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Lignocellulose to Transportation Fuels—Historical Perspectives and Status of Worldwide Facilities in 2011–2012

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Cover photos by David Nicholls.

Abstract

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The U.S. Forest Service Forest Products Laboratory (FPL), located in Madison, Wisconsin, celebrated its centennial in 2010, and one of the lab's signature research areas during this century of achievement has been lignocellulosic transportation fuels. Many of these research advances have occurred either during wartime emergencies or times of economic crisis. Although great progress has been made, commercial production of lignocellulosic fuels has been limited. In this paper, we take an indepth look at advances, breakthroughs, and motivating factors in liquid fuels research both at the FPL and in the private sector. We examine the current status of lignocellulosic transportation fuels as well as near-term prospects for commercialization. We then summarize leading efforts at lignocellulosic fuel production in a comprehensive table. We consider the role that the FPL might have in developing lignocellulosic fuels during its second century as well as the commercial potential for private sector firms.

Keywords: Biomass, fossil fuel, cellulosic ethanol, Forest Products Laboratory.

Contents

Introduction

The U.S. Forest Service, Forest Products Laboratory (FPL) celebrated its centennial in 2010 (Koning 2010) and has contributed significantly to the development of lignocellulosic transportation fuels among other wood-based products. Watershed events that have motivated liquid fuels research over the past century include World War I, World War II, and the oil embargoes of the 1970s. At the FPL, research efforts have been aimed at commercializing processes for liquid fuel production, particularly ethanol, from wood. Despite several research breakthroughs, this goal has largely proven to be elusive because the production economics have not been competitive with petroleum. In this review, we explain recent progress in commercializing biomass-derived fuels as the FPL begins its second century of operations. We do this by discussing national and international trends in implementing biofuels, and by summarizing commercial biofuels facilities as well as considering facilities nearing commercial production.

By mid-2012, several firms have announced plans to build commercial facilities, but little if any cellulosic ethanol is actually being used on America's highways. Several estimates place the amount of cellulosic ethanol produced nationally in 2010 at less than 1 million gal (Maron 2011). Economic considerations notwithstanding, there is now a greater need for renewable liquid fuels for myriad reasons, including assuring supplies during times of national emergencies, reducing greenhouse gases, and reducing other pollutants such as sulfur and heavy metal compounds normally associated with coal. During much of 2011, oil prices continued to rise, stymying the difficult economic recovery that has been several years in the making.

On the other hand, various support programs sponsored by national and regional governments help make lignocellulosic biomass-based fuels more competitive with fossil fuel sources. Within the past decade, these have included (BRDI 2008):

- The Biomass Research and Development Act of 2000
- The Energy Policy Act of 2005 (calling for 7.5 billion gal of renewable fuel by 2012)
- The Energy Independence and Security Act of 2007 (calling for 36 billion gal per year of biofuels by 2022
- The 2002 and 2008 Farm Bills

The next few years (2012 and beyond) could very well prove to be a litmus test of whether large-scale biomass utilization efforts should be focused on transportation fuels versus other products providing greater economic and environmental benefits (e.g., biomass for electrical and thermal energy generation, or sequestering carbon in durable wood products). For example, Campbell et al. (2009) suggested that biomass used for electricity production could ultimately provide 81 percent more transportation miles versus using equivalent feedstocks to produce cellulosic ethanol. Others have identified important obstacles to overcome for commercialization of cellulosic ethanol (Margeot et al. 2009), including improved pretreatment processes, reduced enzyme costs, maximizing the conversion of pentose sugars, minimizing water demands, and valuing and utilizing lignin co-products.

A Brief History of Cellulosic Ethanol as a Motor Fuel

Early 20th Century—Henry Ford and the Model T

Ethanol from biomass was not always uneconomical for use as a motor fuel. One of the most successful automobiles of the 20th century, the Model-T Ford, was actually a flexible fuel vehicle, designed to run on ethanol, gasoline, or kerosene. However, reductions in the cost of gasoline and, later the onset of Prohibition, made ethanol impracticable.

World War I Era—American Process for Manufacture of Ethanol

A batch process for making ethanol from cellulosic residues using dilute acid hydrolysis was developed in the late 1800s (Simonsen 1898). Simonsen concluded that the best conditions for hydrolyzing sawdust consisted of short runs (15 minutes) combined with mild sulfuric acid at about 9 atmospheres pressure. The FPL, in Madison, Wisconsin, helped refine this process further with a series of experiments at the pilot plant scale.

These successes led to the full-scale version for producing ethanol, known as the "American Process" (Hajny 1981). During World War I, two American Process plants were established in the United States (Georgetown, South Carolina, and Fullerton, Louisiana). The FPL provided assistance, development, and pilot plant testing for both facilities. An engineering study at the Georgetown facility found that production costs were as low as $0.25 per gallon (Hajny 1981). A yield of 20 gallons of ethanol per ton of dry wood was achieved, somewhat less than that obtained in the pilot-plant work.

World War II Era—Scholler, Concentrated Acid, and Madison Processes

During World War II, the demand for ethanol fuel again intensified, and the FPL was selected to work toward the goal of increasing production. Batch processes had become obsolete since World War I; instead the new standard was percolation processes having higher ethanol yields. In batch processes, sugar yields were limited to about 33 percent of the theoretical level (Hajny 1981). To make this ratio more favorable, a percolation process was developed in Germany (the Scholler process).

During World War II, developments in ethanol production were concentrated in Europe. There were Scholler process plants at three locations in Germany (in Tornesch, Holzminden, and Dessau). There also were plants in Ems, Switzerland, and Korea (Hall et al. 1956). The Swiss plant produced about 52 gallons of absolute ethanol per ton of dry wood, somewhat greater than the yields indicated by Hall et al. (1956). The Ems plant continued some work on saccharification, and in 1949 it branched into development, production, and pursuit of textile fibers. During the period following World War II, there were some wood hydrolysis plants making ethanol in the former Soviet Union (including Kirov) and at least one in Bulgaria.

Also during World War II, ethanol plants using concentrated acid processes operated in Italy and Germany. Hall et al. (1956) summarized the advantages and disadvantages of the strong acid processes for producing ethanol.[1] Advantages included (1) a high yield of alcohol; (2) increased recovery of furfural, acetic acid, and ethereal oils; and (3) the possibility of using sawdust feedstocks as well as chips. Disadvantages included (1) a high consumption of acid, and (2) the need to dispose of large quantities of calcium sulfate.

A commercial plant using the modified Scholler process was constructed in Springfield, Oregon, starting in 1944. Although the preparation and fermentation of wood hydrolysate at the Springfield plant proved successful, technical challenges remained with the sugar production. When the war ended, the contract for the uncompleted plant was cancelled by the federal government. Construction was later resumed, and after some engineering and economic compromises, the plant was completed in 1947, allowing partial operation. Marked changes in the Scholler process were necessary before it could be economical in postwar America.

In the late 1940s, the Tennessee Valley Authority became interested in wood saccharification because of the large amount of low-value wood waste available regionally. In 1952, Nathan Gilbert and his co-workers collaborated on pilot-plant studies in cooperation with the FPL. The purpose of this work was to prepare molasses for animal feeding tests and to improve and simplify the hydrolysis process. However, owing to the risks involved and modest profit margins, this process was not widely pursued.

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[1] Originally reported by Centola at the sixth meeting of the Food and Agriculture Organization Technical Panel on Wood Chemistry in Rome in 1954.

The 1970s—Oil Crisis

Rapid high temperature dilute acid hydrolysis—

Although wars had been a major factor stimulating liquid fuels research during the first half of the 20th century, quite different motivating factors were present in the 1970s. The Arab oil embargo provided new incentives to commercialize alternative transportation fuels based on woody biomass feedstocks. The FPL responded by collaborating with researchers from the Tennessee Valley Authority with a goal of improving the Madison Process for producing ethanol from wood. Much of this work focused on improving yields by refining parameters for a two-stage high temperature, dilute acid hydrolysis process. In this process, hemicelluloses were first removed from wood in a prehydrolysis step, followed by a second-stage hydrolysis for glucose removal. By 1985, research successes had led to near-commercialization of both the percolation and two-stage processes of ethanol production. The two-stage process showed promise for overcoming many of the disadvantages inherent in the percolation process, but to a lesser extent than had been hoped (Harris et al. 1985). Major problem areas still remained including improved utilization of pentose sugars, increased yields of marketable products from cellulose, and development and evaluation of processing equipment.

Enzyme hydrolysis—

At about the same time that the two-stage high-temperature dilute acid hydrolysis process was being developed, research at the FPL and elsewhere led to improved organisms for fermenting sugars in wood to ethanol. Wood sugars include both five carbon and six carbon sugars, and the primary ones are glucose, mannose, galactose, xylose, and arabinose. Glucose is the most common sugar in wood and it together with mannose has been fermented. Xylose is the second most common sugar in wood, although not as easily fermented.

Now, with new micro-organisms, xylose may be converted to ethanol. Enzymes may also sometimes be used for hydrolysing cellulose to sugars. Different approaches may be used with various micro-organisms or treatment processes to produce ethanol from lignocellulose. Currently, the lack of low-cost and high-activity cellulose hydrolytic enzymes remains a barrier to commercial production of cellulosic ethanol (Zhu et al. 2008). In 2009, projected costs of enzymes were 24 percent of the cost of producing cellulosic ethanol from corn stover (Aden et al. 2002). Improved agents for conducting saccharifications and fermentations, sometimes simultaneously, are under development by companies including Novozymes, Genencor, and DuPont.

Other Processes for Biomass-Derived Fuels

Gasification (to produce methanol)—
Methanol was first produced from wood through destructive distillation as a byproduct of charcoal manufacture, but today is made in a thermochemical process with an initial gasification step. Fixed bed gasifiers are often used to create producer gas made up of hydrogen and carbon monoxide (CO), as well as other gases that must be removed before further processing.

In methanol production, the producer gas that is formed is deficient in hydrogen. Therefore, a water gas shift reaction is used with some of the CO to provide a hydrogen to CO ratio of 2 to 1. Next, carbon dioxide (CO_2) and nitrogen are removed and discarded. Other steps that may follow include removal of additional CO_2 formed in the water gas shift, removal of hydrocarbons (primarily methane), catalyzed conversion of hydrogen and CO to methanol under high pressure, and refining crude methanol through distillation (Hokanson and Rowell 1977).

Fischer-Tropsch (to produce alcohols and alkanes)—
The Fischer-Tropsch synthesis process is often applied to make fuels such as gasoline, diesel, and jet fuel from synthesis gas[2] derived from coal or lignocelluloses. With suitable catalysts, this process may be modified to produce various specific alcohols, or more commonly a mixture of alcohols. The Fischer-Tropsch process normally produces straight chain nonoxygenated hydrocarbons known as alkanes. There also may be some alkanes with branched carbon chains. Some methane is often produced, but is considered undesirable in large quantities.

Fermentation (to produce butanol)—
Besides the previously mentioned batch and percolation processes for producing ethanol, fermentation may be used to provide butanol. Butanol has four isomers: 1-butanol (n-butanol), 2-butanol, 3-butanol (tertiary butyl alcohol), and isobutanol. These isomers, owing to their different structures, have somewhat different melting and boiling points. Like many alcohols, butanol is toxic. Because 1-butanol has received the most attention in the literature, our discussion focuses on this compound (rather than isobutanol), unless otherwise stated.

Today the greatest impediment to establishing cellulosic ethanol in the marketplace is probably competition from corn-based ethanol. The same is likely true for butanol produced from wood. However, butanol does have some notable properties that could potentially provide a competitive advantage over ethanol. Butanol is

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[2] Synthesis gas (or syngas) is the name given to a gas mixture that contains varying amounts of carbon and hydrogen. This gas can then be used directly as a fuel or converted into other fuels and chemicals.

less miscible in water (resulting in reduced water contamination), and is also less-corrosive. Further, butanol may be more amenable to pipeline transportation versus ethanol, which is not permitted in pipelines (but rather is transported by trucks or tank cars at greater expense). Also, unlike ethanol, butanol production does not consume additional water when using dry biomass feedstocks, an advantage when water is scarce. This could have important implications when considering liquid fuel production from woody biomass in dry Western States. Lastly, because butanol has an energy density much closer to gasoline than ethanol, its fuel economy is commensurately greater than ethanol's. Besides having lower energy density than gasoline, butanol does have other disadvantages. Similar to E-85 fuels, butanol added to gasoline in large proportions could have some degree of incompatibility with the existing infrastructure used by petroleum fuels, as well as use in internal combustion engines.

Esterification (to produce biodiesel)—
Biodiesel has become a proven renewable energy product, and today displaces significant fossil fuel use in Europe and the United States. Worldwide biodiesel production in 2009 was estimated to be about 14.7 billion gallons, with Europe accounting for about 70 percent of this total (Anon. 2011). Just as ethanol can be in direct competition with food for corn supplies, biodiesel also can compete with supplies of canola oil or soybean oil for use as food. However, this is not the case when biodiesel is made from animal fats or restaurant wastes. When ethanol, jet fuel, gasoline, diesel, or other fuels are made from lignocellulosic sources, there is no direct competition with food. Today, esterification of plant and animal feedstocks is more convenient than applying the high temperature and pressure required in the Fischer-Tropsch process.

However, biodiesel fuels ordinarily produced from lipidic sources are not the same as diesel from synthesis gas. Diesel from synthesis gas generally has properties close to diesel from petroleum. Synthetic fuels made from synthesis gas are called "drop in" fuels; essentially fuels that can be "dropped in" to existing systems, whether for automobiles, jet aircraft, or other vehicles. Jet fuel, gasoline, and alcohols from synthesis gas can all be produced as "drop in" fuels without the need to modify engines or other infrastructure. On the other hand, biodiesel is usually used in a mixture with petroleum diesel; for example "B20" fuels that include 20 percent biodiesel and 80 percent petroleum diesel.

Hydrogenation (to produce biodiesel or jet fuel)—
In the hydrogenation process, paraffin waxes are produced that refineries can turn into diesel and jet fuel distillates. Most of the initial products are solid at room temperature and need further refining. Hydrogenation-derived renewable diesel

(HDRD) can be produced by refining animal fats or vegetable oils, either alone or blended with petroleum. This typically involves hydrogenation of triglycerides using oil refinery infrastructure. Gasoline can be produced using a similar refining process, but this process is in an earlier stage of development. A number of manufacturers around the world are developing HDRD refining processes and testing them in commercial trials. With this process, it is possible to produce true hydrocarbons with the same feedstocks used to make biodiesel.

Commercial Producers of Lignocellulosic Fuels (Status in 2011)

Commercial biofuel production in 2011 included two primary products: ethanol from corn and biodiesel from plant oils and animal fats. These are examples of first-generation biofuels, while second-generation biofuels would include lignocellulosic ethanol. The distinction between first- and second-generation biofuels is important because second-generation fuels do not compete directly with human food. Although the current production (2010) of second-generation biofuels is limited, several companies are making significant strides toward commercialization. A brief summary of some of these cutting-edge firms follows, supplementing those listed in table 1.

Some firms that were highlighted by the Environmental Protection Agency in 2012 included Zeachem in Boardman, Oregon; Fulcrum Bioenergy in McCarraan, Nevada; KL Energy in Upton, Wyoming; KiOR in Houston, Texas; Fiberight in Blairstown, Iowa; Dupont Danisco Cellulosic Ethanol in Vonore, Tennessee; KiOR in Columbus, Mississippi; and INEOS Bio in Vero beach, Florida (Voegele. 2011)

Abengoa—Hugoton, Kansas, USA

Abengoa Bioenergy is among the leaders in developing the first commercial-scale cellulosic ethanol facility. As of late 2011, Abengoa Bioenergy had received its air quality permits, allowing construction of a 23-million-gallon-per-year facility in Hugoton, Kansas (Epoverviews 2011a).

The company is also on track to secure all of the necessary biomass feedstock for this biorefinery, approximately 315,000 dry tons of biomass per year. Financing is aided by a $132 million loan guarantee that Abengoa received from the U.S. Department of Energy U.S. (DOE) in 2011. The USDA Biomass Crop Assistance Program is also expected to benefit this facility as six counties in southwest Kansas have enrolled in this program. In addition to liquid fuels, the plant is expected to generate 25 megawatts (MW) of electric power, allowing the ethanol conversion to be self-sufficient. Startup of this plant is expected in 2013, and should increase

Table 1—Lignocellulose to transportation fuels

Producer (listed alphabetically)	Plant location	Feedstock	Product	Expected start date	Capacity
Abengoa Bioenergy	Hugoton, Kansas	Maize straw, wheat	Ethanol	Early 2013	25 million gallons per year; 25 MW electricity
Chemrec AB	Pitea, Sweden	Black liquor	Black liquor gasification combined cycle	Started June 2003. Pilot plants in Sweden	4 to 5 metric tons per day
China Resources Alcohol Corporation	ZhaoDong, China	Corn stover	Ethanol	Began production in 2006	Goal of 1.7 million gallons per year by end of 2013
Coskata (with General Motors)	Warrenville, Illinois	Underutilized biomass	Ethanol	Retail availability end 2010 at earliest	40,000 gallons per year
DuPont Danisco (with Univ. of Tennessee, Genera)	Vonore, Tennessee	Switchgrass, wood chips, corn stover, sugar cane bagasse, corn cobs	Ethanol	Plant is operational	250,000 gallons per year
Dupont (with Poet)	Scotland, South Dakota corn cobs	Corn stover, corn fiber,	Ethanol	Pilot in 2007; development through 2009	30 million gallons per year
Enerkem	Edmonton, Alberta,	Sorted municipal solid	Methanol, ethanol	Commence operations	9.5 million gallons per year
Enerkem (with Three Rivers Solid Waste Management Authority)	Pontotoc, Mississippi	Municipal solid waste, treated wood residues	Methanol, Ethanol	Construction start 2011	10 million gallons per year
Fiberight (with CleanTech)	Blairstown, Iowa	Municipal solid waste	Cellulosic ethanol	Start construction 2011; running 2012	3.6 million gallons per year
Fulcrum Bioenergy Inc, (with InEnTec, Fluor)	Reno Industrial Center, Storey County, Nevada	Sorted household garbage	Ethanol, propanol, electricity, chemicals	Construction 2011	10.5 million gallons per year, 16 MW electricity
INEOS (with New Planet Energy)	Vero Beach, Florida	Wood, wood wastes, vegetative wastes, tires	Ethanol, power, and chemical intermediates	Expected operation in 2012	Up to 14 million gallons per year
Iogen (with Shell and Codexis)	Ottawa, Ontario, Canada	Wheat and barley straw	Ethanol, gasoline, diesel		500,000 gallons per year
KiOR	Columbus, Mississippi	Wood and agricultural residues	Biofuels that can be converted to gasoline, diesel, and jet fuels	Began operations May 2012	4 million gallons per year

Table 1—Lignocellulose to transportation fuels (continued)

Producer (listed alphabetically)	Plant location	Freedstock	Product	Expected start date	Capacity
Lignol Energy Corp	Burnaby, BC, Canada	Wood chips and other cellulosic biomass	Ethanol, lignin	First "end-to-end" production June 2009	26,000 gallons per year
Neste Oil	Porvoo, Finland	Palm oil, canola oil, animal fats	Diesel	Completion expected 2011	240 million gallons per year
Rentech	Hawaii	Sugar cane bagasse			
Terrabon	Port Arthur, Texas	Biomass	Gasoline	Earliest production 2012	700,000 gallons per year
Verenium Corp (with BP)	Highlands County, Florida, USA	Energy cane, sorghum	Ethanol	Break ground in July 2010; production 2011	30 million gallons per year
Virent Energy Systems (with Shell Hydrogen)	Madison, Wisconsin	Biomass-derived feedstocks including glycerin	Hydrogen, gasoline, diesel, jet fuel	Startup expected 2012	
Western Biomass Energy (and KL Process Design Group)	Upton, Wyoming	Ponderosa pine sawdust, logging residues	Ethanol	Startup January 2008	1.5 million gallons per year
ZeaChem	Boardman, Oregon	Poplar trees and other biomass	Biofuels	Production in 2011	250,000 gallons per year

Note: Developers near commercial standing, April 2011.

Abengoa's total U.S. production of ethanol to about 400 million gal. per year (with the remainder being first-generation biofuels) (Epoverviews 2012a).

Beta Renewables—Crescentino, Italy

Construction began in April 2011 for the world's first commercial cellulosic ethanol facility (Epoverviews 2012b). The Crescentino, Italy, plant will have a capacity of 13 million gallons per year and was scheduled to begin production in 2012. The facility will be self-sufficient for its energy needs, and lignin byproducts will be burned to generate electricity in an adjacent powerplant. Cellulosic ethanol firm Beta Renewables is a partner in this project, and their "PROESA" process will be used as part of a technology licensing agreement.

BlueFire Renewables—Fulton, Mississippi, USA

BlueFire Renewables (formerly BlueFire Ethanol) is constructing a facility near Fulton, Mississippi, to produce up to 19 million gallons per year of ethanol from cellulosic waste materials including wood wastes. A memorandum of understanding has been entered into with China Huadian Engineering Co. LTD to help finance this facility and up to five more plants in the United States (Epoverviews 2011b). A feedstock supply deal has been arranged to supply locally sourced wood chips from forest residues, precommercial trimmings, and construction wood waste. A smaller demonstration facility in Lancaster, California, is expected to produce close to 4 million gal. per year of cellulosic ethanol (Epoverviews 2010a).

BlueFire Renewables uses a concentrated sulfuric acid hydrolysis process to produce a variety of biofuels including cellulosic ethanol, biodiesel, jet fuel, and other "drop-in" fuels. They have demonstrated capabilities to produce fuels from postsorted municipal solid waste, rice and wheat straws, wood waste, and other agricultural residues, indicating the versatility of their process. Their high-yield processing has achieved conversions of 85 percent or higher (Epoverviews 2011b).

BlueFire's acid process allows for operation at low temperatures and atmospheric pressure without the need for genetically modified organisms. Its core technology allows for isolating xylose, glucose, and other sugars for custom delivery (Epoverviews 2011b). A wholly owned subsidiary (SucreSource) was formed so that cellulosic sugars could be provided to companies specializing in back-end processing including fermentation. BlueFire has received $88 million under the American Recovery and Reinvestment Act.

Blue Sugars Corp.—Upton, Wyoming, USA

This is a demonstration plant to produce 1.5 million gallons per year of ethanol from ponderosa pine sawdust and logging residue. In addition to domestic production, Blue Sugars is planning to provide its technology to three Brazilian facilities by 2015 (Bloomberg 2012). Blue Sugars recently shipped 24,000 gallons of its cellulosic ethanol to the Brazilian firm Petrobas to be used at an event in Rio de Janeiro.

BP Biofuels and Mendel Biotechnology—Jennings, Louisiana, USA

Mendel Biotechnology Inc. has partnered with BP Biofuels to conduct demonstration trials of Miscanthus for use in cellulosic ethanol production. A 1.4 million gallon-per-year demonstration facility has been established in Jennings, Louisiana, to evaluate the initial 100-ac planting. A commercial-scale project is already underway in Highlands County, Florida. Here, a $400 million 36-million-gallon-per-year facility is expected to be completed within the next few years, also using Mendel's trademarked "PowerCane Miscanthus" as the primary feedstock (Epoverviews 2012c).

Choren—Freiburg, Saxony, Germany

A plant to produce 18 million liters of diesel per year has been planned. Choren has started work on using organic residues or residual waste to make diesel with a two-stage process. This process includes a low-temperature gasifier to produce syngas and char and a high temperature gasifier to make diesel. Pilot and demonstration plants have been successful, and Choren is interested in a commercial plant. However, in 2011, Choren filed for bankruptcy and sold its main business segment, Carbo-V, to Linde Engineering Dresden (Rapier 2011).

Coskata—Warrenville, Illinois, USA

Coskata, Inc. has partnered with Westinghouse Plasma Corp. to construct a waste-to-ethanol facility in Madison, Pennsylvania, called "Project Lighthouse." High-temperature plasma gasification is used to create syngas from a variety of nonfood biomass waste, which is then fermented to ethanol. As of late 2011, Project Lighthouse had completed 2 years of successful operation, logging more than 15,000 hours of production (Epoverviews 2011c). Coskata is also planning a commercial cellulosic ethanol facility near Boligee, Alabama, and in mid-2011 received a USDA loan guarantee for this project (Epoverviews 2011d).

DuPont Danisco—Vonore, Tennessee and Nevada, Iowa, USA

In early 2010, DuPont Danisco Cellulosic Ethanol LLC and the University of Tennessee opened a pilot cellulosic ethanol facility in Vonore, Tennessee (Epoverviews 2010b). The facility will initially use corn cobs as a feedstock before transitioning to switchgrass. An estimated 4,000 ac of switchgrass will become the primary feedstock.

In mid-2011, DuPont Danisco selected Nevada, Iowa, to be the site of a commercial-scale cellulosic ethanol facility having a planned capacity of 25 million gallons of ethanol per year and costing $235 million (Epoverviews 2011e). The facility will be unique in that it plans to utilize corn stover, corn cobs, and leaves. A Stover Collection Program has been set up to encourage cost-effective harvesting, transportation, and storage techniques.

Enerkem—Canada

Enerkem is a Canadian waste-to-biofuels company that has partnered with GreenField Ethanol (Canada's largest alchohol producer) to build a facility in Varennes, Quebec (Epoverviews 2012d). The Varennes facility is Enerkem's third effort at cellulosic ethanol, with waste-to-biofuel facilities also planned in Edmonton, Alberta, and a location in Mississippi. Recently, Enerkem reached a "significant milestone" by successfully producing cellulosic ethanol from used telephone poles at its demonstration plant in Westbury, Quebec (Epoverviews 2012e). Enerkem's process first produces methanol, which is then converted to ethanol. The Westbury plant has been used to test a number of nonrecyclable municipal waste feedstocks.

Fiberight, LLC—Blairstown, Iowa, USA

Fiberight LLC has completed the first stage of construction to convert a corn ethanol facility in Blairstown, Iowa, to produce cellulosic ethanol. The $60 million project will use municipal solid waste and industrial pulps to produce about 3.6 million gallons of cellulosic ethanol per year (Epoverviews 2012f). A cellulosic microbe, developed by Fiberight, will allow up to 15 percent greater ethanol production versus traditional fermentation processes, while reducing energy inputs.

INEOS—Vero Beach, Florida, USA

INEOS Bio-Energy LLC has constructed a waste-to-energy facility near Vero Beach, Florida, using a feedstock-flexible process capable of using yard trimmings, waste wood, and other vegetational wastes (Epoverviews 2012g). The ethanol facility is a joint venture between New Planet Energy (based in California) and INEOS (based in the United Kingdom) and is expected to generate 8 million gallons of ethanol per year plus 6 MW of electric power while consuming 150,000 tons of yard wastes. The INEOS process is a unique gasification and fermentation process in which naturally occurring bacteria are used to create ethanol from numerous feedstocks (including organic municipal wastes). The INEOS facility has received a conditional commitment for a $75 million loan guarantee from the USDA Biorefinery Assistance Program.

Iogen—Ottawa, Ontario, Canada

This is a demonstration plant to produce 500,000 gal per year of ethanol, gasoline, and diesel from wheat and barley straw. The plant produces fuel for use in-house, use at an Ottawa service station, and use in automobile races. In 2010, Iogen partnered with Shell to fast-track their plans to produce cellulosic ethanol at a demonstration facility in Ottawa. However, as of May 2012, this partnership was scaled back to include only small-scale research but not include a larger scale ethanol facility. Although Iogen had been unable to solve engineering challenges associated with larger scale ethanol production (Epoverviews 2012h), it will continue to produce biofuel enzymes.

KiOR—Pasadena, Texas, USA

KiOR Inc. has a demonstration plant near Houston, Texas, and expects to have a commercial plant with 50 times the capacity of the demonstration plant on line by the end of 2011. The Environmental Protection Agency is dependent on this producer to help meet 2011 goals. The product is a substitute crude oil made from wood and agricultural residues that can be converted into diesel and gasoline.

Lignol—British Columbia, Canada

Lignol Energy Corporation signed an agreement with Denmark's Novozymes to optimize ethanol production from wood chips and other forestry residues at Lignol's industrial pilot plant in Burnaby, British Columbia, Canada (Epoverviews 2010c). Ultimately, Lignol plans to construct large-scale biorefineries for the production of cellulosic ethanol and biochemicals from wood chips and forestry residues. As of April 2011, design and engineering work was completed for a 20-million-gallon-per-year cellulosic ethanol plant. In July 2011, Lignol no longer qualified for $30 million in funding from the U.S. DOE to construct a demonstration plant in Colorado; however, the firm plans to move forward on this project using internal funding. Lignol has been instrumental in forming ethanol partnerships through its "Sustainable Development Technology Canada" consortium, which includes FPInnovations, Novozymes, and Metso Paper (Epoverviews 2011f).

Mascoma—Lebanon, New Hampshire, USA

Mascoma is planning a 40-million-gallon-per-year, $350 million ethanol plant in Michigan to use switchgrass and hardwood to make ethanol. Partner Valero Energy plans to invest $50 million in this plant, to be constructed near Kinross, Michigan

(Epoverviews 2012i). Mascoma's consolidated bioprocessing platform will be used, allowing ethanol production in a single step using engineered micro-organisms to produce cellulases (avoiding the need to purchase cellulose directly). Hardwood pulpwood will be the primary feedstock for the Michigan facility.

Poet—Sioux Falls, South Dakota, USA

Poet is a corn ethanol manufacturer that hopes to have a 25-million-gallon-per-year cellulosic ethanol plant under construction in Emmetsburg, Iowa, by the end of 2011. Proposed feedstocks are corncobs and corn fiber. In early 2012, Poet formed a joint venture with Dutch enzyme company Royal DSM to privately finance the Emmetsburg facility (rather than utilize a $105 million U.S. DOE loan guarantee) (Epoverviews 2012j). As of late 2011, Iowa farmers had baled close to 61,000 bone-dry tons of corn cobs and stover for delivery to the ethanol plant. Total feedstock requirements are estimated to be 285,000 tons per year (Epoverviews 2011g).

Range Fuels—Soperton, Georgia, USA

A facility to produce 20 million gallons per year of methanol and ethanol using unmerchantable timber and forest residues was planned. However, the plant was closed in January 2011 after having produced limited quantities of methanol and ethanol. The plant equipment was sold to LanzaTech Corporation for use in its ethanol production plant (Epoverviews 2012k).

ZeaChem, Inc.—Boardman, Oregon, USA

ZeaChem has completed construction of a core demonstration facility to produce 250,000 per year of cellulosic ethanol and other biochemical at Boardman, Oregon (Epoverviews 2012l). Plans are underway to expand this to a 25-million-gallon-per-year biorefinery by late 2014, using 70 percent woody biomass and 30 percent agriculture residues (including wheat straw and corn stover). ZeaChem is also leading research and demonstration trials for production of "drop-in" transportation fuels, including jet fuels, diesel fuels, and bio-based gasoline (Epoverviews 2012l). A unique aspect of this plant is its use of fast-growing poplar trees from nearby plantations.

Discussion and Considerations

For decades, researchers and entrepreneurs have tried to produce liquid fuels from lignocellulosic biomass for transportation vehicles with little commercial success. Although successful feedstocks and processes have been identified, the inherent disadvantage that biofuels face vs. petroleum fuels remains a significant barrier.

Worldwide ethanol production is primarily by fermentation, with Brazil and U.S. production combining for close to 70 billion liters per year (Perrone et al. 2011), and other countries playing secondary roles. Most of the worldwide production (73 percent) is used for transportation fuels (Perrone et al. 2011). In the United States, a mandate of 16 billion gallons of cellulosic biofuels by 2022 has been established to supplement the goal of 15 billion gallons per year of corn ethanol. Biodiesel, green gasoline, and jet fuel could also play important roles in utilizing cellulosic feedstocks (Regalbuto 2009). One study estimates that second-generation woody feedstocks (including logging residues, thinnings, mill residues, and urban wood waste) could contribute up to 4 billion gallons of ethanol per year (BRDI 2008).

Several key barriers to cellulosic ethanol production remain. Some of these challenges include further research to quantify life cycle greenhouse gas emission benefits of biofuels, advances in improving process economics, and improvements in fermentation and product recovery (Wyman 2007). Three economic hurdles must also be overcome for financial viability according to the U.S. DOE and the U.S. Department of Commerce: (1) reduce cellulosic feedstock costs to $30 per ton, (2) increase ethanol yields to 90 gallons per dry ton, and (3) reduce costs of enzymes used in the production process to $0.05 per gallon (Maness 2008). Reduction in feedstock costs will be particularly important as it is estimated that this contributes from 35 to 50 percent of total production costs for cellulosic ethanol (Hess et al. 2007).

Further, unproven business models for cellulosic ethanol systems and greater transportation logistics (versus corn ethanol) add to the uncertainty of reaching significant production levels (Waltz 2008). Despite these obstacles, numerous firms were engaged in developing ethanol from cellulosic feedstocks as of 2008 using wide-ranging feedstocks and technologies (Waltz 2008). As of April 2011, groundbreaking ceremonies were held in Italy for construction of a 50-million-liter (12.9-million-gallon)-per-year cellulosic ethanol facility—evidence of strong support for commercialization (Canadian Biomass 2011). This facility, scheduled to start production in 2012, would be 10 times larger than the current largest demonstration facility, and could pave the way for other commercial facilities.

The goal of commercializing lignocellulosic fuel production within the next few years is the basis for great optimism, and this is starting to translate into policy actions. Biofuel support policies that have proven beneficial in Europe can broadly be classified as production subsidies, incentives for biofuel users, and feedstock subsidies (Wiesenthal et al. 2009). For large-scale biofuel production, an efficient and complementary mix of biofuel policies is warranted. Presently, some second-generation fuels are being produced, and although mandates for annual production have been significantly reduced for the current year, there remains confidence that these numbers can grow, and commercial-scale operations can begin to flourish.

Metric Equivalents

When you know:	Multiple by:	To find:
Acre (ac)	.405	Hectares
Gallons (gal)	3.78	Liters
Tons (ton)	907	Kilograms

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Glossary

B-20: Fuels that include 20 percent biodiesel and 80 percent petroleum diesel.

Batch process: Batch processing is similar to cooking whereby ingredients are mixed in a vessel and subjected to specified heat or pressure over a given time interval to gain a product for further processing or sale.

E-85: Fuels that include up to 85 percent ethanol and 15 percent gasoline or other hydrocarbons.

First-generation fuels: There are different interpretations of the meaning of first-generation biofuels. In this report first-generation fuels are considered to be those that are most commonly on the market (i.e., ethanol produced from starch and biodiesel produced through esterification of vegetable oil or plant fats).

Furfural: A dehydration product from further reaction after producing xylose and other five-carbon sugars from hemicelluloses by acid hydrolysis. There is some thought that furfural along with hydroxymethylfurfural can serve as a building block for other potential transportation fuels including dimethylfuran and ethyl levulinate.

Percolation process: In saccharification by percolation processing, wood in a pressure vessel is hydrolyzed by acid injected into the top of the vessel and sugar is withdrawn through a filter at the bottom. In this way, sugar production and extraction occur simultaneously. The sugar is separated and cooled as soon as possible to avoid decomposition or reversion to higher polymeric form.

Second-generation fuels: Second-generation fuels may be considered to be those produced from lignocelluloses derived from nonfood crops. Examples, depending on the source, are hydrogen, methanol, Fischer-Tropsch diesel, and mixed alcohols.

Third-generation fuels: Generally taken to mean a fuel derived from algae.

Two-stage dilute acid hydrolysis: A method of processing in which hydrolysis proceeds in two steps. First there is a mild prehydrolysis to separate sugars from the hemicelluloses of lignocelluloses. This is followed by hydrolysis of the cellulose.

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