CREATING CELLULOSIC ETHANOL

SPINNING STRAW INTO FUEL

The prospects to replace gasoline by converting cellulosic biomass feedstocks into ethanol are looking brighter. Now the challenge is to get the right policy changes to make that transition.

Diane Greer

IN THE Grimm Brother's fairy tale, Rumpelstiltskin spins straw into gold. Thanks to advances in biotechnology, researchers can now transform straw, and other plant wastes, into "green" gold — cellulosic ethanol. While chemically identical to ethanol produced from corn or soybeans, cellulose ethanol exhibits a net energy content three times higher than corn ethanol and emits a low net level of greenhouse gases. Recent technological developments are not only improving yields but also driving down production cost, bringing us nearer to the day when cellulosic ethanol could replace expensive, imported "black gold" with a sustainable, domestically produced biofuel.

Cellulosic ethanol has the potential to substantially reduce our consumption of gasoline. "It is at least as likely as hydrogen to be an energy carrier of choice for a sustainable transportation sector," say the National Resources Defense Council (NRDC) and the Union of Concerned Scientists in a joint statement. Major companies and research organizations are also realizing the potential. Shell Oil has predicted "the global market for biofuels such as cellulosic ethanol will grow to exceed $10 billion by 2012." A recent study funded by the Energy Foundation and the National Commission on Energy Policy, entitled "Growing Energy: How Biofuels Can Help End America's Oil Dependence", concluded "biofuels coupled with vehicle efficiency and smart growth could reduce the oil dependency of our transportation sector by two-thirds by 2050 in a sustainable way."

ISN'T ALL ETHANOL THE SAME?

Conventional ethanol and cellulosic ethanol are the same product, but are produced utilizing different feedstocks and processes. Conventional ethanol is derived from grains such as corn and wheat or soybeans. Corn, the predominant feedstock, is converted to ethanol in either a dry or wet milling process. In dry milling operations, liquefied corn starch is produced by heating corn meal with water and enzymes. A second enzyme converts the liquefied starch to sugars, which are fermented by yeast into ethanol and carbon dioxide. Wet milling operations separate the fiber, germ (oil), and protein from the starch before it is fermented into ethanol.

Cellulosic ethanol can be produced from a wide variety of cellulosic biomass feedstocks including agricultural plant wastes (corn stover, cereal straws, sugarcane bagasse), plant wastes from industrial processes (sawdust, paper pulp) and energy crops grown specifically for fuel production, such as switchgrass. Cellulosic biomass is composed of cellulose, hemicellulose and lignin, with smaller amounts of proteins, lipids (fats, waxes and oils) and ash. Roughly, two-thirds of the dry mass of cellulosic materials are present as cellulose and hemicellulose. Lignin makes up the bulk of the remaining dry mass.

As with grains, processing cellulosic biomass aims to extract fermentable sugars from the feedstock. But the sugars in cellulose and hemicellulose are locked in complex carbohydrates called polysaccharides (long chains of monosaccharides or simple sugars). Separating these complex polymeric structures into fermentable sugars is essential to the efficient and economic production of cellulosic ethanol.

Two processing options are employed to produce fermentable sugars from cellulosic biomass. One approach utilizes acid hydrolysis to break down the complex carbohydrates into simple sugars. An alternative method, enzymatic hydrolysis, utilizes pretreatment processes to first reduce the size of the material to make it more accessible to hydrolysis. Once pretreated, enzymes are employed to convert the cellulosic biomass to fermentable sugars. The final step involves microbial fermentation yielding ethanol and carbon dioxide.

Grain based ethanol utilizes fossil fuels to produce heat during the conversion process, generating substantial greenhouse gas emissions. Cellulosic ethanol production substitutes biomass for fossil fuels, changing the emissions calculations, according to Michael Wang of Argonne National Laboratories. Wang has created a "Well to Wheel" (WTW) life cycle analysis model to calculate greenhouse gas emissions produced by fuels in internal combustion engines. Life cycle analyses look at the environmental impact of a product from its inception to the end of its useful life.

"The WTW model for cellulosic ethanol showed greenhouse gas emission reductions of about 80 percent [over gasoline]," said Wang. "Corn ethanol showed 20 to 30 percent reductions." Cellulosic ethanol's favorable profile stems from using lignin, a biomass by-product of the conversion operation, to fuel the process. "Lignin is a renewable fuel with no net greenhouse gas emissions," explains Wang. "Greenhouse gases produced by the combustion of biomass are offset by the CO_2 absorbed by the biomass as it grows."

Feedstock sources and supplies are another important factor differentiating the two types of ethanol. Agricultural wastes are a largely untapped resource. This low cost feedstock is more abundant and contains greater potential energy than simple starches and sugars. Currently, agricultural residues are either plowed back into the soil, composted, burned or disposed in landfills. As an added benefit, collection and sale of crop residues offer farmers a new source of income from existing acreage.

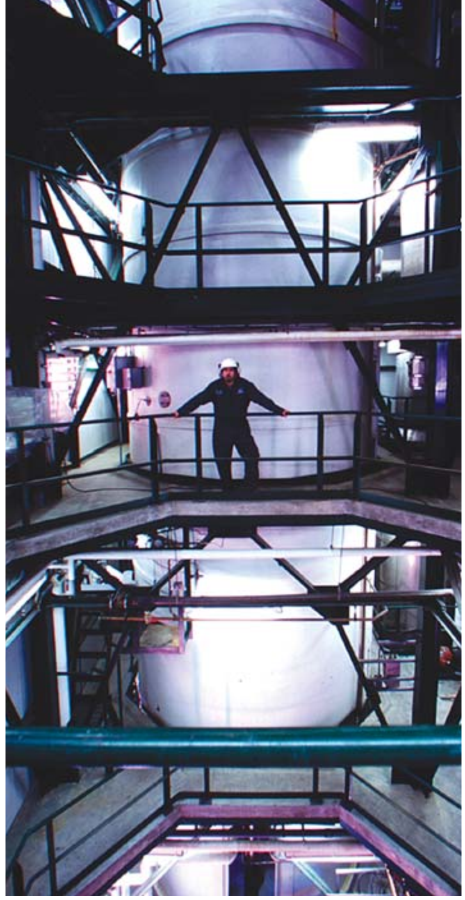
Industrial wastes and municipal solid waste (MSW) can also be used to produce ethanol. Lee Lynd, an engineering professor at Dartmouth, has been working with the Gorham Paper Mill to convert paper sludge to ethanol. "Paper sludge is a waste material that goes into landfills at a cost of $80/dry ton," says Lynd. "This is genuinely a negative cost feedstock. And it is already pretreated, eliminating a step in the conversion process."

Masada Oxynol is planning a facility in Middletown, New York, to process MSW into ethanol. After recovering recyclables, acid hydrolysis will be employed to convert the cellulosic materials into sugars. "The facility will provide both economic and environmental value," explains David Webster, Executive Vice President of Masada. From an environmental standpoint, the process reduces or eliminates the landfilling of wastes. By-products of the process include gypsum, lignin and fly ash. "Under normal operations, enough lignin will be recovered to make the plant self-sufficient in energy," notes Webster.

Perennial grasses, such as switchgrass, and other forage crops are promising feedstocks for ethanol production. "Environmentally switchgrass has some large benefits and the potential for productivity increases," says John Sheehan of the National Renewable Energy Laboratory (NREL). The perennial grass has a deep root system, anchoring soils to prevent erosion and helping to build soil fertility. "As a native species, switchgrass is better adapted to our climate and soils," adds Nathanael Greene, NRDC Senior Policy Analyst. "It uses water efficiently, does not need a lot of fertilizers or pesticides and absorbs both more efficiently.

OVERCOMING THE RECALCITRANCE OF BIOMASS

Reducing the cost and improving the efficiency of separating and converting cellulosic materials into fermentable sugars is one of the keys to a viable industry. "On the technology side, we need a major push on overcoming the recalcitrance of biomass," continues Greene, referring to the difficulty in breaking down complex cellulosic biomass structures. "This is the greatest difficulty in converting biomass into fuel." R&D efforts are focusing on the development of cost-effective biochemical hydrolysis and pretreatment processes. Technological advances promise substantially lower processing costs in these fields compared to acid hydrolysis. "In the enzyme camp, we have only scratched the surface of the potential of biotechnology to contribute to this area," adds Reade Dechton of Energy Futures Coalition. "We are at the very beginning of dramatic cost improvements."

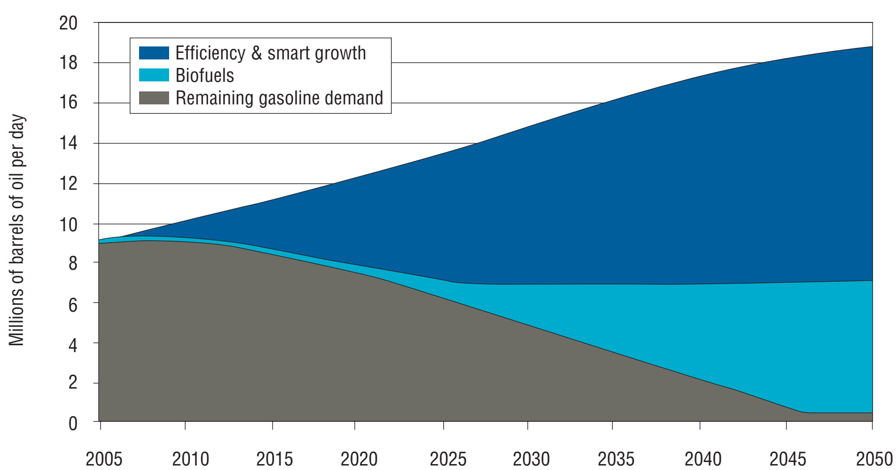


While researchers seek to combine enzymatic hydrolysis and fermentation, a facility in Ottawa uses a fermenter to produce 260,000 gallons/year of ethanol from wheat straw.

The Department of Energy (DOE) Biofuels program has identified the high cost of cellulase enzymes as the key barrier to economic production of cellulosic ethanol. Two enzyme producers, Genencor International and Novozymes Biotech, have received research funding from DOE to engineer significant cost reductions and efficiency improvements in cellulase enzymes. In October of 2004, Genencor announced a 30-fold reduction in the cost of enzymes to a range of $0.10-$0.20 per gallon of ethanol. To achieve the savings, Genencor developed a mixture of genetically modified enzymes that act synergistically to convert cellulose into glucose. Novozymes Biotech has also progressed in reducing enzyme costs from $5.00 to $0.30 per gallon of ethanol. In April of 2004, Novozymes was granted a one year extension and awarded an additional $2.3 million to further reduce the cost of enzymes to $0.10 per gallon.

Another major thrust of R&D efforts is devoted to improving pretreatment technologies. Pretreatment is required to break apart the structure of biomass to allow for the efficient and effective hydrolysis of cellulosic sugars. "Seventy percent of total mass is composed of structural carbohydrates, either five or six carbon sugars," explains Bruce Dale, a chemical engineering professor at Michigan State University. "Getting higher yields of those sugars efficiently without degrading the materials is the focus of pretreatment."

Figure 1. Reducing total transportation oil demand through efficiency, smart growth, and biofuels



Source: Nathanael Greene *et al.*, "Growing Energy: How Biofuels Can Help End" America's Oil Dependence," prepared for the National Commission on Energy Policy, (Natural Resources Defense Council, 2004).

Pretreatment technologies utilize dilute acid, steam explosion, ammonia fiber explosion (AMFE), organic solvents or other processes to disrupt the hemicellulose/lignin sheath that surrounds the cellulose in plant material. Each technology has advantages and disadvantages in terms of costs, yields, material degradation, downstream processing and generation of process wastes.

One of the most promising pretreatment technologies, Ammonia Fiber Explosion (AMFE), employs liquid ammonia under moderate heat and pressure to separate biomass components. "The goal is to get the plant material to provide you with a lot of sugar without a lot of extra cost," says Dale who is working on optimizing the process.

A report indicates that expansion of biomass supplies needed to achieve production levels would not have large impacts on the agricultural system.

CONSOLIDATED BIOPROCESSING

Many experts believe consolidated bioprocessing (CBP) shows the greatest potential for reducing conversion costs. CBP employs recombinant DNA technology to alter the DNA of a microbe by joining it with genetic material from one or more different organisms. In the case of cellulosic ethanol production, the goal is to genetically engineer microbes with the traits necessary for one step processing of cellulosic biomass to ethanol.

Dartmouth engineering professor Lynd is utilizing CBP techniques to produce microbial systems combining both enzymatic hydrolysis and fermentation operations. Lynd's group is working to consolidate cellulase production, cellulose hydrolysis, hexose fermentation and pentose fermentation into one organism while maintaining sufficiently high yields.

FEEDSTOCK RESOURCES

Can American agricultural systems support large-scale cellulosic ethanol production? That is the big question. Do we have sufficient land? Can biomass be supplied without impacting the cost of agricultural land, competing with food production and harming the environment? The answer to these questions ranges from no to a qualified yes, contingent upon R&D efforts, technological innovation and government policy.

Battelle's recent report entitled, "Near-Term U.S. Biomass Potential", looked at a scenario for producing 50 billion gallons of ethanol per year from cellulosic biomass. "The primary biomass supply would consist of waste biomass streams plus the production of energy crops." The waste stream was estimated to contribute 40-50 percent of the supply. The report concluded that the expansion of biomass supplies needed to achieve this level of production "would not result in large impacts on the agricultural system". Beyond this level of production, "dedicated energy crops would be required with implications for the cost of cropland and competition with food crops."

The NRDC "Growing Energy" report approached the question from a different angle. It asked if there were technological, process and policy changes that would allow biofuels to fulfill a large proportion of energy required by vehicles. The research constrained land utilization to the amount already under cultivation while insuring sufficient land for food and textile production in addition to employing resources in a sustainable manner.

"There is a lot that needs to happen if we are going to take advantage of this technology," says Nathanael Greene, author of the "Growing Energy" report. "If we are serious about ending our dependency on oil, we need to innovate and change." Greene and his colleagues identified several areas crucial to making biofuels work: increased vehicle efficiency, smart growth policies, improvements in conversion efficiencies, utilization of energy crops such as switchgrass, coproduction of animal protein and increased switchgrass yields.

Assuming no increase in vehicle efficiency and a continued growth in driving, the U.S. is on a path to consume 290 billion gallons of gasoline in our cars and trucks by 2050. The report found increasing vehicle efficiencies to 50 mpg or better and instituting smart growth policies could reduce consumption to 108 billion gallons by 2050. "Our goal is mobility, not energy consumption," says Lynd. "For a given unit of energy, two-thirds can be replaced by efficiency and one third by supply. We are kidding ourselves if we think we can supply our way out of this. We can make the biggest impacts fastest by impacting the efficiency equation."

The "Growing Energy" report projects conversion efficiencies, the number of gallons of ethanol produced per dry ton of biomass, to improve from 50 gallons per dry ton to 117 gallons per dry ton. One hundred seventeen gallons of ethanol per dry ton equates to 77 gallons of gas equivalent per dry ton (one gallon of ethanol contains 66 percent of the energy content of gasoline). The bulk of the increase is expected to come from R&D driven advances in biological processing.

"The key to producing enough ethanol is switchgrass," says Greene. Switchgrass shows great potential for improving yields, offers environmental benefits and can be grown in diverse areas across the country. Current average yields are five dry tons per acres. Crop experts have concluded standard breeding techniques, applied progressively and consistently, could more than double the yield of switchgrass. Yield improvements predicted by the report of 12.4 dry tons per acre are in keeping with results from breeding programs with crops such as corn and other grasses. The innovations discussed have a net effect of reducing the total land required to grow switchgrass to an estimated 114 million acres. Sufficient switchgrass could be grown on this acreage to produce 165 billion gallons of ethanol by 2050, which is equivalent to 108 billion gallons of gasoline. The next logical question is how do we integrate switchgrass production into our agricultural systems. The answer lies with the ability to produce animal protein from switchgrass. "If we have cost-effective agricultural policy, farmers will rethink what they plant," says Lynd. "For example, we are using 70 million acres to grow soybeans for animal feed. You can grow more animal feed protein per acre with switchgrass. If there were a demand for biomass feedstocks to produce ethanol and other biofuels, farmers would be able to increase their profits by growing one crop producing two high value products."

While the promise of higher profits and more products is enticing, planting new crops and introducing new methodologies will present risks to farmers. Switchgrass is a perennial that takes several years to mature. Farmers will not make such a commitment unless they feel confident in the economics.

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TRANSITIONING TO CELLULOSIC ETHANOL

One of the attractions of biofuels is they can be utilized in today's internal combustion engines with little or no changes. "The only source of liquid transportation fuels to replace oil is biomass," says Greene. "Everyone is excited about hydrogen but there are some very serious technical and infrastructure challenges. If you can stick with a liquid fuel which is compatible with our infrastructure and the vehicles we use, it is an easier transformation."

Light duty cars and trucks can already run on gasoline containing 10 percent ethanol. There are an estimated 1.2 million flex fuel cars on the road capable of running on a wide range of biofuels including E85, a mixture of 85 percent ethanol and 15 percent gasoline. "Manufacturing flex fuel vehicles is a trivial change," said Dechton. "It costs less than $200 per vehicle. They are selling them now and people do not know that they are buying them."

New vehicles with catalyst systems, certified for California Level II or Federal Tier 2 standards, have very low CO, VOC and NO_x emissions. Using higher blends of ethanol in these vehicles should not pose any problem in increased NO_x emissions. Any increase in NO_x emission due to ethanol use will be short-term, dependent upon the rate at which old cars are replaced with new, lower emission models.

ECONOMICS, THE ENVIRONMENT AND ENERGY SECURITY

The arguments in favor of cellulosic ethanol as a replacement for gasoline in cars and trucks are compelling. Cellulosic ethanol will reduce our dependence on imported oil, increase our energy security and reduce our trade deficit. Rural economies will benefit in the form of increased incomes and jobs. Growing energy crops and harvesting agricultural residuals are projected to increase the value of farm crops, potentially eliminating the need for some agricultural subsidies. Finally, cellulosic ethanol provides positive environmental benefits in the form of reductions in greenhouse gas emissions and air pollution.

There is a growing consensus on the steps needed for biofuels to succeed: increased spending on R&D in conversion and processing technologies, funding for demonstration projects and joint investment or other incentives to spur commercialization. "If you do not do all three of these pieces, the effort is likely to stall," said Greene. "The challenge is to be really focused and make the commitment to make biofuels a part of our economy. We need to make these technologies work."

There is also agreement on one of the main factors impeding the development of biofuels – inadequate government funding. "We are grossly under investing in this area," says Dechton. "We are piddling along at 30 or 40 million dollars per year. This is a national security issue." Sheehan agrees, adding "the other problem is over the last several years Congressional earmarking has been horrendous. It is splintering critical resources, as a result effectiveness is way down. We do not have well aligned, consistently directed R&D effort."

The "Growing Energy" report calls for $2 billion in funding for cellulosic biofuels over the next ten years, with $1.1 billion directed at research, development and demonstration projects and the remaining $800 million slated for the deployment of biorefineries. Other advocated subsidies and incentives for the industry include production tax credits, bond insurance for feedstock sellers and biofuels purchasers and efficacy insurance. "We would like to see private insurance but lacking private sector involvement, government should offer the insurance," said Greene. "The idea has two features, the amount of money available goes down over time, so by 2015 the industry is ready to stand on its own two feet and, second the dollars available to developers is in a menu format. We will let them pick subsidies that works best for their product."

Given sufficient investment in research, development, demonstration and deployment, the report projects biorefineries producing cellulosic ethanol at a cost leaving the plant between $.59-$.91 per gallon by 2015. The price range is dependent upon plant scale and efficiency factors. At these prices, biofuels would be competitive with the wholesale price of gasoline.

In the past, discussions regarding ethanol as a potential replacement for gasoline have centered on the availability of suitable land in addition to a food versus fuel debate. Technological and process advances coupled with the promise of biorefineries are allowing us to refocus the debate. Scenarios exist where well directed public policies emphasizing biofuels investment and incentives in addition to fuel efficiency could promote a transition to cellulosic ethanol. Given the right policy choices, America's farmers could one day be filling both our refrigerators and our gas tanks. ■

DEVELOPMENT OF BIOREFINERIES

ONE of the essential elements in the economical and efficient production of cellulosic ethanol is the development of biorefineries. The concept of a biorefinery is analogous to a petroleum refinery where a feedstock, crude oil, is converted into fuels and coproducts such as fertilizers and plastics. In the case of a biorefinery, plant biomass is used as the feedstock to produce a diverse set of products such as animal feed, fuels, chemicals, polymers, lubricants, adhesives, fertilizers and power.

While similar to oil refineries, biorefineries exhibit some important differences. First, biorefineries can utilize a variety of feedstocks. Consequently, they require a larger range of processing technologies to deal with the compositional differences in the feedstock. Second, the biomass feedstock is bulkier (contains a lower energy density) relative to fossil fuels. Therefore, economics dictate decentralized biorefineries closer to feedstock sources.

The economics of biorefineries are dependent upon the production of coproducts such as power, protein, chemicals and polymers to provide revenue streams to offset processing costs, allowing cellulosic ethanol to be sold at lower prices. Generation of coproducts also results in greater biomass and land use efficiencies along with a more effective use of invested capital.

Process and technological innovations are focusing on utilizing every component of the biomass feedstock. Essentially, the waste or by-products from one process become the raw materials for another product. "The objective will be to utilize the entire barrel of biomass," adds Bruce Dale, professor of chemical engineering at Michigan State. Economics will drive biorefineries to undergo "continuous, incremental process improvements" in a quest to improve yields, increase the value of coproducts and utilize "every fraction of the raw materials."

Lignin and protein, two important coproducts, have the potential to significantly improve the economics of biorefineries. Lignin is a nonfermentable residue from the hydrolysis process. It has an energy content similar to coal and is employed to power the operation thereby reducing production costs. "There is enough residue [lignin] left over to meet the energy needs of the process plus make additional ethanol or electricity," says Eric Larson, a research engineer at the Princeton Environmental Institute.

Power can be produced from lignin via direct combustion with steam power generation or gasification. Gasification burns the lignin in a closed process with elevated air pressure and small amounts of oxygen. The result is a raw fuel gas and ash. Ash is a good material to put back on the field, while waste heat is recovered from the process and reused.

Production of protein will not only bolster process economics but also increase land efficiencies by allowing the production of both fuel and animal feed on the same acre. The NRDC "Growing Energy" report estimates the coproduction of animal protein could lower the cost of cellulosic ethanol by $0.11-$0.13 per gallon, depending on the size of the production facility.

The leaves and stems of the plants are the source of protein found in cellulosic biomass feedstocks. The protein, referred to as leaf protein, is used in animal feed. Agricultural residues contain four to six percent protein while crops like switchgrass and alfalfa contain 10 percent and 15 to 20 percent respectively. Leaf protein is extracted from the feedstock utilizing an alkaline water solution heated to 50 to 60 degrees centigrade. Standard membrane filtration technology is employed to separate the protein from the other feedstock components. "You get 60 percent of the protein," says Dale. "Up to 80-90 percent of the protein can be extracted with extensive washing."

COMMERCIALIZING BIOREFINERIES

To date, only a few small demonstration biorefineries are producing ethanol from cellulosic feedstock. Iogen is operating a facility in Ottawa, Canada, utilizing proprietary enzyme hydrolysis and fermentation techniques to produce 260,000 gallons a year of ethanol from wheat straw. The company has announced plans for a commercial-scale facility in either western Canada, the U.S. or Germany. Iogen is seeking government financial support and other incentives to help fund the $350 million expected cost.

"The technology is ready for commercial-scale demonstration," says Reade Dechton, of the Energy Futures Coalition. "The industry is stuck on first of a kind technology. There is a role and need for government assistance. We think that the investment that would be required to get these first plants built is very small compared to the benefits that would result and the risks that we are facing."

John Sheehan of National Renewable Energy Laboratory has been utilizing process simulation software to look at biorefinery design. "Scale is a huge issue," said Sheehan. "The cost of capital is extremely scale specific." He has discovered that biorefineries need to be able to process 5,000 to 10,000 tons of biomass per day to be economically viable. "Below 2,000 tons per day, capital costs skyrocket."

"Capital is a problem," says Brent Erikson, Vice President of the Biotechnology Industry Organization (BIO). "Nobody has constructed a commercial size biorefinery. They cost between $200 and $250 million to build." Erickson's group is trying to facilitate funding of commercial biorefineries. "We have a proposal sent to the White House for federal loan guarantees to build these biorefineries," comments Erikson. The proposal requests upwards of $750 million in loan guarantees for full-scale commercial plants.

Sheehan believes existing niche markets can play a vital role in the development of cellulosic biorefinery technologies. "There is technology now, under niche market circumstances, that is almost ready to go," says Sheehan. "A good place to put investments is testing core pieces of the technology in existing corn ethanol plants."

Two companies are exploring new technologies and processes to integrate cellulosic biomass in existing corn ethanol and wet grain milling facilities. Broin has received a $5.4 million grant from DOE to investigate employing fiber and corn stover in the production of ethanol. A $17.7 million grant from DOE is funding Abengoa's research on processes to pretreat a blend of distillers' grain and corn stover to produce ethanol. The project calls for the building of a pilot-scale facility in York, Nebraska.

Several biorefineries under development are focused on applying innovations to existing acid hydrolysis processing techniques. BC International is applying a proprietary acid hydrolysis technology to agricultural residues and forest thinning feedstocks to produce ethanol. The company is developing facilities in Louisiana, California and Asia and claims their process produces ethanol at costs lower than conventional ethanol plants. Arkenol and Masada Corporation (mentioned earlier) are also developing biorefineries in the U.S. utilizing acid hydrolysis process to convert cellulosic wastes into ethanol. A Japanese company, licensing Arkenol's acid hydrolysis technology, is already producing ethanol in a plant in Izumi, Japan from waste.