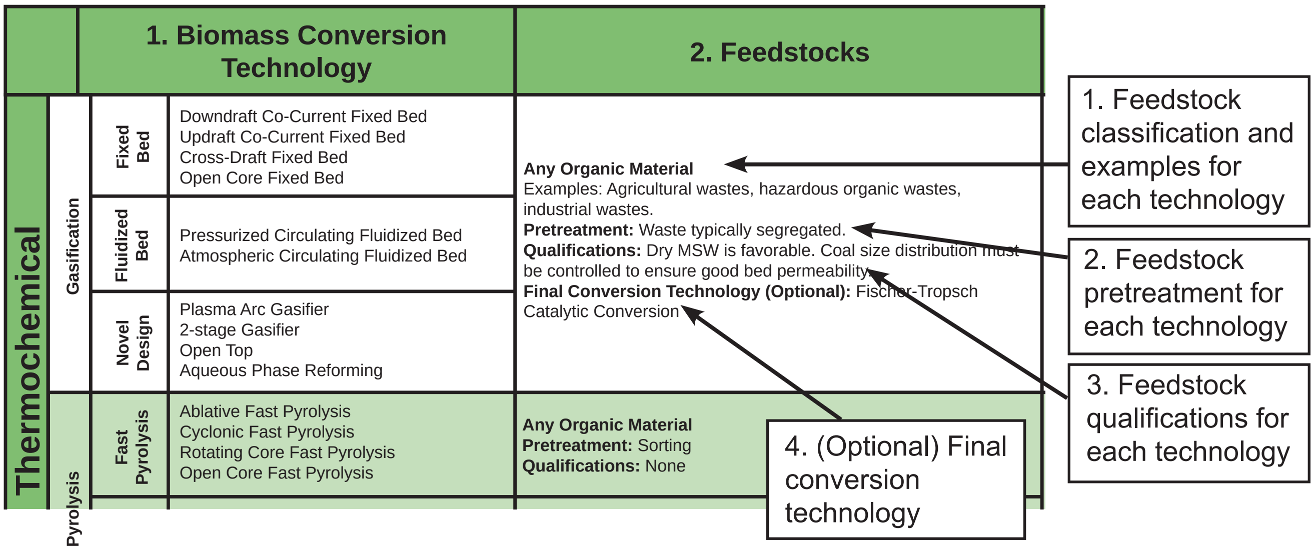

Figure 7. Feedstocks for Biofuels, Bioenergy, and Bioproducts
(See Appendix C for greater detail.)

Particular feedstocks may also need to be prepared through specific physical processes, such as sorting, shredding, hydrolysis, or drying. This section also discusses the feedstocks appropriate for certain technologies, and includes pretreatment options and feedstock qualifications.

Gasification systems can accept any organic material, including agricultural wastes, black liquor from pulping operations, hazardous organic wastes, and industrial wastes. Dry, uniformly sized organic material is preferable. This organic material is typically segregated in a pretreatment process before gasification.[58]

Pyrolysis systems can accept any organic material, including agricultural wastes and municipal solid wastes. For fast pyrolysis systems, dry, sorted, and homogeneously sized (<6mm) organic material typically achieves a high heat transfer rate.[59]

Starch and sugar fermentation systems can accept any sugar- or starch-containing material such as grains, sugarcane, beets, beer, and waste sugars. Typically, wet-mill fermentation uses grains, while dry-mill fermentation uses grains, sugars, starches, and sugar wastes. In wet-mill fermentation, grains

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58 Emanuele Scoditti and N. Parker, "IEA Bioenergy Agreement, Task 33: Thermal Gasification of Biomass, Review of Energy Conversion Devices" (2003), < http://media.godashboard.com/gti/IEA/ReviewofEnergyConversionDevicesrev.pdf>.; Wisconsin Biorefining Development Initiative, Biorefining Process: Biomass Gasification (2007), <http://www.wisbiorefine.org/proc/biomassgas.pdf>.

59 Wisconsin Biorefining Development Initiative, Biorefining Process: Fast Pyrolysis (2007), <http://www.wisbiorefine.org/proc/fastpyro.pdf>.

are preprocessed, so as to separate the oil, protein, fiber, and nutrients from the starch. In dry-mill fermentation, the grains are grinding and cooking before fermentation.[60]

Lignocellulosic biomass fermentation systems can accept any lignin-, cellulose-, and/or hemicellulose-containing material, including forest residue, crop residue, and switchgrass. Lignocellulosic material should be preprocessed in order to break lignocellulosic material into sugars. This is most commonly achieved though hydrolysis, a process in which water is used to break apart a chemical compound. Common types of hydrolysis include dilute acid hydrolysis, concentrated acid hydrolysis, enzymatic hydrolysis, and steam explosion.[61]

Transesterification systems can accept any oil, fat, or grease, including used cooking oils, animal fat, and plant oils. Typically, feedstocks with fatty acid content exceeding 4 percent must be pretreated in an esterification process—a chemical process that reduces the fatty acids in the feedstock to an acceptable concentration for the transesterification reaction.[62]

Anaerobic digestion systems can accept any organic material, including sewage, animal wastes, grass clippings, and paper. Wet organic material is favorable, and water may be used to moisten dry material. The material may need to be preprocessed to remove inorganic material.[63]

Landfill gas collection systems can accept any organic material, including agricultural wastes, and organic municipal solid wastes. Because landfill gas is a product of natural decomposition, the higher the organic content of the waste, the more methane is produced. This organic material is typically segregated before being landfilled.

Aerobic digestion systems can accept any organic material, including agricultural wastes, manures, and food waste. The organic material is typically separated from inorganic contaminants before being digested.[64]

Final Processing: Intermediate, Final, and Co-products

Intermediate products consist of output from the primary conversion processes; these intermediate products require further processing to obtain the desired final products. Principal intermediate products include: pyrolytic bio-oil, combustible gas, inert gases, pelletized feedstock, fertilizer, lipids, biodiesel, steam, methane, ethanol, and butanol. These products are then processed and converted into the desired final energy product using technologies such as turbines, engines, and boilers. The final products that result from this processing and conversion include electricity, heat, and fuel.

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60 Wisconsin Biorefining Development Initiative, Biorefining Process: Dry Mill Corn Processing (2007) <http://www.wisbiorefine.org/proc/drycorn.pdf>; ibid, Biorefining Process: Wet Mill Corn Processing, <http://www.wisbiorefine.org/proc/wetcorn.pdf>.; ibid, Biorefining Process: Fermentation of 6-Carbon Sugars and Starches, <http://www.wisbiorefine.org/proc/fermentss.pdf>.

61 Wisconsin Biorefining Development Initiative, Biorefining Process: Fermentation of Lignocellulosic Biomass (2007), <http://www.wisbiorefine.org/proc/fermlig.pdf>.

62 Wisconsin Biorefining Development Initiative, Biorefining Process: Esterification/ Transesterification (2007), <http://www.wisbiorefine.org/proc/ester.pdf>.

63 Wisconsin Biorefining Development Initiative, Biorefining Process: Anaerobic Digestion (20007), <http://www.wisbiorefine.org/proc/anaerobic.pdf>.

64 Wisconsin Biorefining Development Initiative, Biorefining Process: Aerobic Digestion/ Composting (2007), <http://www.wisbiorefine.org/proc/aerobic.pdf>.

Co-products, also called biobased products, are products output from the primary conversion process that require minimal or no further processing. Co-products may have substantial economic value that adds to the proceeds from the principal energy product being sought. These products include chemical feedstock, animal feed, food items, charcoal, and fertilizers.

Table 9 below illustrates these intermediate, final, and co-products.

Table 9. Technologies and Intermediate, Co-products, and Final Products

<table>
<tr><th>Technology</th><th colspan="2">Intermediate Products</th><th>Bio-based Co-products</th><th>Final Products</th></tr>
<tr><td>Gasification</td><td colspan="2">Combustible gases
Combustible liquids
Combustible tars
Inert fluidized gases</td><td>Charcoal
Ash
Carbon dioxide</td><td>Electricity
Heat
Fuel</td></tr>
<tr><td>Pyrolysis</td><td colspan="2">Syngas
Bio-oil
Charcoal</td><td>Charcoal
Non-combustible gases</td><td>Electricity
Heat</td></tr>
<tr><td rowspan="2">Starch and Sugar Fermentation</td><td>Wet-mill glucose fermenta-tion</td><td>Mash and sugar</td><td>Distillers grains
Carbon dioxide</td><td rowspan="2">Fuel
Electricity
Heat</td></tr>
<tr><td>Dry-mill glucose fermenta-tion</td><td>Starch and sugar</td><td>Corn oil
Corn gluten meal
Corn gluten feed
Carbon dioxide
Liquid biofertilizers</td></tr>
<tr><td>Lignocellulosic Biomass Fermentation</td><td colspan="2">Cellulose
Hemicellulose
Lignin</td><td>Carbon dioxide
Residual cellulose and Lignin</td><td>Fuel
Electricity
Heat</td></tr>
<tr><td>Transesterification</td><td colspan="2">n/a</td><td>Methyl ester (biodiesel), Methanol, Glycerin (for soaps, lubricants, and chemical feedstock)</td><td>Fuel
Electricity
Heat</td></tr>
<tr><td>Anaerobic Digestion</td><td colspan="2">Biogas
Thermal energy
Digestate</td><td>Liquid fertilizers
Solid fertilizers</td><td>Electricity
Heat</td></tr>
<tr><td>Landfill Gas Collection</td><td colspan="2">Biogas (a mixture of methane, carbon diox-ide, nitrogen, hydrogen, oxygen, and hydrogen sulfide)</td><td>Carbon dioxide
Uncomposted refuse
Biofertilizers
(Co-products of landfill gas processing minimal)</td><td>Electricity
Heat</td></tr>
<tr><td>Aerobic Digestion</td><td colspan="2">Heat and fertilizer</td><td>Carbon Dioxide</td><td>Heat</td></tr>
</table>

More detailed information on intermediate, final, and co-products can also be obtained from the Appendix C matrix, as indicated in Figure 8 below.

Intermediate and Co-products are detailed in the "Products" column

	1. Biomass Conversion Technology		2. Feedstocks	3. Products
Gasification	Fixed Bed	Downdraft Co-Current Fixed Bed Updraft Co-Current Fixed Bed Cross-Draft Fixed Bed Open Core Fixed Bed	**Any Organic Material** Examples: Agricultural wastes, hazardous organic wastes, industrial wastes. **Pretreatment:** Waste typically segregated. **Qualifications:** Dry MSW is favorable. Coal size distribution must be controlled to ensure good bed permeability. **Final Conversion Technology (Optional):** Fischer-Tropsch Catalytic Conversion	**Intermediate Products:** Combustible gases, liquids, tars, and inert fluidizing gases. **Final Products:** Electricity, Thermal Energy, Hydrogen, Ethanol and other alcohols, Diesel type fuels, Gasoline. **Co-products:** Charcoal, Ash, Carbon Dioxide.
	Fluidized Bed	Pressurized Circulating Fluidized Bed Atmospheric Circulating Fluidized Bed		
	Novel Design	Plasma Arc Gasifier 2-stage Gasifier Open Top Aqueous Phase Reforming		

Figure 8. Intermediate and Co-products in the Biomass Conversion Matrix

Energy Conversion Processes

In the previous section, the various products of conversion technologies were outlined, and intermediate, final, and co-products were defined. The section also suggested that various energy conversion processes must be employed in order to convert intermediate products to final energy products and co-products such as electricity, heat, fuels, and chemical feedstock. The accompanying matrix does not currently outline in detail the technologies that convert intermediate products to variable energy and co-products. In many cases, the technologies are well understood and developed and thus were not selected as the focus of this report. However, the following section will briefly outline the methods through which intermediate products are converted to final energy and co-products.

Table 10 below illustrates some of the conversion methods frequently employed to convert intermediate products into final energy and co-products.

Table 10. Intermediate Products, Energy Conversion Methods, and Final Products

Intermediate Product	Energy Conversion Method	Final Product (Energy and Co-Products)
Biodiesel	n/a	Chemical Feedstock
Glycerin	Chemical processing	
Cellulose, Hemicellulose, and Lignin	1. Hydrolysis 2. Fermentation	
Mash and sugar	Fermentation (and often, subsequent distillation)	
Distillers grains, corn gluten feed	Processing	Co-Product (Animal feed and other food products)
Carbon Dioxide	n/a	Co-product (Industrial Use)
Bio oil	Combustion	Electricity Heat
Biodiesel	Combustion	
Cellulose, Hemicellulose, and Lignin	1. Hydrolysis 2. Fermentation 3. Combustion	
Combustible Biogas	Combustion	
Combustible gases (from gasification, anaerobic digestion, or landfill gas collection)	Combustion	
Mash and sugar	1. Fermentation (and often, subsequent distillation) 2. Combustion	
Combustible liquids	Combustion	Electricity
Combustible tars	Combustion	
Inert noncombustible gases (syngas from gasification, pyrolysis, anaerobic digestion, or landfill gas collection)	Turbine	

Table 10. (continued)

Intermediate Product	Energy Conversion Method	Final Product (Energy and Co-Products)
Liquid and Solid Fertilizers	n/a	Fertilizer
Digestate	n/a	
Charcoal	n/a	
Biodiesel	n/a	Fuel (Biodiesel)
Cellulose, Hemicellulose, and Lignin	1. Hydrolysis 2. Fermentation	Fuel (Ethanol)
Inert noncombustible gases (syngas)	Fischer-Tropsch Catalytic Conversion	
Mash and sugar	Fermentation (and often, subsequent distillation)	
Thermal Energy	Boiler system	Heat

It is important to understand the variety of energy production capabilities for all conversion technologies. Some technologies yield a wide variety of high-value end products, while others yield few. However, both have viable applications. For example, gasification systems may be appropriate for disaster clean-up, because they accept a wide variety of feedstocks and because their final and co-products have a wide variety of applications (e.g., fuel, electricity, heat, and chemical feedstocks).[65] Conversely, in the case of more particular technologies such as anaerobic digestion, the distribution of the final product is often an issue.

65 Emanuele Scoditti and N. Parker, "IEA Bioenergy Agreement, Task 33: Thermal Gasification of Biomass, Review of Energy Conversion Devices" (2003), < http://media.godashboard.com/gti/IEA/ReviewofEnergyConversionDevices rev.pdf>.

Appendix A.
Selected Online Resources

BIOconversion Blog. An online journal that covers international issues, facility deployments, and new developments, at <http://bioconversion.blogspot.com>. Three other three related blogs are **BIOstock Blog** at <http://biostock.blogspot.com>, **BIOoutput Blog** at <http://biooutput.blogspot.com/>, and **BIOwaste Blog.** <http://biowaste.blogspot.com>.

Bioenergy Feedstock Information Network (BFIN). A gateway to biomass feedstock information resources from the U.S. Department of Energy, DOE national laboratories, and other research organizations. <http://bioenergy.ornl.gov/main.aspx>.

Bioenergy Wiki. An open electronic forum to promote the utilization of bioenergy in a sustainable manner. It advances understanding of relevant issues and facilitates sharing of information, views and experience. <http://www.bioenergywiki.net/>.

Biomass Energy Center (BEC). A UK site providing links to information on fuel processing and supply chains, emphasizing woodfuel and heat production; also offers a query service focusing on biomass fuel types that are commercially available or being researched. <http://www.biomassenergycentre.org.uk/portal/page?_pageid=73,1&_dad=portal&_schema=PORTAL>.

Biomass Program of the Department of Energy. A site describing the development of technology for converting biomass to fuels, chemicals, materials, and power, thus fostering growth of biorefineries and reducing dependence on imported oil. <http://www1.eere.energy.gov/biomass>.

California Biomass Collaborative. An organization based at the University of California, Davis aimed at enhancing the sustainable management and development of biomass in California. <http://biomass.ucdavis.edu>.

California Biomass Facilities Reporting System (BFRS). A source of extensive searchable data on California biomass facilities and other resources. <http://cbc2.ucdavis.edu>.

Conversion and Biomass to Energy. A site of the California Integrated Waste Management Board. <http://www.ciwmb.ca.gov/organics/conversion>.

Gasifier Inventory. An overview of existing biomass gasifier installations and accompanying manufacturers. Users submit an input form for access to the database. <http://www.gasifiers.org>.

Great Lakes Biomass State-Regional Partnership. One of five regional programs supported by the U.S. Department of Energy to encourage greater production and use of biomass for energy generation. <http://www.cglg.org/biomass/index.asp>. (Others are the Northeast Regional Biomass

Program <http://www.nrbp.org>; Pacific Regional Biomass Energy Partnership <http://www.pacificbiomass.org>; Southeastern Regional Biomass Partnership <http://www.serbep.org>; and Western Regional Biomass Energy Program <http://www.westgov.org/wga/initiatives/biomass>).

IEA Bioenergy. An organization established by the International Energy Agency in 1978 to accelerate use of environmentally sound and cost-competitive bioenergy on a sustainable basis. <http://www.ieabioenergy.com>.

Oregon Department of Energy: Biomass Energy. A site providing general and detailed information in the technology and development of biomass energy. <http://www.oregon.gov/ENERGY/RENEW/Biomass/BiomassHome.shtml>.

Phyllis: The Composition of Biomass and Waste. A database created by the Netherlands Energy Research Center, which enables users to analyze data on individual biomass or waste materials and to obtain the average composition of any combination of groups or subgroups. <http://www.ecn.nl/phyllis>.

U.S. Environmental Protection Agency. Several EPA-managed bioenergy technical assistance programs promote the development of bioenergy products that reduce greenhouse gas emissions. The **AgStar program** encourages the use of methane recovery (biogas) at confined animal feeding operations ("CAFO") that manage manure as liquids or slurries <www.epa.gov/agstar>. The **Landfill Method Outreach Program (LMOP)** promotes the use of landfill gas as a renewable green energy source <www.epa.gov/lmop>. The **Combined Heat and Power (CHP) Partnership** fosters the use of highly efficient biomass CHP and other CHP systems <www.epa.gov/chp>.

Wisconsin Biorefining Development Initiative. An introduction to biorefining processes that can transform low-value biobased feedstocks into multiple, higher-value biobased products. <http://www.wisbiorefine.org/index.html>.

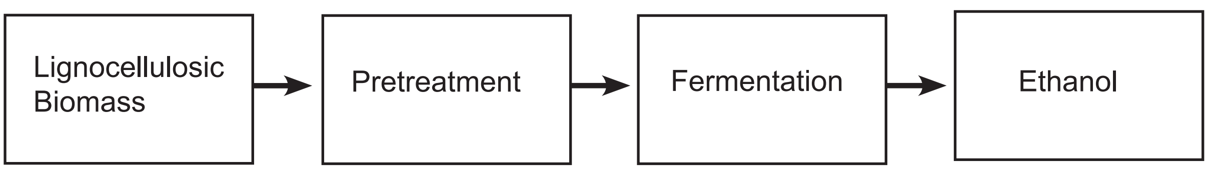
Appendix B.
Ethanol Production Technologies

Ethanol can be produced from several types of feedstocks. Starch and sugars can be directly fermented with minimal pretreatment, as illustrated in Figure 9 below.

Figure 9. Ethanol Production from Starches and Sugars

However, lignocellulosic biomass, which is comprised of Lignin, Cellulose, and Hemicellulose, requires more pretreatment before it can be fermented. Thus, in the process of lignocellulosic biomass fermentation, the feedstock must first be pretreated with hydrolysis or one of several other treatments. Pretreatment breaks the feedstock into component sugars, where it can then be fermented as in starch and sugar fermentation above. Due to national goals for cellulosic ethanol this pretreatment step in currently being intensively researched, especially the development of special enzymes and genetic modifications.[66] This process is illustrated in Figure 10 below:

Figure 10. Pretreatment of Cellulosic Biomass



[66] U.S Department of Energy (2006) Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda. Washington, DC: Department of Energy, Offices of Science/Energy Efficiency and Renewable Energy. http://genomicsgtl.energy.gov/biofuels/2005workshop/2005low_feedstocks.pdf

Appendix C.
Biomass Conversion Matrix

Category	Process	Subtype	1. Biomass Conversion Technology	2. Feedstocks	3. Products
Thermochemical	Gasification	Fixed Bed	Downdraft Co-Current Fixed Bed Updraft Co-Current Fixed Bed Cross-Draft Fixed Bed Open Core Fixed Bed	**Any Organic Material** Examples: Agricultural wastes, hazardous organic wastes, industrial wastes. **Pretreatment:** Waste typically segregated. **Qualifications:** Dry MSW is favorable. Coal size distribution must be controlled to ensure good bed permeability. **Final Conversion Technology (Optional):** Fischer-Tropsch Catalytic Conversion	**Intermediate Products:** Combustible gases, liquids, tars, and inert fluidizing gases. **Final Products:** Electricity, Thermal Energy, Hydrogen, Ethanol and other alcohols, Diesel type fuels, Gasoline. **Co-products:** Charcoal, Ash, Carbon Dioxide.
Thermochemical	Gasification	Fluidized Bed	Pressurized Circulating Fluidized Bed Atmospheric Circulating Fluidized Bed		
Thermochemical	Gasification	Novel Design	Plasma Arc Gasifier 2-stage Gasifier Open Top Aqueous Phase Reforming		
Thermochemical	Pyrolysis	Fast Pyrolysis	Ablative Fast Pyrolysis Cyclonic Fast Pyrolysis Rotating Core Fast Pyrolysis Open Core Fast Pyrolysis	**Any Organic Material** **Pretreatment:** Sorting **Qualifications:** None	**Intermediate products:** Syngas and Charcoal **Final Products:** Bio-Oil and Charcoal **Co-products:** Electricity and Thermal Energy
Thermochemical	Pyrolysis	Slow Pyrolysis	Vacuum Pyrolysis Flash Pyrolysis	**Any Organic Material** **Pretreatment:** Sorting. **Qualifications:** Waste must be pre-sorted and processed to <6 mm (1 to 2 mm. preferred) and <10% moisture content to assure high heat transfer rate.	
Biochemical	Ethanol Production		Wet-Mill Fermentation	**Grains** Mostly: Corn **Pretreatment:** Separation of the oil, protein, fiber and the bulk of the nutrients from the starch	**Intermediate Products:** Mash, Sugar **Final Products:** Ethanol **Co-products:** Distillers grains plus solubles, Carbon Dioxide
Biochemical	Ethanol Production		Dry-Mill Fermentation	**Grains, Sugars and Waste , Starches and Sugars** Examples: Grains (corn, sorghum, barley), Sugars (Sugarcane and beets), Beer, and other waste sugars and starches. **Pretreatment:** Grinding, cooking and fermentation	**Intermediate Products:** Starch, Sugar **Final Products:** Ethanol **Co-products:** Corn oil, corn gluten meal, corn gluten feed, carbon dioxide, liquid bio-fertilizers
Biochemical	Ethanol Production		Lignocellulosic Biomass Fermentation	**Cellulosic/Woody Biomass** **Pretreatment:** Hydrolysis (Dilute Acid, Concentrated Acid, Enzymatic, Steam explosion)	**Intermediate Products:** Cellulose, hemicellulose. lignin **Final Products:** Ethanol **Co-products:** Carbon Dioxide, residual cellulose and lignin, electricity and thermal energy
Biochemical	Anaerobic Digesters	Mesophilic Process or Thermophilic Process	Anaerobic activated sludge process Anaerobic clarigester Anaerobic contact process Anaerobic expanded-bed reactor Anaerobic filter Anaerobic fluidized bed Anaerobic lagoon Anaerobic migrating blanket reactor Batch system anaerobic digester Expanded granular sludge bed digestion Hybrid reactor Imhoff tank One-stage anaerobic digester Submerged media anaerobic reactor Two-stage anaerobic digester Upflow anaerobic sludge blanket digestion Upflow and down-flow anaerobic attached growth	Almost any organic material: paper, grass clippings, leftover food, sewages, animal wastes; and other forms of biomass such as distillers grains. **Pretreatment:** Sorting or screening to remove inorganic material. **Qualifications:** The material may need to be pre-processed and water added.	**Intermediate products:** N/A. **Final Products: Biogas,** Thermal Energy, Digestate. Co-products: Liquid and Solid Biofertilizers.
Biochemical	Landfill		Bioreactor vessel	**Organic Wastes** **Pretreatment:** Sorting pre-treatment **Qualifications:** The waste must be contained, compacted and covered in a vessel	**Intermediate products:** Biogas composed of Methane, Carbon Dioxide, Nitrogen, Hydrogen, Hydrogen Sulfide and Oxygen. **Final Products:** Electricity, thermal energy, methane. CNG or LNG for vehicle fuel. **Co-products:** Carbon Dioxide for possible use in greenhouse operations, and Biofertilizers.
Biochemical	Landfill		Landfill Site	**Organic Wastes** **Pretreatment:** None **Qualifications:** None	
Biochemical	Aerobic		Static Pile Enclosed Compost Turned Window In-Vessel Compost Transesterification	**Practically any Organic Waste** **Pretreatment:** Sorting **Qualifications:** A separation between organic and contaminants is necessary.	**Intermediate products:** None **Final Products:** Valuable Compost **Co-products:** Heat and Carbon Dioxide. (May be useful in a greenhouse environment or for heating)
Chemical	Biodiesel Production			**Oils, fats, used cooking oils, greases, methanol or ethanol and a catalyst** **Pretreatment:** Used cooking oils, yellow greases, and some tree oils are taken through an esterification process to remove fatty acid that should, preferably, be reduced to less than 1% (at least below 4%). **Qualifications:** Essentially any bio-oil, animal fat or tallow, used cooking oil, yellow/trap grease, plant or tree oil can be converted into biodiesel if the fatty acid content is low enough.	**Intermediate Products:** Oils fats or greases taken through transesterfication **Final Products:** Biodiesel **Co-products:** Glycerin, Soaps

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