The Current Status of Cellulosic Biofuel Commercialization

Paul Winters

Biotechnology Industry Organization (BIO)

The Renewable Fuel Standard (RFS) signed into law in December 2007 as part of the Energy Independence and Security Act of 2007 (EISA) created aggressive mandates for the production and use of advanced and cellulosic biofuels. The benefits anticipated from mandated use of biofuels include energy security through domestic production of transportation fuel and environmental improvement through the reduction of greenhouse gas and other particulate emissions associated with fuel combustion. Additional benefits include creating new markets for agricultural products, keeping productive farm land in use, and improving trade balances. Through the first 12 months of the program (July 2010 - June 2011), however, no cellulosic biofuel production was registered for sale and use under the RFS. The shortfall has led to skepticism of the commercial viability of the technology.

In 2007, at the law's passing, industry and lawmakers expected that since cellulosic biofuel technology was ready for scale-up to commercial production the industry could grow rapidly to produce the volumes required under the RFS, just as the conventional biofuel industry was doing and continues to do. Lawmakers and industry predicted that creation of a guaranteed market – combined with other federal programs such as grants to support continued research and development, loans or loan guarantees to match private capital investment, per gallon tax incentives, and a reverse auction for initial volumes – would hurry the market introduction of these fuels. At the same time, though, a waiver mechanism was established to manage any shortfall in widespread availability of cellulosic biofuels at a competitive cost to all obligated parties in the fuel market.

Blenders and refiners of transportation fuel are obligated under the RFS to include certain percentages of renewable fuels in their total fuel sales. Advanced biofuels, as defined in the law, are renewable fuels other than corn ethanol that achieve a 50 percent reduction in greenhouse gas emissions compared to a baseline estimate of gasoline emissions, as determined by the Environmental Protection Agency (EPA) administrator. Cellulosic biofuels are renewable fuels made from cellulose, hemicellulose or lignin that achieve a 60 percent reduction in greenhouse gas emissions. Conventional biofuel is defined in the law as ethanol from corn starch that reduces greenhouse gas emissions by 20 percent.[1] The inclusion of sufficient gallons of renewable fuel to meet the required percentages is tracked by a renewable identification number (RIN).

Ethanol production from corn starch has rapidly expanded to meet the production and use levels mandated in the RFS. This conventional biofuel is produced commercially through proven technology and has comparatively well-established upstream and downstream value chains. The RFS for conventional biofuel was first established in 2005, through the Energy Policy Act, which required

[1] Energy Independence and Security Act of 2007 (PL 110-140). http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_bills&docid=f:h6enr.txt.pdf.

production and use of 7.5 million gallons by 2012.[2] The 2007 law doubled that production goal to 15 billion gallons by 2015. The industry leveraged existing supply chains for feedstock (corn), existing biorefineries that could be expanded, and newly constructed biorefineries based on replicable models and technology. The industry also benefited from demand for the product by the transportation fuel industry, which was seeking a replacement for the petroleum-derived oxygenate methyl tertiary butyl ether (MTBE).

Advanced biofuels are a collection of technologies at various stages of commercial development. Biodiesel (fatty acid methyl ester) from soy and sugarcane ethanol are two advanced biofuels with established upstream and downstream value chains. Sorghum and other starches have established value chains but are not produced on the same scale as corn, sugarcane and soy. Algae biodiesel and biofuels have made strides toward commercial development since 2008 but were not fully incorporated into the RFS and associated tax incentive policies established in 2007. Other feedstocks – such as animal fats – are currently waste streams from established value chains.

Supply chains for cellulosic and many other advanced biofuel feedstocks, by comparison, are not established. Crop residues are generally used as ground cover or soil amendment in the field or, if collected, in local markets, such as animal bedding and seed coverings. Energy grasses have not been grown on commercial scale, though some large field trials and demonstration-scale farms have been established. Forest thinning and slash traditionally is not collected. Municipal solid waste, while collected, is not sorted by cellulosic and non-cellulosic content. These feedstock supplies must be established in tandem with biorefineries and downstream value chains.

In 2007, when the EISA bill was signed, a few pilot-scale cellulosic and advanced biorefineries existed for proving the technology and working out economic and technical issues prior to scale-up. But no commercial-scale facilities exist even today that can provide easily replicable models. There are many variations on the technology for producing cellulosic biofuels; the list of projects below is not exhaustive but represents a range of technologies at demonstration and pilot scale – thermochemical, biochemical and hybrid, with variations on different process stages. The projects illustrate the progress companies have made in bringing the technology to demonstration scale and in raising capital to build new commercial-scale facilities.

Many pilot and demonstration projects have downstream markets outside of the fuel market governed by the RFS – private and demonstration fleets, for example. For most, due to their small size, registering their fuels for market use under the RFS is not cost competitive, because blenders and refiners obligated to sell cellulosic biofuels can obtain waivers at a cost that is determined by the lowest-cost advanced biofuel on the market.[3] Further, fuels and fuel blends other than ethanol and gasoline need to be certified by the EPA for use in vehicles and dispensing from pumps. The challenges of creating entirely

---

[2] Energy Policy Act of 2005 (PL 109-58). http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=109_cong_bills&docid=f:h6enr.txt.pdf.
[3] Biotechnology Industry Organization. *Industrial Biotechnology.* April 2011, 7(2): 111-117. doi:10.1089/ind.2011.7.111.

new upstream and downstream value chains have proved daunting, and no cellulosic biofuel RINs have been generated in the first 12 months of the program to meet the RFS mandates.

Raising capital to create these value chains has also been a challenge for many projects. A 2009 report from Bio Economic Research Associates, estimated the need to construct 389 new biorefineries ranging from 20 million to 200 million gallons per year in nameplate capacity by 2022 to meet the RFS requirements. The total project capital cost was projected to be more than $95 billion, with total annual costs rising from $2 billion in 2011 to $8.5 billion in 2016 and $12.2 billion in 2022.[4] A report from Sandia National Laboratories found no fundamental barriers to the construction of an even larger-scale biofuel industry than that mandated under the RFS, though capital expenditures on the order of $250 billion were needed to construct a complete value chain from feedstocks to fuel delivery.[5]

While there are no fundamental barriers to achieving the levels of production and use of cellulosic biofuels mandated in the RFS, there are economic, logistic and policy challenges. The formation of capital has been hampered by the recent economic recession and banking crisis. Implementation of the RFS, loan guarantees, and reverse auction has been slow, due to lengthy rulemaking procedures and inconsistent budgetary funding through Congressional appropriations. Additional programs that support the creation of feedstock supply chains also were subject to lengthy rulemakings and Congressional appropriations. Tax credits for cellulosic biofuel production are set to expire at the end of 2012, before most companies will be able to claim them. Enduring federal commitment to the goals of these programs is vital to continued investment and commercialization progress.

The projects listed below are pursuing a range of capital formation strategies, including licensing of technology and adding cellulosic capacity to existing conventional capacity. They are also pursuing a range of feedstock supply chain strategies that are specific to regional supplies and technologies. The growth of the industry is therefore not likely to follow the pattern of the conventional biofuel industry, which was based on a single feedstock and technology strategy (dry mill biorefining). However, the large volumes set in the advanced and cellulosic mandates of the RFS permit any number of technologies and strategies to compete for market space, depending on their ability to achieve cost competitiveness and necessary regulatory approvals. Regulatory neutrality and recognition under existing programs for new fuels and molecules are issues that policy makers must address.

Skepticism of the technology is unwarranted. While individual projects may fail or specific feedstock/technology combinations never reach commercial scale, the full range of projects in diverse areas of the country, combining local feedstocks with tailored technology, represent a robust response to the challenges.

---

[4] Bio Economic Research Associates (bio-era™), "U.S. Economic Impact of Advanced Biofuels Production: Perspectives to 2030." Biotechnology Industry Organization, February 2009.
[5] "90 Billion Gallon Biofuel Deployment Study." Sandia National Laboratories/GM. February 2009.

Abengoa Bioenergy New Technologies

Commercial biorefinery

Hugoton, Kans.

Technology platform:

Abengoa's biorefinery process employs a hybrid of enzymatic hydrolysis and pyrolysis or gasification.

1. biomass is fractionated to separate lignin from cellulose and hemicellulose.
2. Enzymes produced on site hydrolyze the carbohydrates into sugars for ethanol fermentation.
3. The lignin is sent to a gasifier that produces steam and electricity for the biorefinery, a neighboring ethanol plant and the local Kansas electrical grid.

Products:

The Hugoton biorefinery is designed to have a production capacity of 26.5 million gallons per year of cellulosic ethanol and 20 MW of renewable electricity.

Abengoa Bioenergy produces and sells conventional ethanol (370 million gallons in the U.S.) and distillers grains and solubles (980,000 tons in the U.S.).

Status of commercialization:

Construction of the Hugoton biorefinery began in Sept. 2011 and operations are projected to begin in the last quarter of 2013.

Abengoa began operation of a pilot facility (0.11 million gallons per year capacity) in York, Neb. in Oct. 2007, and opened a demonstration facility (1.32 million gallons per year capacity) in Babilafuente, Salamanca, Spain in Sept. 2009.

Funding:

A $34 million cost matching award from the Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy's (EERE) Biomass Program supported the construction of the Abengoa pilot plant in York, Neb. In 2007, DOE entered into a cooperative agreement with Abengoa Bioenergy to provide up to $100 million towards the construction of the commercial facility in Hugoton.

Abengoa finalized a $133.9 million federal loan guarantee from the DOE's Loan Programs Office in September 2011.

In July 2011, the U.S. Department of Agriculture (USDA) created a Biomass Crop Assistance Program (BCAP) project area including several counties in southwest Kansas, with Abengoa's Hugoton biorefinery as the sponsor biomass converter.

Collaborations:

Abengoa Bioenergy has a license from Dyadic for the use and modification of an organism that produces enzymes necessary for conversion of cellulose to sugars.

Future commercialization plans:

Abengoa Bioenergy has plans to incorporate hybrid biomass/bioenergy technology into many of its existing bioenergy plant locations in the United States, Europe and Brazil.

In 2009, Abengoa Bioenergy started the development of an algae program, including a pilot plant in Cartagena, where it will test various process configurations for capturing CO2 generated by fermentation in bioethanol production.

Coskata, Inc.

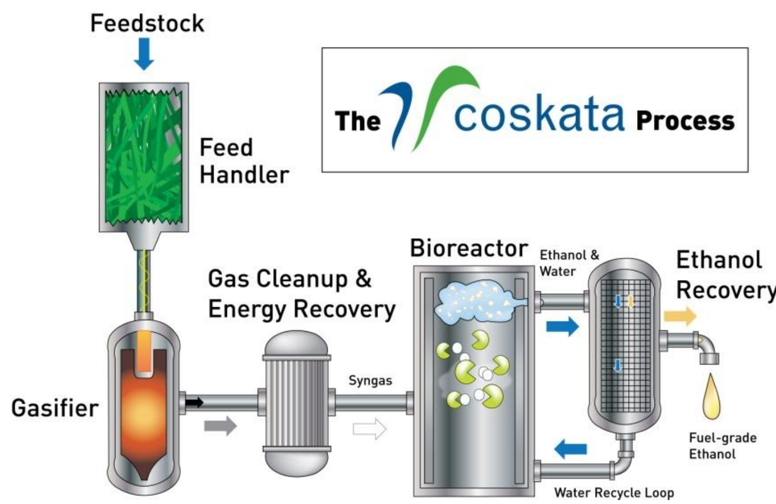
Commercial biorefinery

Boligee, Ala.

Technology platform:

Coskata's three-step process converts a wide variety of feedstocks into ethanol or other fuels and chemicals.

1. Gasification – Breaks chemical bonds in feedstock, converting it into synthesis gas (syngas), providing complete material utilization.
2. Fermentation – Bacterial fermentation of the syngas to produce ethanol (or other target chemical), with no byproducts.
3. Separation – Ethanol recovered via standard distillation and dehydration technology.



Additional highlights of the technology include:

- Feedstock flexibility;
- Yields over 100 gallons of ethanol per dry short ton of biomass;
- Low operating costs of production; complete material use reduces the costs and complexities of handling;
- No enzymes or pretreatment required;

Products:

The total capacity of the facility will be 80 million gallons of cellulosic ethanol, with portions of the plant starting in phases.

Status of commercialization:

Construction of the commercial scale facility will begin as soon the debt and equity financing are finalized.

Coskata has operated a semi-commercial 40,000 gallon per year FlexEthanol© facility in Madison, Pa. since October 2009.

Funding:

In Jan. 2011, Coskata received an initial letter of intent from USDA for $250 million loan guarantee. The parties are currently negotiating final amount and terms.

Collaborations:

Fagen, Inc. has been chosen as the Engineering, Procurement, and Construction firm for the commercial plant, in collaboration with The Harris Group International.

Future commercialization plans:

Coskata is scaling up a platform technology for the production of fuels and chemicals. It plans to license this technology as well as own commercial facilities. The company reports multiple commercial projects in the development phase around the globe.

DuPont

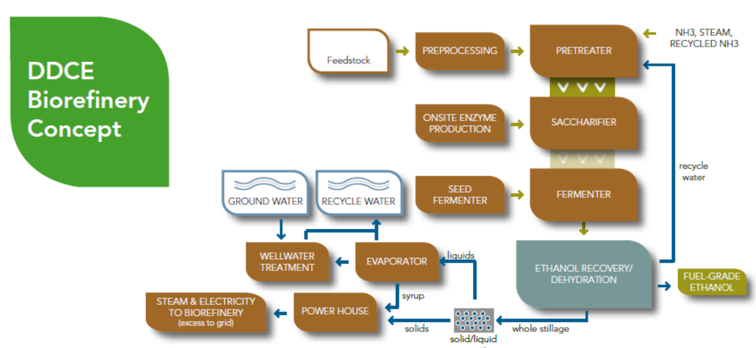
Pre-commercial biorefinery

Vonore, Tenn.

Technology platform:

DuPont employs a three-step process for converting lignocellulosic biomass (corn stover and switchgrass) to ethanol:

1. Pretreatment – dilute ammonia process, at low temperature and pressure, opens plant cell walls and provides a fermentation nutrient.
2. Saccharification – enzymes developed by Genencor are deployed in whole-broth formulation from on-site production to take advantage of complex cellulolytic activities.
3. Fermentation – a mixed-sugar ethanologen based on the bacterium *Zymomonas mobilis*.



> DuPont has optimized a strain developed with the National Renewable Energy Lab and applied advanced metabolic engineering to the xylose pathway to significantly improve the organism's ability to use C5 sugars (from hemicellulose) for ethanol production.*Z. mobilis* has high ethanol yield as well as high tolerance to ethanol in the hydrolysate, in excess of 100 g/l.

Products:

The demonstration facility has a capacity of 250,000 gallons per year, but its primary purpose is as an R&D facility to scale up the technology.

The company's primary products include ethanol, lignin co-product, and licensing technology packages for biorefineries based on regional feedstock needs.

Status of commercialization:

This pre-commercial facility began operation in Dec. 2009.

Funding

DuPont and Danisco created a 50/50 joint venture in May 2008, agreeing to an initial three-year funding of $140 million for ongoing development of the technology and the construction of demonstration plants. DuPont Danisco Cellulosic Ethanol LLC (DDCE) is now a wholly owned subsidiary of DuPont.

DDCE's partners, Genera Energy LLC and the University of Tennessee, received a $70.5 million grant to establish the Tennessee Biofuels Initiative. Genera and UT also received a $4.9 million grant from the U.S. Department of Energy to develop switchgrass as an energy crop.

Collaborations:

DDCE has partnered with the University of Tennessee (UT) Research Foundation, through its Genera Energy LLC, to construct the pilot biorefinery and a co-located research and development facility. The project leverage's UT's research in cellulosic feedstock production and its work with Tennessee farmers to develop the first dedicated cellulosic energy crop (switchgrass) supply chain for future testing at the facility.

DDCE is also launching a Stover Collection Program to support plans for a new commercial facility in Nevada, Iowa. DDCE is also collaborating with Pioneer Hi-Bred, also a DuPont Company, and Iowa State University, to establish best practices in harvesting, storage, and transportation.

Future commercialization plans:

DuPont is planning to break ground in 2012 on a commercial scale facility to convert corn stover to fuel , in Nevada, Iowa. The company has entered into an agreement to purchase a parcel of land adjacent to Lincolnway Energy LLC's conventional ethanol plant. The plant will prove the technology on commercial scale and support a global licensing business.

Enerkem Mississippi Biofuels LLC

Commercial biorefinery

Pontotoc, Miss.

Technology platform:

Enerkem's proprietary technology platform converts wastes and residues into second-generation biofuels through a partial oxidation, thermochemical process that involves low temperature and pressure and the use of commercially available catalysts. It is based on a gasification system coupled with an extensive cleaning and conditioning process and a sequential catalytic conversion process.

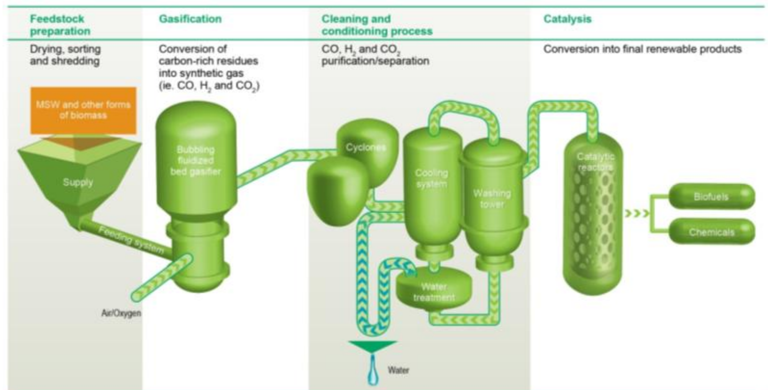


Figure 1: Enerkem's thermochemical technology platform

Enerkem's competitive strengths:

- The technology platform enables conversion of heterogeneous waste, such as MSW, into biofuels and chemicals.
- MSW is an abundant, low-cost feedstock that is already collected and is otherwise landfill-bound.
- Biorefineries are compact, modular and scalable for ease of replication.

Products:

Enerkem's primary focus is the commercial production of cellulosic ethanol. Its process first requires the production of methanol as a chemical building block for the production of ethanol. Enerkem can also sell its methanol as an end-product, or use it as a key intermediate to produce other renewable chemicals.

Status of commercialization:

Enerkem is expected to begin construction over the next few months. The company in 2009 signed a memorandum of intent with Three Rivers Solid Waste Management Authority of Mississippi (TRSWMA) for the supply of municipal solid waste. The company has completed federal environmental assessment requirements and is underway with state permitting processes.

Enerkem began operating a 1.3 million-gallons-per-year commercial demonstration plant in Westbury, Quebec, Canada in 2009 with the production of conditioned syngas from used electric utility poles. Production of biomethanol at the facility started in 2011 and will be followed by cellulosic ethanol.

Funding:

Enerkem was awarded funding worth up to $50 million under the Department of Energy's Recovery Act - Demonstration of Integrated Biorefinery Operations program in December 2009.

In January 2011, Enerkem received a conditional commitment for an $80 million loan guarantee under the USDA 9003 Biorefinery Assistance Program.

Collaborations:

Enerkem reports key strategic relationships with Valero Energy Corp. and Waste Management.

The Enerkem Mississippi Biofuels LLC project has been planned with cooperation from the Three Rivers Planning and Development District and the Three Rivers Solid Waste Management Authority.

Future commercialization plans:

In addition to its commercial plant under development in Mississippi and another one under construction in Edmonton, Alberta, Canada, Enerkem is developing several similar facilities in North America that will convert municipal solid waste into biofuels and chemicals.

As part of its business strategy, Enerkem has developed a modular, copy-exact and scalable approach, It's systems can be manufactured by third parties as prefabricated and replicable modules.

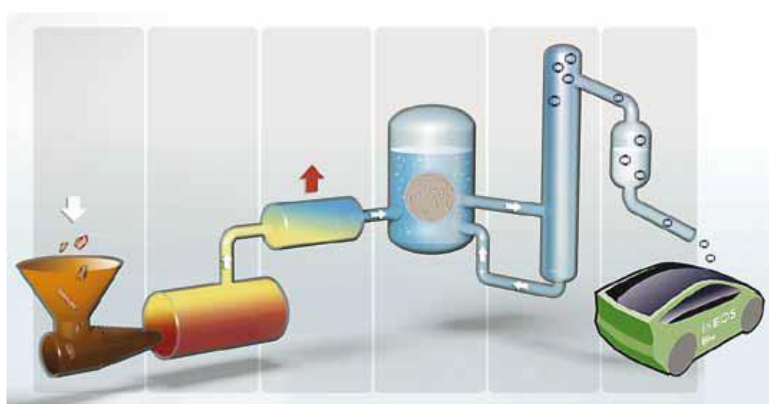
Enerkem will continue its R&D efforts to expand its current product range beyond ethanol, by taking advantage of its ability to produce a chemical-grade syngas that can serve as a key intermediate for the production of renewable chemicals.

INEOS New Planet BioEnergy

Commercial biorefinery

Vero Beach, Fla.

Technology platform:



The INEOS Bio process is feedstock flexible.

1. Organic materials are dried using heat from the process then gasified with oxygen at high temperature under controlled conditions to produce synthesis gas (syngas), a mixture of principally carbon monoxide and hydrogen.
2. The hot syngas is cooled and cleaned before being introduced to the fermenter. The heat recovered from the hot syngas is used to generate renewable power for use in the process. The

cool, clean syngas is introduced to bacteria (*Clostridium ljungdahlii*), which convert it selectively to ethanol.

3. Most of the water is removed from the ethanol to produce hydrous ethanol, at about 96 percent concentration. The water is returned to the fermenter. The ethanol product is refined to produce anhydrous ethanol (>99.7% ethanol).

Products:

The Indian River BioEnergy Center will produce 8 million gallons of advanced biofuels and six megawatts of renewable power annually from renewable biomass including local yard, vegetative and household wastes.

Status of commercialization:

Construction is approximately 20 percent complete and is scheduled to be completed by the end of April 2012.

INEOS Bio operates a pilot plant in Fayetteville, Ark. The pilot plant was built by Bioengineering Resources Inc (BRI) in 1994 and expanded in 2003 with the addition of a gasifier.

Funding:

In August 2011, INEOS New Planet BioEnergy (INPB) finalized $75 million in private financing utilizing the U.S. Department of Agriculture (USDA) loan guarantee program. This is the first commercial advanced bioenergy project in the United States to finalize its financing under the USDA program. The financing concludes all necessary funding to complete the project and will be used for equipment, engineering and construction.

In 2009, the BioEnergy Center project was awarded a $50 million cost matching grant from the U.S. Department of Energy (DOE) and a $2.5 million dollar cost matching grant from the state of Florida.

Collaborations:

INEOS New Planet BioEnergy (INPB) is a joint venture between INEOS Bio and New Planet Energy, a project development firm.

Future commercialization plans:

INEOS Bio will enter into licensing agreements with third parties to build similar commercial bioenergy plants to supply advanced bioethanol and renewable electricity around the U.S. and the world.

KiOR, Inc.

Initial-scale commercial facility

Columbus, Miss.

Technology platform:

KiOR's process converts cellulosic biomass into a renewable crude oil that can be refined in a conventional hydrotreater into light refined products, such as gasoline and diesel blendstocks. Their platform combines proprietary catalyst systems with well-established fluid catalytic cracking (FCC) processes that have been used in crude oil refineries for more than 60 years. The biomass fluid catalytic cracking (BFCC) process operates at moderate temperatures and pressures.

KiOR's technical and commercial strengths include:

- Combination of proprietary technology with well-established FCC and other refining processes.
- As of June 9, 2011, the company had 70 pending original patent application families containing over 2,000 pending claims.
- Realized yield of gasoline and diesel blendstocks from renewable crude oil is approximately 90 percent.
- Feedstock flexible and successfully tested on a variety of biomass. KiOR's Columbus, Miss. production facility selected Southern Yellow Pine whole tree chips as a primary feedstock.

According to KiOR, "Our two-train centralized hydrotreaters will be constructed in phases, with each train expected to support up to two standard commercial production facilities. By employing larger plant designs and shared hydrotreating facilities, we expect to be able to more effectively allocate our fixed costs and stage our capital program to reduce the capital intensity of our commercial expansion. By staging the expansion of our standard commercial facilities in discrete facility-by-facility projects that are independently viable, we believe that we will have flexibility to plan our growth in response to capital availability and market conditions."

Products:

The Columbus facility will have a 500 BDT per day feedstock capacity and is expected to produce 11 million gallons of renewable gasoline, diesel and fuel oil blendstocks per year.

Status of commercialization:

KiOR began construction of its first initial-scale commercial facility in the first quarter of 2011 and expects to have construction 40 percent complete by mid-November 2011, aiming to bring the facility online in the second half of 2012.

KiOR currently operates a demonstration faciltiy in Pasadena, Texas, producing up to 15 barrels per day of renewable crude oil.

KiOR has off-take agreements in place to supply gasoline and diesel blendstocks from the Columbus facility to Hunt Refining Company and Catchlight Energy (a joint venture between Chevron and Weyerhaeuser) and provide diesel blendstocks to FedEx Corporate Services.

Funding:

KiOR has received no federal funding or loan guarantees to date.

It received a $75 million loan from the state of Mississippi in the fall of 2010 to help fund the construction of the commercial facility in Columbus, Miss. Private investors supplied the remainder of the approximately $207-211 million in capital for the plant.

Future commercialization plans:

KiOR plans to deploy a “copy exact” strategy of standardized, modular 1,500 bone dry tons (BDT) per day designs to facilitate fast deployment of new production facilities with reduced capital costs and operating costs.

KiOR reports that much of its planning for transportation fuel market expansion comes from R&D with specific feedstock types.

KiOR intends to construct 1,500 BDT per day standard commercial production facilities (with three times the capacity of the initial-scale commercial production facility in Columbus) beginning in the third quarter of 2012, with the first facility planned in Newton, Miss.

These standard commercial production facilities are being designed to utilize a centralized hydrotreating facility rather than dedicated, standalone hydrotreaters, such as the one being constructed at the Columbus facility.

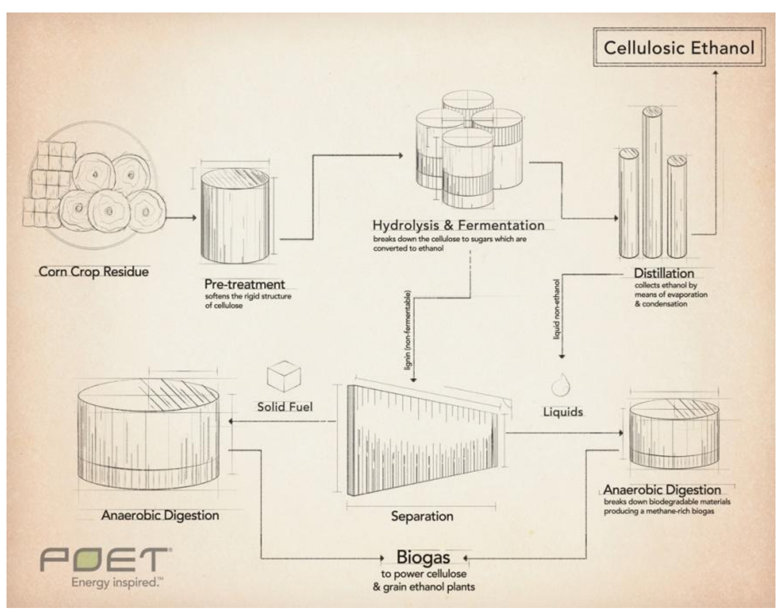
POET Project Liberty

Commercial biorefinery

Emmetsburg, Iowa

Technology platform:

POET uses enzymatic hydrolysis to unlock the cellulose from biomass for fermentation. Once pre-treated, the material is fermented and distilled in a process similar to that for grain-based ethanol.



Products:

Project Liberty will have a planned capacity of 25 million gallons per year of cellulosic ethanol, with sufficient biogas to power the plant and a neighboring grain ethanol plant.

Status of commercialization:

Construction on the biorefining facility is expected to start in early 2012 and be completed in late 2013. Last harvest, POET took delivery of 56,000 tons of corn cobs, leaves, husks and stalks from farmers in the Emmetsburg area. A weigh station is currently under construction with more biomass to be collected this fall.

The POET Research Center, with a capacity of 20,000 gallons per year, began producing cellulosic ethanol in late 2008. It is also testing an anaerobic digester that will provide power to Project Liberty and POET's adjacent grain-based ethanol plant, POET Biorefining - Emmetsburg.

POET reports a drop in the estimated cost of cellulosic ethanol from about $4.13 per gallon upon starting the pilot plant to about $2.35 today.

POET operates 27 conventional corn biorefineries in seven states, producing annually 1.6 billion gallons of ethanol, 5 million tons of Dakota Gold® DDGs for animal feed, Inviz™ zein for chemical applications, and Voila™ corn oil.

Funding:

In September 2011, POET finalized a $105 million DOE loan guarantee.

In December 2010, POET Project Liberty, POET Research Center and POET Biorefining - Chancellor, S.D., became qualified processing centers under the USDA Biomass Crop Assistance Program.

In Jan. 2010, The Iowa Department of Economic Development approved an agreement for $5.25 million in financial assistance to POET's Project Liberty.

Collaborations:

Novozymes North America provides enzyme technology for Project Liberty.

Agriculture equipment manufacturers, including AGCO, Case IH, John Deere, and Vermeer, are developing equipment for collection of corn cobs, leaves, husks and stalks.

Future commercialization plans:

POET plans to have a hand in producing 3.5 billion gallons of cellulosic ethanol by 2022:

- 1 billion gallons by introducing Project LIBERTY technology to the rest of POET's network of 27 plants in seven states.
- 1.1 billion gallons by licensing this technology to other ethanol producers.
- 1.4 billion gallons by expanding to new feedstock such as wheat straw, rice hulls, woodchips or switchgrass.

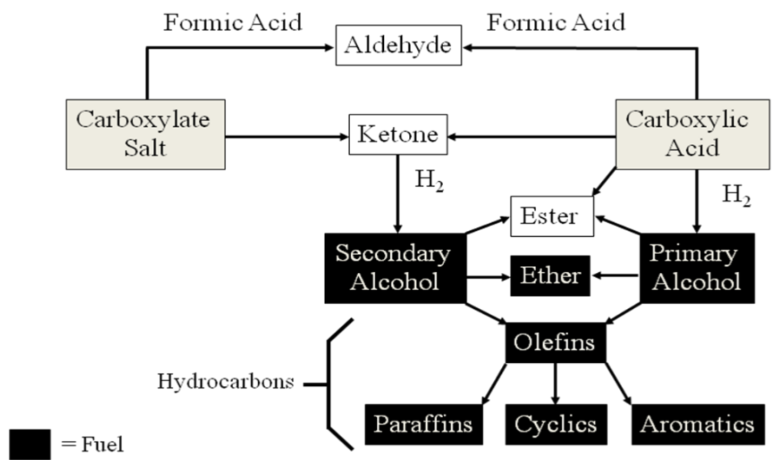
Terrabon, Inc.

Demonstration plant

Bryan, Texas

Technology platform:

Terrabon's MixAlco® process converts any anaerobically biodegradable material (e.g., proteins, cellulose, hemicellulose, fats and pectin) into a wide array of chemicals (e.g., ketones, secondary alcohols) and fuels (e.g., drop-in biofuels such as gasoline, diesel and jet fuel). The conversion occurs by non-sterile, anaerobic fermentation of biomass into mixed carboxylic acids and salts by a mixed culture of naturally occurring microorganisms. The conversion of the mixed acids and salts into the desired chemicals or fuels employs conventional chemistry.



- Terrabon uses Municipal Solid Waste (MSW), sewage sludge, forest product and agricultural residues such as wood chips, wood molasses and corn stover, and non-edible energy crops such as sweet sorghum as the feedstock for the MixAlco® process to make ketones, secondary alcohols and gasoline.
- This process can increase landfill life and replace non-renewable petroleum resources.
- According to a Life Cycle Analysis (LCA) using the GREET model, MixAlco® will reduce greenhouse gas emissions by over 78 percent compared to conventional gasoline pathways.
- This process may also use other waste products of environmental concern such as leachate from landfills and raw sewage.

Products:

The plant can potentially process the equivalent of 5 dry tons per day of biomass and generate enough anaerobic fermentation products to produce 100,000 gallons of green gasoline and green jet fuel per year. Depending on chemical pathway chosen, we can produce mixed primary alcohols, mixed secondary alcohols, ethers, esters, ketones, green gasoline, green diesel and green jet fuel.

Status of commercialization:

Terrabon opened the demonstration plant in Bryan, Texas, in July 2010.

Funding:

In July 2011, Terrabon was awarded a $9.6 million, 18-month contract by Logos Technologies to design a more economical and renewable jet fuel (BioJet™) production solution for the Defense Advanced Research Projects Agency (DARPA). Started in April of 2011, a customized production process for DARPA will be engineered, constructed and operated at Terrabon's Bryan demonstration facility and capable of producing 6,000 liters of jet fuel through the use of the company's advanced bio-refining MixAlco® technology.

In July 2010, Terrabon was awarded $2.75 million from the Texas Emerging Technology Fund.

Collaborations:

Waste Management Corporation is a feedstock supplier and investor in Terrabon. Valero Energy Corporation is an off-take partner and investor.

In January 2011, Terrabon announced that the company had successfully produced 70 gallons of renewable cellulosic biofuel blendstock per ton of MSW by leveraging CRI/Criterion's renewable fuel catalyst technologies.

Future commercialization plans:

By 2013, Terrabon expects to be operating a 240-dry ton per day MSW biorefinery, with production capacity of 5.2 million gallons per year of green gasoline, optimally sited between Waste Management's MSW operations and Valero refineries.

Vercipia

Commercial biorefinery

Highlands County, Fla.

Technology platform:

1. Acid Hydrolysis of Hemicellulose – biomass undergoes mild acid hydrolysis and steam explosion to break down plant matter and convert the hemicellulose fraction into pentose (C5). The result is a fibrous slurry mixture of liquid pentose sugar and cellulose/lignin solids (fiber).
2. Pentose (C5) Fermentation – pentose sugars are separated from the fiber solids through mechanical de-watering. C5 sugar syrup is recovered and fermented into a dilute ethanol beer.
3. Cellulose Hydrolysis and Ethanol Fermentation (C6) – cellulose and lignin residues are recovered and subjected to simultaneous enzymatic hydrolysis of cellulose into glucose sugars and fermentation of the glucose into a dilute ethanol beer. Commercial enzymes for this step are produced on site.
4. Beer Well – C5 and C6 beers are collected and distilled into high-grade ethanol. Lignin-rich residue left over from distillation is burned, yielding steam for the process.

Products:

The plant has a planned capacity of 36 million gallons per year of cellulosic ethanol.

Status of commercialization:

Vercipia intends to break ground on the Highlands County, Fla. facility in 2011. Production is expected to begin in 2013.

The company has reported delays in obtaining necessary permits to widen roads for access to the facility.

Vercipia's parent company, BP, owns and operates a 1.4 million gallon pilot facility in Jennings, La.

Funding:

In April 2010, Verenium Corp. (an original collaborator and joint partner) received a $4.9 million grant from the DOE for research conducted at the Jennings, La., pilot facility. This supplemented a previous July 2008 grant.

In June 2009, Verenium and BP were invited to the due diligence phase of the DOE loan guarantee process.

The project was awarded a $7 million grant in Jan. 2009 under Florida Agriculture and Consumer Services Commissioner Charles H. Bronson's "Farm to Fuel" initiative.

Collaborations:

Vercipia was established in April 2009 as a 50/50 joint venture between Verenium Corp. and BP. BP acquired full control in September 2010.

The Company has entered into a long-term agreement with Lykes Bros., Inc, a family-owned Florida agricultural business, to provide the energy grasses for conversion to fuel.

Future commercialization plans:

None announced.

ZeaChem, Inc.

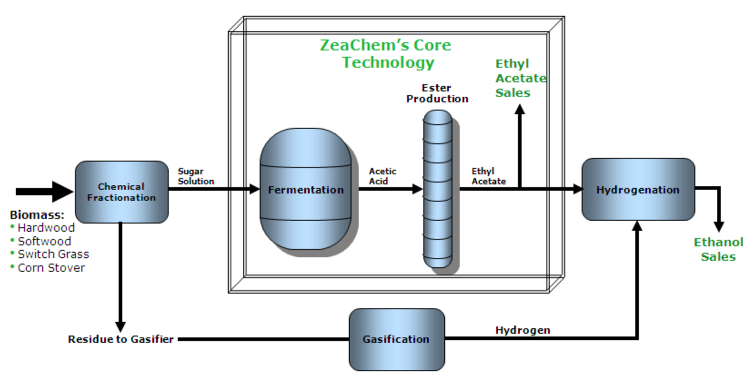
Demonstration facility

Boardman, Ore.

Technology platform:

ZeaChem utilizes a hybrid approach of biochemical and thermochemical processing. ZeaChem's technology, while protected intellectual property, utilizes no new organisms or processes.

1. After fractionating the biomass, the sugar stream – made up of both xylose (C5) and glucose (C6) – is fermented to acetic acid by a



naturally occurring bacteria. Without CO_2 as a by-product, the carbon efficiency of the ZeaChem acetogenic fermentation process is nearly 100 percent, compared to 67 percent for yeast.
2. The acetic acid is converted to an ester, which when reacted with hydrogen forms ethanol.
3. ZeaChem takes the lignin residue from the fractionation process and gasifies it to create a hydrogen-rich syngas stream.

The process presents technological, economic and environmental highlights:

- Feedstock agnostic: ZeaChem's technology can utilize various feedstocks including wood, grasses, and residues. ZeaChem's feedstock strategy is to utilize sustainable dedicated energy crops and to supplement with local residuals (agriculture and forest), which allows for geographic diversity of biorefinery locations.
- The hybrid process: ZeaChem incorporates biochemical and thermochemical processes to deliver a 40 percent yield advantage. This leads to competitive economics and significant environmental benefits.
- Product flexibility: ZeaChem's technology can produce C2 (acetic acid, ethyl acetate, ethanol, ethylene), C3 (propionic acid, propanol, propylene), C4 (butanol) and C6 (hexene, hexanol) products. ZeaChem biorefineries will be capable of generating products that yield the best margin. Should market conditions change (policy, economics, etc), ZeaChem facilities will have the flexibility to change the products, providing valuable flexibility and establishing opportunities for multiple product off-take partners.

Products:

The demonstration integrated biorefinery (IBR) in Boardman, Ore. will have a capacity of 250,000 gallons per year. The facility will produce acetic acid, ethyl acetate and ethanol. An expansion of the IBR facility will enable the production of bio-based jet and diesel fuel.

Status of commercialization:

ZeaChem's IBR facility will begin operations by the end of 2011. The first commercial biorefinery is currently under development at a site adjacent to the IBR facility in Boardman, Ore. The biorefinery is expected to have capacity of 25M or more GPY and is expected to begin operations in 2014. At this time, 100 percent of the feedstock for the commercial biorefinery has been secured.

Funding:

ZeaChem has raised $40 million in private funding to date. ZeaChem's investors include Firelake Capital; Globespan Capital Partners; Mohr, Davidow Ventures; PrairieGold Venture Partners; and Valero Energy Corporation.

In December 2009, ZeaChem was selected for a $25 million grant from the U.S. Department of Energy (DOE) to fund the independent front and back-end cellulosic process components of the IBR facility, enabling ZeaChem to produce fuel grade ethanol as well as intermediate chemicals from non-food related biomass. The award was granted in May 2010.

In July 2011, USDA announced that Boardman, Ore. has been selected as a Biomass Crop Assistance Program (BCAP) project area, with ZeaChem as the sponsor biomass converter. USDA will fund the establishment and maintenance of 7,000 acres of intercropped, coppice hybrid poplar trees at GreenWood Resources' 28,000 acre existing tree farm in Boardman for the production of advanced biofuels and bio-based chemicals by ZeaChem.

Collaborations:

In May 2011, ZeaChem Inc. signed a long-term binding term sheet with GreenWood Tree Farm Fund (GTFF), managed by GreenWood Resources (GWR), to supply hybrid poplar woody biomass for its first commercial cellulosic biorefinery planned for Port of Morrow, Boardman, Ore.

In June 2011, ZeaChem announced a binding multi-year joint development agreement with Procter & Gamble that will accelerate development of ZeaChem's product platform beyond C2 through the commercialization of "drop-in" bio-based chemicals and other products.

In August 2011, Chrysler Group LLC and ZeaChem Inc. announced they had entered into a Memorandum of Understanding (MOU) to accelerate the development and market adoption of advanced cellulosic ethanol and strengthen the credibility among regulators and American consumers of cellulosic ethanol as a cost-effective green transportation alternative.

Future commercialization plans:

ZeaChem is developing commercial biorefineries for the production of economical and sustainable advanced biofuels and bio-based chemicals. The first commercial biorefinery is under development and is expected to begin operations in 2014 in Boardman, Ore.

Acknowledgements.

The author thanks the following for contributions to and review of the material: Christopher G. Standlee, Executive Vice President, Abengoa Bioenergy U.S. Holding, Inc.; Wesley J. Bolsen, Chief Marketing Officer & VP, Government Affairs, Coskata, Inc.; Jennifer Hutchins, Director of Marketing & Communications , DuPont Danisco Cellulosic Ethanol (DDCE); Marie-Hélène Labrie, Vice President, Government Affairs and Communications, Enerkem; Tim O'Keefe, Dig Communications for KiOR; Molly LeCronier, Ward Creative Communications for Terrabon; Carrie Atiyeh, Director, Public Affairs, ZeaChem Inc.