United States
Department of
Agriculture

Office of
the Chief
Economist

Office of
Energy Policy
and New Uses

Agricultural
Economic
Report
Number
842

New Technologies in Ethanol Production

C. Matthew Rendleman
Hosein Shapouri

United States Department of Agriculture

Office of the Chief Economist

Office of Energy Policy and New Uses

Agricultural Economic Report Number 842

February 2007

New Technologies in Ethanol Production

C. Matthew Rendleman and Hosein Shapouri

Abstract

Fuel ethanol production has increased steadily in the United States since the 1980s, when it was given impetus by the need to reduce energy dependence on foreign supplies. The momentum has continued as production costs have fallen, and as the U.S. Clean Air Act has specified a percentage of renewable fuels to be mixed with gasoline. The fraction of annual U.S. corn production used to make ethanol rose from around 1 percent in 1980 to around 20 percent in 2006, and ethanol output rose from 175 million gallons to about 5.0 billion gallons over the same period. New technologies that may further increase cost savings include coproduct development, such as recovery of high-value food supplements, and cellulosic conversion. High oil prices may spur the risk-taking needed to develop cellulose-to-ethanol production. Developments such as dry fractionation technology, now commercially viable, may alter the structure of the industry by giving the cheaper dry-grind method an edge over wet milling. Dry milling requires smaller plants, and local farmer cooperatives could flourish as a result. Though improvements in processing and technology are important, however, the fluctuating price of inputs such as corn, the cost of energy alternatives, and environmental developments play larger roles in the fortunes of the industry.

Acknowledgments

The authors wish to thank a number of people who made valuable suggestions and corrections to the paper. They include Don Erbach and Andrew McAloon of the Agricultural Research Service, USDA, Jack Huggins of the Nature Conservancy, and Vijay Singh of the Dept. of Engineering at the University of Illinois at Urbana-Champaign.

About the Authors

C. Matthew Rendleman is with the Dept. of Agribusiness Economics, Southern Illinois University, and Hosein Shapouri is with the Office of Energy Policy and New Uses, USDA.

Contents

Introduction

The use of ethanol for fuel was widespread in Europe and the United States until the early 1900s (Illinois Corn Growers' Association/Illinois Corn Marketing Board). Because it became more expensive to produce than petroleum-based fuel, especially after World War II, ethanol's potential was largely ignored until the Arab oil embargo of the 1970s. One response to the embargo was increased use of the fuel extender "gasohol " (or E-10), a mixture of one part ethanol made from corn mixed with nine parts gasoline. Because gasohol was made from a renewable farm product, it was seen in the United States as a way to reduce energy dependence on foreign suppliers.

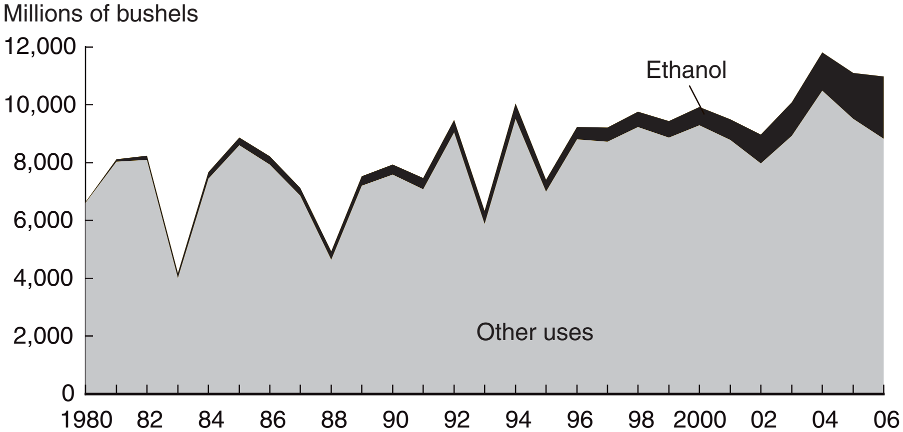
After the oil embargo ended, the use of ethanol increased, even though the price of oil fell and for years stayed low. Ethanol became cheaper to make as its production technology advanced. Agricultural technology also improved, and the price of corn dropped. By 1992, over 1 billion gallons of fuel ethanol were used annually in the United States, and by 2004 usage had risen to over 3.4 billion gallons. Many farm groups began to see ethanol as a way to maintain the price of corn and even to revitalize the rural economy. This economic support for ethanol coincided with a further justification for its use: to promote clean air. A 10-percent ethanol mixture burns cleaner than gasoline alone (reducing the emission of particulate matter, carbon monoxide, and other toxins), giving ethanol a place in the reformulated gasoline (RFG) market.

Ethanol use has also been boosted by the U.S. Clean Air Act and its various progressions. Originally, the Clean Air Act required wintertime use of oxygenated fuels in some urban areas to ensure more complete burning of petroleum fuels. Since ethanol contains 35 percent oxygen, this requirement of the act could be met by using an ethanol-containing blend. The current Energy Act eliminates the need for oxygenates per se in RFG, but it specifies the minimum amount of renewable fuels to be added to gasoline.

Figure 1

Ethanol's use of U.S. corn production

Millions of bushels



Source: *Feed Situation and Outlook Yearbook*, USDA, Economic Research Service, various years.

By 1980, fuel ethanol production had increased from a few million gallons in the 1970s to 175 million gallons per year. During the 1990s, production increased to 1.47 billion gallons, and total production for 2006 is expected to be about 5.0 billion gallons. Annual U.S. plant capacity is now over 4.5 billion gallons, most of it currently in use. Demand is rising partly because a number of States have banned (or soon will ban) methyl tertiary-butyl ether (MTBE), and ethanol is taking over MTBE's role (Dien et al., April 2002). Ethanol provides a clean octane replacement for MTBE. The California Energy Commission and the California Department of Food and Agriculture now support ethanol development, and ethanol's use in California alone is expected to reach 1.25 billion gallons by 2012 (Ross).

The fraction of the Nation's annual corn production used to make ethanol rose from around 6.6 million bushels in the early 1980s (1 percent) to approximately 2 billion bushels in 2006 (20 percent) (fig. 1).

Changes Since the 1993 ERS Analysis of Ethanol Production

In 1993, USDA's Economic Research Service (ERS) published *Emerging Technologies in Ethanol Production,* a report on the then-current state of ethanol production technology and efficiency (Hohmann and Rendleman). The report included a summary of production costs (table 1) and predictions of "near-term" and "long-term" technological advances that many believed would bring down ethanol costs.

The numbers were based on the costs of wet milling, which was then by far the greatest source of output. (Milling types are explained in the next section.) The estimate included a capital cost component, which distinguished this estimate from others done at the time. Other estimates ranged from $1.08 to $1.95 per gallon.

The near-term technologies listed in the ERS report were as follows:

- Gaseous injection of sulfur dioxide and the use of special corn hybrids,
- Membrane filtration,
- Other advances, including improved yeast strains and immobilization of yeast in gel substrates.

Long-term technologies (potentially available in 5 to 10 years) were as follows:

- Bacterial fermentation,
- Conversion of corn fiber to ethanol (cellulosic conversion),
- Coproduct development.

Though the savings from technological improvements are significant, they tend to be small compared with fluctuations in the net cost of corn, the main ethanol feedstock. This is illustrated in table 2, which presents data on corn costs and profits from the coproduct DDGS (distiller's dried grains with solubles) in dry-mill ethanol production from 1981-2004. Since 1981, sales of DDGS have recovered nearly half the cost of each bushel of corn used to produce ethanol, peaking in 1986, when over 66 percent of the feedstock cost was recovered this way. In recent years, the percentage of recovery has fallen because increased demand for ethanol has led to an abundance of DDGS, lowering its price on the feed market.

The near- and long-term technologies listed in the 1993 ERS analysis were predicted to save from 5 to 7 cents per gallon in the short term and from 9

Table 1
Ethanol wet-mill cost estimates, 1993

Cost category	Cost per gallon
Feedstock	$0.44
Capital	$0.43
Operating	$0.37
Total	$1.24

Source: Hohmann and Rendleman (1993).

Table 2
Net corn costs of dry milling,1981-2004[1]

Year	Corn value	DDGS* value	Byproduct value	Net corn cost	Net corn cost
	$/bu	*$/bu*	*% corn cost*	*$/bu*	*$/gal. ethanol*
1981	2.47	1.25	50.5	1.22	0.45
1982	2.55	1.21	47.5	1.34	0.50
1983	3.21	1.47	45.7	1.74	0.65
1984	2.63	0.83	31.6	1.80	0.67
1985	2.23	0.92	41.1	1.31	0.49
1986	1.50	1.00	66.4	0.50	0.19
1987	1.94	1.16	59.9	0.78	0.29
1988	2.54	1.20	47.2	1.34	0.50
1989	2.36	1.06	44.8	1.30	0.48
1990	2.28	1.08	47.3	1.20	0.45
1991	2.37	1.04	43.9	1.33	0.49
1992	2.07	1.04	50.4	1.03	0.38
1993	2.50	1.05	42.1	1.45	0.54
1994	2.26	0.91	40.1	1.35	0.50
1995	3.24	1.29	39.7	1.95	0.72
1996	2.71	1.21	44.8	1.50	0.55
1997	2.43	0.93	38.4	1.50	0.55
1998	1.94	0.72	37.2	1.22	0.45
1999	1.82	0.68	37.3	1.14	0.42
2000	1.85	0.69	37.0	1.16	0.43
2001	1.97	0.68	34.6	1.29	0.48
2002	2.32	0.75	32.3	1.57	0.58
2003	2.42	0.98	40.6	1.44	0.53
2004	2.06	0.65	31.3	1.41	0.52
Average	2.32	0.99	43.0	1.33	0.49

*Distiller's dried grains with solubles.
[1]2.7 gal. of ethanol and 17 lbs of DDGS per bushel of corn.
Source: ERS Feedgrains Database, http://www.ers.usda.gov/db/feedgrains.

to 15 cents by 2001. The savings have been as anticipated, but they have not come in the manner predicted.

Gaseous injection of sulfur dioxide was beginning in 1993 and is a part of the quick-germ (QG) and quick-fiber (QF) techniques currently being developed. There is revived interest in the use of special corn hybrids high in starch, though their use is still not widespread. Membrane filtration and yeast immobilization were being used in some plants in 1993, but their use, contrary to expectations, has not increased. Bacterial fermentation is still not used commercially, nor is cellulosic conversion of corn fiber. There have been no outstanding developments in coproducts, but the potential remains for their future exploitation. Most of the cost savings have been through plant automation and optimization of existing processes.

The industry is still improving technologically. It is far more mature than in 1993, and new developments appear poised to bring costs down further and to reduce the environmental impact of producing ethanol. In this report, we examine various production technologies, beginning with input improvements and then discussing process improvements, environmental technologies, and technologies involving coproducts. Finally, we look at niche markets and briefly examine cellulosic conversion.

Ethanol's Energy Efficiency

Improvements in ethanol's energy consumption have continued since large-scale commercial production began in the 1970s. The process has become more efficient at using the starch in the corn kernel, approaching the theoretical limit of about 2.85 gallons of ethanol per bushel. Energy for conversion has fallen from as high as 70,000 Btu's per gallon in the late 1970s (Wang, August 1999) to 40,000 Btu's or less for modern dry mills and to 40,000-50,000 Btu's for wet mills. Modern energy-saving technology and process optimization account for the improvement.

In 2002, Shapouri et al. surveyed energy values and reported that fuel ethanol from corn produced about 34 percent more energy than it took to produce it. That figure was based on a weighted average of a 37-percent increase in energy from ethanol produced in dry mills and a 30-percent increase from wet mills. This value was revised in 2004 by updating energy estimates for corn production and yield, improving estimates of energy required to produce nitrogen fertilizer and energy estimates for seed corn, and using better methodologies for allocating energy for producing coproducts. With these revisions, the energy gain is 57 percent for wet milling and 77 percent for dry milling, yielding a new weighted average of 67 percent.

The energy content, however, may be less important than the energy replaced. A gallon of ethanol can save 26,575 Btu's of energy by replacing a gallon of gasoline because of ethanol's higher combustion efficiency (Levelton Engineering Ltd. and (S&T)2 Consulting Inc.). A gallon of ethanol containing 76,330 Btu's is able to replace a gallon of gasoline containing about 115,000 Btu's because ethanol's higher octane rating (113-115, compared with 87) allows high-compression engines to perform as well with fewer Btu's.

Ethanol Production Processes

Though new technology may eventually blur the distinction between them, ethanol is produced by one of two processes: wet milling and dry milling. Wet mills are more expensive to build, are more versatile in terms of the products they can produce, yield slightly less ethanol per bushel, and have more valuable coproducts. Wet milling initially accounted for most of the ethanol fuel production in the United States, but new construction has shifted to dry mills, partly because dry mills cost less to build. In 2004, 75 percent of ethanol production came from dry mills and only 25 percent from wet mills (Renewable Fuels Association). As a result, most new technologies are being developed for dry-mill production.

Dry-milling plants have higher yields of ethanol; a new plant can produce 2.8 gallons per bushel, compared with about 2.7 gallons for wet mills. The wet mill is more versatile, though, because the starch stream, being nearly pure, can be converted into other products (for instance, high-fructose corn syrup (HFCS)). Coproduct output from the wet mill is also more valuable.

In each process, the corn is cleaned before it enters the mill. In the dry mill, the milling step consists of grinding the corn and adding water to form the mash. In the wet mill, milling and processing are more elaborate because the grain must be separated into its components. First, the corn is steeped in a solution of water and sulfur dioxide (SO_2) to loosen the germ and hull fiber. This 30- to 40-hour extra soaking step requires additional tanks that contribute to the higher construction costs. Then the germ is removed from the kernel, and corn oil is extracted from the germ. The remaining germ meal is added to the hulls and fiber to form the corn gluten feed (CGF) stream. Gluten, a high-protein portion of the kernel, is also separated and becomes corn gluten meal (CGM), a high-value, high-protein (60 percent) animal feed. The corn oil, CGF, CGM, and other products that result from the production of ethanol are termed coproducts.

Unlike in dry milling, where the entire mash is fermented, in wet milling only the starch is fermented. The starch is then cooked, or liquefied, and an enzyme added to hydrolyze, or segment, the long starch chains. In dry milling, the mash, which still contains all the feed coproducts, is cooked and an enzyme added. In both systems a second enzyme is added to turn the starch into a simple sugar, glucose, in a process called saccharification. Saccharification in a wet mill may take up to 48 hours, though it usually requires less time, depending on the amount of enzyme used. In modern dry mills, saccharification has been combined with the fermentation step in a process called simultaneous saccharification and fermentation (SSF).

Glucose is then fermented into ethanol by yeast (the SSF step in most dry-milling facilities). The mash must be cooled to at least 95^{o} F before the yeast is added. The yeast converts the glucose into ethanol, carbon dioxide (CO_2), and small quantities of other organic compounds during the fermentation process. The yeast, which produces almost as much CO_2 as ethanol, ceases fermenting when the concentration of alcohol is between 12 and 18 percent by volume, with the average being about 15 percent (Shapouri and Gallagher). An energy-consuming process, the distillation step, is required to separate the ethanol from the alcohol-water solution. This two-part step consists of primary distillation and dehydration. Primary distillation yields ethanol that is up to 95-percent free of water. Dehydration brings the concentration of ethanol up to 99 percent. Finally, gasoline is added to the ethanol in a step called "denaturing," making it unfit for human consumption when it leaves the plant.

The coproducts from wet milling are corn oil and the animal feeds corn gluten feed (CGF) and corn gluten meal (CGM). Dry milling production leaves, in addition to ethanol, distiller's dried grains with solubles (DDGS). The feed coproducts must be concentrated in large evaporators and then dried. The CO_2 may or may not be captured and sold.

Input Improvements: Higher-Ethanol-Yielding Corn

Efficient ethanol plants can convert 90-97 percent of the corn's starch content to ethanol. However, not all batches of corn leave the same amount of starch residue. Studies of ethanol yields from different batches show significant variability (Dien et al., March 2002). Even though it is the starch that is turned into ethanol, researchers have been unable to find a correlation between starch content (or even starch extractability) and the final yield of ethanol (Singh and Graeber). Researchers believe some starches are in a more available form (Dien et al., March 2002). They do not know, however, what makes the starch break down easily to simple sugars and why this trait varies from hybrid to hybrid (Bothast, quoted in Bryan, 2002). Some research shows that although the ease with which the starch breaks down varies among hybrids, most of the variability in the breakdown is due to other factors (Haefele et al.).

Seed companies like Pioneer, Monsanto, and Syngenta are working to create corn that will boost ethanol yield. "Current work centers on identifying highly fermentable hybrids we already have," says a Monsanto spokesman (Krohn). Pioneer reports yield increases of up to 6 percent in batches using what it calls HTF corn (High Total Fermentables), compared with the yields from unselected varieties (Haefele et al.). Monsanto calls its selected varieties HFC for High Fermentable Corn.

Syngenta Seeds' Gary Wietgrefe points out several of the impediments to widespread adoption of HTF corn (Ed Zdrojewski in *BioFuels Journal*, 2003b). To begin with, starch and ethanol yield vary by geographic region and from year to year, making an optimizing hybrid choice difficult. Further, choosing a hybrid that maximizes ethanol qualities may mean a tradeoff with yield and other potentially valuable qualities, such as protein content and even test weight (because of moisture). Testing equipment presents its own challenges. Not all units are calibrated the same, creating uncertainty. The technology may be less available to farmers than to ethanol plants, and even if it were to become more readily available, sorting grain by starch availability and making marketing decisions would be problematic for the grower. Finally, with ethanol plants already able to convert between 90 and 97 percent of the corn's starch, any new HTF or HFC genetics or technology would have to overcome the problems and significantly improve the profits of the ethanol plant and the farmer.

Higher ethanol yield leaves less DDGS for animal feed, possibly changing the quality as well as the quantity of the feed coproduct. A lower quantity might raise the protein percentage, but it could also concentrate some of the undesirable contents of the DDGS. Any changes, however, are expected to be minor. (See Haefele et al., p.14, on the selection of hybrids.)

Unlike many technologies that are adopted because they show an immediate improvement in profit or a reduction in risk, corn with a higher ethanol yield does not necessarily lead to additional profits for the farmer in today's marketing environment. Corn is not graded on the basis of fermentability, nor is a premium offered in the wider marketplace for this trait. In order to overcome this market drawback, companies like Monsanto and Pioneer are developing programs to encourage the adoption of their selected hybrids.

So far, hybrid-testing research has centered on dry-mill production, the lower investment technique of choice for the new cooperatively owned plants. The seed companies are targeting their incentive programs on dry mills. Monsanto's program, "Fuel Your Profits," provides the participating ethanol plant with high-tech equipment that profiles the genetics of incoming corn and is calibrated to maximize ethanol yield (Rutherford). As an incentive, Monsanto gives rebates on E85 vehicles (those designed to run on 85%-ethanol fuel) and fueling stations. Pioneer has developed a whole-grain Near Infrared Test (NIT) to identify ethanol yield potential quickly.

Process Improvements

New construction today is mostly of dry mills, and most new technology is designed for them. Major technology changes are made more efficiently while a plant is being built than when they are adopted later.

Advances in Separation Technologies

New techniques that separate corn kernel components before processing will blur the distinction between wet and dry milling (dry grind) by allowing the dry mill to recover the coproducts from the germ. Process improvements are also being made that will reduce the cost of wet milling, generally by shortening the soaking step. Some of the separation improvements we describe here, though promising, are still experimental.

Germ and Fiber Separation

Modifications of the dry-grind facility have made the recovery of corn germ possible in dry milling. Normally, neither corn germ nor any other corn fraction is separated out before becoming part of the mash; all components go through fermentation and become part of the feed coproduct, DDGS. Various modifications of the process have made it possible to recover fiber and corn germ—and thus corn oil—from both the endosperm and the pericarp (outer covering) of the kernel.

A technique developed at the University of Illinois called Quick Germ (QG) allows recovery of corn oil and corn germ meal from the germ, making the dry mill a more profitable operation (Singh and Eckhoff, 1996, 1997; Taylor et al., 2001; Eckhoff, 2001). Results published in 1995 and 1996 demonstrated that with a 3- to 6-hour soak step (as opposed to 24 to 48 hours for the soak step in wet milling), the corn germ could be removed. Since then, research has explored the parameters of the process and its savings potential (Singh and Johnston). Another process, Quick Fiber (QF), can be used with QG to recover fiber from the pericarp, a source of potentially valuable food coproducts. Though these processes have not been used in commercial applications, they hold promise for reducing the net cost of the input corn. The tanks and equipment for the additional steps would increase the plant's capital cost, but could increase its capacity by reducing the amount of nonfermentables in the mash.

Enzymatic Dry Milling

This process, which uses newly developed enzymes, is another method with the potential for cost savings. In addition to recovering the germ and fiber from the pericarp, it allows recovery of endosperm fiber. Savings come from the recovered coproducts and from reduced energy consumption—the process requires less heat for liquefaction and saccharification. Plant capacity should be enhanced as well, since there is less nonfermentable material in the substrate because it is removed earlier in the process. The amount of DDGS is smaller, but of higher quality. Ethanol concentrations in the mash are also higher. Industrial- and food-grade products can be recovered from the fiber. Alternatively, the fiber can be fermented.

Dry Fractionation

This recent technology separates the corn kernel into its components without the soaking step. Depending on the process—several companies currently offer similar technologies—the feedstock may be misted with water before being separated into bran, germ, and the high-starch endosperm portion of the kernel (*BioFuels Journal,* 2005d,e).

The advantages of dry fractionation over processes that require a soak step are threefold: lower costs because less energy is required for drying the feed coproduct, lower emissions, and greater coproduct output because the mash is more highly concentrated. The germ can be sold or pressed for corn oil, and the bran also has potential for food or energy use.

Dry fractionation is a process that has been tested and is in use in the food industry (Madlinger). Both new and planned ethanol plant construction employ the technology. Unlike some other new technologies, the dry fractionation equipment can be added to an existing dry mill.

With all the separation techniques, there appears to be less total ethanol recovered per bushel than with conventional dry-milling techniques, probably due to removal of some starch with the coproducts (Singh and Johnston). Each technique will change the nature of the resulting distiller's grains, potentially raising their value due to a higher protein content; the feed coproduct from the separation processes is purported to be higher in protein and lower in fiber than ordinary DDGS. However, research is needed to determine the feed value of this altered coproduct. Preliminary feed trials with poultry and hogs, as yet unpublished, are promising (Madlinger).

Ammoniation Process in the Wet Mill

Researchers have also investigated a separation technique involving pretreatment with ammonia (Taylor et al., 2003). This process would facilitate removal of the pericarp and reduce the soak time in wet milling or the QG process. Anhydrous ammonia would take the place of the caustic soda solution usually used in debranning. In laboratory research, the pericarp was more easily removed through ammoniation, but though the oil was not degraded, its quantity was reduced compared with conventional techniques.

Continuous Membrane Reactor for Starch Hydrolysis

This process, still experimental, uses enzymatic saccharification of liquefied corn in a membrane reactor. In a continuous membrane reactor, as opposed to the traditional batch process, starch would be broken down and glucose extracted continuously. Theoretically, the yield would increase, and the automated continuous process would enable better control than the batch process.

Alkali Wet Milling

In an experimental modification of the wet-milling process, corn was soaked briefly in sodium hydroxide (NaOH) and debranned (Eckhoff et al.). This process cut the costly soaking time to 1 hour. The pericarp removed in alkali wet milling becomes a potentially valuable part of the coproduct stream. Additional work is needed to develop ways of disposing of or recycling the NaOH before the technique can be commercialized.

New Ways of Fermentation

High-Gravity Fermentation

This technique, still experimental, would lower water use in ethanol production. Potential savings would come from the reduced cost of water and wastewater cleanup, as well as from reduced energy use. This process would involve less heating and cooling per gallon of ethanol. Very-high-gravity fermentation accomplishes this saving in energy by using a highly concentrated mash with more than 30 percent solids. Experiments have resulted in a 23 percent-alcohol fermentation, much higher than with the conventional process. Commercial production at that level is not likely in the near future because of difficulty in staying within the required tolerances. However, incremental moves toward higher concentrations open the possibility of lower production costs.

Improved Yeast

For many years, researchers have been trying to improve yeast, which is a highly effective converter of sugars to ethanol. The desired end product is a yeast that would be more heat tolerant and better able to withstand high alcohol concentrations, that would produce fewer undesirable byproducts, and that might even be able to convert more types of sugar to ethanol. Developers have already made progress in some of these areas. For example, the ethanol tolerance of yeast is at least one-third higher today than in the 1970s.

Some researchers believe a yeast tolerant of temperatures as high as 140º F is the ideal. If such a yeast were to be developed—something increasingly possible with recombinant DNA techniques—the ethanol conversion process would look completely different than it does today (Novozymes and BBI International). Another goal of industry researchers is to produce less glycerol, which is produced in response to stress and represents a loss of ethanol during conversion.

Conversion of Pentose Sugars to Ethanol

Sucrose from starch is not the only type of sugar in the corn kernel. Some of the sugars are pentoses, or five-carbon sugars not normally utilized by common yeast. Any organism that could ferment pentoses to ethanol would be a valuable contribution to corn-ethanol conversion efficiency. This conversion has been achieved in the laboratory using genetically modified yeasts (Moniruzzaman et al.) and in bacterial fermentation using *E. coli* (Dien et al., 1997). These processes are not in commercial use, partly because the engineered organisms are less hardy and less tolerant of environmental changes than conventional organisms. Researchers are also concerned about how the nutritional content of the resulting feed coproduct would differ from conventional DDGS and about whether the genetically modified organisms remaining in the feed would be acceptable in the commercial feed market.

New Enzymes

Enzymes for Liquefaction and Saccharification

Enzymes were first used in ethanol production in the 1950s, but they have recently been improved and their cost brought down through the use of special fermentations of microorganisms. Costs have fallen 70 percent over the last 25 years (Novozymes and BBI International).

Enzymes enable chemical reactions to occur more easily, with less heat or a more moderate pH, and therefore more cost effectively. Their use in ethanol production improves liquefaction, saccharification, and fermentation. Enzyme use also results in reduced soak time, higher starch and gluten yield, better protein quality, and reduced water and energy use. USDA's Agricultural Research Service (ARS) is working with enzyme manufacturers to further reduce cost and improve effectiveness.

Enzymes To Reduce Sulfur Dioxide and Steep Time in Wet Milling

Part of the additional expense in wet milling as opposed to dry milling is the necessity of soaking the corn before separation of the germ from the kernel. The tanks increase capital cost, and the soak time slows the process. Soak time can be reduced by adding sulfur dioxide to the steep water, but research shows that the sulfur dioxide can be reduced or eliminated by using enzymes. Recently, an experimental two-stage procedure reduced soak time by up to 83 percent (Johnston and Singh; Singh and Johnston). In the saccharification step, the protease enzyme hydrolyzed the protein matrix around the starch granules and made it available for further breakdown. As with most enzymes, cost is still an issue; however, small-scale experiments seeking to optimize the process have so far reduced the enzyme requirement severalfold. Research trials show that using a low level of sulfur dioxide (more than 90 percent less than conventional levels) greatly reduces the enzyme requirement. Small amounts of sulfur dioxide are still effective in reducing bacterial contamination, a potential problem in continuous processes. Though enzymes are an added expense, the procedure has the potential to increase plant capacity (through the time savings), reduce energy costs, and allow the use of otherwise unusable broken grains. Replacing the conventional liquefaction and saccharification steps with a single, low-temperature enzyme step has already been discussed in the section "Advances in Separation Techniques."

Distillation Technology

Standard distillation techniques leave about 4-percent water in the final ethanol. In the early days of ethanol distillation, the basic production design came from the beverage alcohol industry, where there is no need to remove all the water (Swain). Fuel ethanol, however, must be almost pure or dry, so ethanol producers began dehydrating their ethanol using a technique called azeotropic distillation. This technique requires use of an ingredient, usually benzene or cyclohexane, to break the azeotrope—the point after which distillation becomes ineffective. The adoption of molecular sieves allows the modern plant to use less power, reduce original capital outlay, and eliminate potential exposure of workers to dangerous chemicals.

Molecular sieves use materials with microscopic pore sizes large enough to allow a molecule of one size to get through while blocking another. For example, in ethanol dehydration the molecular sieves have a pore diameter that allows a water molecule to enter and be trapped but keeps out the larger ethanol molecule. Since the late 1980s, vapor-phase molecular sieves have been the industry standard, improving on the liquid-phase sieves by reducing the required size (Novozymes and BBI International).

Control Systems

The 1993 prediction of cost reductions in ethanol production (Hohmann and Rendleman) overlooked the incremental changes in efficiency that were taking place due simply to increased control of fermentation and other processes. Distributed control systems were already being used, but with the evolution of technology, especially computing capabilities, these systems have continued to reduce costs while optimizing the production process.

Distributed control systems are used in industrial and other engineering applications to monitor and control a process remotely. Human operators manage equipment distributed throughout the plant (or other application). Examples, besides ethanol plants, include power distribution systems, traffic signals, water management systems, and biorefineries. Instruments to measure and control, usually digital, are wired ultimately to computers, allowing a human-to-machine interface.

Merging the distributed control system with computer programs allows timely monitoring of processes, and even allows prediction. Reports can be compiled from stored data, and alarms can be set to alert operators if established parameters are breached.

Distributed control systems have cut costs in ethanol plants mainly by reducing the labor required, but they have also improved production efficiency in other ways, letting operators fine-tune processes they could not control as closely in the past. Better process control also reduces downtime and maintenance.

Environmental Technologies

In addition to reducing the amount of energy required for production, modern ethanol plants give off fewer odors and emissions than ever before. Technological advances hold promise for converting more of the feed coproducts into ethanol, for reducing components of DDGS that might harm the environment, and for utilizing waste streams from the process.

As noted, modern ethanol production uses less energy as techniques and technologies improve. Both wet and dry millers are using less fuel and electricity per gallon produced, and farmers are producing corn more efficiently. All these savings are an environmental plus for ethanol.

Ethanol plant emissions are a second area of improvement. In 2002, Minnesota producers signed an agreement with the Environmental Protection Agency (EPA) to reduce emissions coming from their plants. That agreement has become an industry standard. Since then, ethanol producers in several States have agreed to install thermal oxidizers or other technologies that eliminate nearly all volatile organic compounds (VOCs) and other pollutants, adding equipment that averages more than $2 million per plant. The EPA estimates that the agreement will eliminate more than 63,000 tons of pollution annually.

Though pollutants, like particulate matter and even VOCs, can originate from fermentation and from other parts of the plant such as grain-handling areas, most of the attention has been focused on dryer stacks. Thermal oxidizers are now standard equipment in most new ethanol facilities. They convert carbon- and hydrogen-bearing compounds into CO_2 and water through high-temperature oxidization. Besides eliminating odors and visible emissions, thermal oxidizers can eliminate over 99 percent of oxides of nitrogen and other hazardous air pollutants, as well as certain particulates.

Wastewater emission problems have been largely solved by the development of anaerobic digester systems. Majumdar et al. report using membrane technology to recover VOCs such as hexane from process air emissions, giving membranes a role in environmental remediation.

New techniques may make processing itself more environmentally friendly. For example, a corn-steeping process being developed by scientists from ARS and the University of Illinois uses enzymes and reduces the need for sulfites.

Another discovery—one that may hold the most promise for the future—is the conversion of low-value and waste stream products into valuable coproducts. (This will be discussed in the next section, “Technologies Involving Coproducts.”)

Finally, overfeeding phosphorus to animals can be an environmental concern because the phosphorus ends up on the land as manure. The phosphorus available in DDGS is more than is needed for proper animal nutrition. If the level excreted over time is excessive, phosphorus can move into ground or surface water and create problems such as algae in the waterways. Researchers are experimenting with membrane technology that would remove phosphorus from the thin stillage (the liquid remaining after removal of the wet distiller’s grains) before it becomes feed. The result is likely to be more efficient feed rations and reduced environmental impact.

Technologies Involving Coproducts

In addition to animal feeds, other potential coproducts are produced along with the ethanol. Both wet and dry milling create CO_2 during fermentation. Minor components, such as glycerol, may be collected from the processing stream. Some research directions may alter the entire process, using different fermentations to produce entirely different product lines. Researchers are also hoping to turn much of the nonfuel product into ethanol, or even something more valuable than the fuel that is currently the primary product. Possibilities include protein and fiber that could be added to human foods to increase nutritional value.

Enzymatic milling may also allow recovery of valuable coproducts. Conventional dry milling leaves as coproducts distiller's dried grains with solubles and, if recovered, CO_2. ARS scientists from USDA's Agricultural Research Service are adapting the concept of enzymatic milling to the dry-mill ethanol process, partly to recover additional high-value coproducts.

The Growing Supply of Feed Coproducts

Ethanol production does not exhaust the feed value of corn; it merely uses up the starch portion, leaving protein, minerals, fat, and fiber to be dried and sold for feed. A high percentage of ethanol producers' revenue comes from the feed coproduct. Dry milling turns a bushel of corn (56 lb) into 2.7 or more gallons of ethanol and leaves 17 lb of distiller's grains. Wet milling produces only slightly less ethanol and coproduces around 16 lb of corn gluten meal (CGM, 2.65 lb) and corn gluten feed (CGF, 13.5 lb), in addition to corn oil. In 2004, 7.3 million metric tons of DDGS, 426,400 metric tons of CGM, and 2.36 million metric tons of CGF were produced (Renewable Fuels Association). Predictions for near-term increases are as high as 10 million tons by 2007-08, which would constitute a significant portion of all the cattlefeed in the United States (*BioFuels Journal*, 2005c).

Because feed coproducts and ethanol are produced in fixed proportions, increased demand for ethanol will result in greater output of DDGS, putting downward pressure on its price. Partly for this reason, research is continuing on alternative coproducts.

Proving the nutritional value of DDGS for new uses will expand the market. Most of the DDGS produced is fed to dairy and beef cows, but it is increasingly being tested and used in swine and poultry rations. Research is planned on DDGS in equine diets.

The nonuniform character of DDGS makes it difficult to establish feeding parameters because the product varies in consistency and nutritional value. Ongoing research is aimed at establishing feed values for various forms of DDGS, and some producers are developing proprietary DDGS brands with guaranteed nutritional properties.

Sequential Extraction

Lawrence Johnson of Iowa State University has initiated several projects exploring the parameters of the sequential extraction process, or SEP (see, for example, Hojilla-Evangelista and Johnson). SEP uses alcohol rather than water to separate kernel components in an otherwise wet-mill process. The researchers claim increased ethanol production (10 percent), higher quality protein extracts (with no SO_2 needed for extraction, and therefore less degradation of the protein portion), and the production of corn fiber gum, a gum arabic substitute, as a coproduct. Gum arabic is used in producing soft drinks, candy, and pharmaceuticals. Cost remains a problem with the SEP process: The initial capital outlay for an SEP plant would be much higher than for a conventional wet mill. Extraction of proteins from the separated germ remains a problem as well.

Corn Germ Recovery for the Dry-Mill Process

As explained in the "Process Improvements" section, both dry fractionation and the quick-germ technique modify the dry-mill process and make the recovery of corn germ possible. Recovery of the germ, and thus of the oil, can make dry milling more profitable. The soak step in the quick-germ process takes less time than in wet milling, 3-6 hours as opposed to 24-48 hours. The process has not yet been used commercially. Plants using dry fractionation, however, are underway. Profitability will depend on the relative cost of corn oil and the capital costs of the additional equipment required.

Centrifugal Corn Oil Separation from the Distiller's Grain Stream

An additional technology for separating corn oil from distiller's grain has recently become available to dry millers. SunSource, a coalition of ethanol producers and a technology company, is licensing a system that can be installed in new plants or retrofitted to existing ones (Walker). The technology makes an additional coproduct available to ethanol producers, most likely to be used in biodiesel production. The process uses centrifuge technology to extract the oil from the distiller's grains in the evaporation step. The developers of the process claim that removing the oil from the distiller's grains does not lower the value of the feed coproduct and makes it easier to handle. The process also reduces volatile organic compounds emitted from the dryers, an environmental bonus.

CO_2 Recovery

Ethanol's most abundant coproduct is CO_2, produced by yeast in about the same proportion as ethanol itself. Only about 25 U.S. plants find uses for the gas (Lynn Grooms in *BioFuels Journal,* 2005b); the other plants, because of the low commercial value of CO_2, simply vent it into the air. Most CO_2 sold commercially is used in soft drinks and food processing, while other uses, such as water treatment, welding, chemical processing, refrigerants, and hydroponics, consume some of the remainder.

Another approach would be to find new uses for the gas, raising its value and expanding the market. One experiment uses CO_2 to enhance the recovery of oil from depleted oilfields. The gas is pumped into the oil production zones, forcing residual oil to the surface. If successful, the technique could greatly expand the market for CO_2.

A number of experiments with CO_2 are taking place at the basic science level (Bothast). One idea, successful at that level, is to turn the gas into ethanol or other fuel. However, the techniques are not yet commercially viable.

Bioconversion offers hope for increased CO_2 exploitation. Through biological processes, it turns organic materials into usable products or energy. In corn ethanol production, the possibility of bacterial bioconversion of CO_2 into fuel (e.g., ethanol or methanol) is under study.

Stillage Clarification and Other Uses of Membranes

Membrane separation is now used in dry mills to treat incoming boiler water and in wet mills to clarify dextrose. Based on the molecular size of the particles permitted to pass through, membranes are classified as reverse osmosis, nanofiltration, ultrafiltration, or microfiltration. They are made of various materials, including organic polymer, ceramics, and stainless steel.

Membranes were once thought promising for removing the last of the water from ethanol—the portion left by ordinary distillation—as processors looked for substitutes for hazardous materials like benzene that were then used for that purpose. In plants built today, however, the drying part of ethanol production is done with molecular sieves.

Membrane systems are used in industry to separate, clarify, and concentrate various feed streams and are most efficient when used on dilute broths. In the future, they may be used to reduce the cost of production through recovering and purifying minor components of the ethanol product stream. The recovery of lactic acid and glycerol from thin stillage is an application of this research that may soon be commercially viable. Corn oil and zein, a protein, are also potentially recoverable (Kwiatkowski and Cheryan). Researchers think membranes can be useful in continuous (though not in batch) reactors (Escobar et al.).

Biorefinery

One definition for a biorefinery is “a facility that integrates biomass conversion processes and equipment to produce fuels, power, and value-added chemicals from biomass.” The concept is a bit like wet milling, but with more coproduct possibilities. Corn or another feedstock might be decomposed and recombined into a number of products other than, or in addition to, ethanol. Some of the products might be high-value, low-volume ones, outside the traditional ethanol market, that could supplement a plant’s primary, lower value product line.

Extraction of Compounds from DDGS

The biorefinery concept meshes with a new area of research known as functional foods or nutraceuticals. Two categories of functional foods, dietary fibers and oligosaccharides, can be derived from grains.

Several Canadian companies and some universities are experimenting with extracting new coproducts from the distiller's grains generated from alternative feedstocks. Examples include cosmetics from oat derivatives, phenolic avenanthramides (useful in low-density liproprotein resistance to oxidation) from oats and wheat, and beta-glucan, a fiber-type complex sugar derived from yeast, oats, and barley fiber and useful in reducing cholesterol.

A biorefinery may also yield purified proteins used as human food or in industrial processes. A potentially recoverable coproduct is zein, a corn protein that can be used in adhesives and in coatings for pharmaceuticals and packaging materials because of its good water-vapor barrier properties. ARS scientists are working to develop a cost-effective way to recover zein from the milling stream, potentially making its use more common.

Corn Fiber Oil Recovery

Corn fiber is a byproduct of corn wet milling and may be a future product of dry milling. ARS has been developing methods to obtain enriched protein, starch, and fat from corn fiber. Corn fiber is also a source of corn fiber oil, a valuable dietary supplement that contains high levels of cholesterol-lowering and antioxidant phytosterols. Corn fiber can also be recovered by other means, such as the quick-fiber technique. Its economical recovery could give ethanol production another valuable coproduct line.

Regional Impacts of Ethanol Plants

Ethanol production holds promise for rural communities that hope to add value to locally produced corn. A new ethanol plant is seen as a way to create jobs and revitalize the local rural economy. Such scenarios seem more likely with widely dispersed, smaller scale plants—the kind that could spring up to service small specialty markets with an unusual coproduct or to take advantage of a local feedstock or other regional characteristic.

In the future, corn-processing facilities may be able to recover special healthful elements. One example might be proteins recovered from the process stream by ultrafiltration and made available as food.

Minor producers may take advantage of discard items like soft drinks or candy past their expiration date or other unusual sources of feedstock. Two cheese plants in California produce ethanol and at the same time solve a disposal problem by using the whey—generally regarded as waste—as a feedstock. Cheese whey contains lactose that, if not fermented, may require special processing at the cheese plant to avoid extra charges for municipal water-disposal treatment.

Some ethanol producers take advantage of their location to reduce production costs by selling coproducts otherwise too bulky to transport, such as steep-water. Or they save by avoiding drying, for instance, by feeding their wet distiller's grains to cattle or even fish. Others may sell CO_2, or may at least capture some value from it by using it in greenhouses to boost plant growth.

With the development of commercial cellulosic techniques, ethanol producers may actually be paid to take away material that they can use for feedstock—for instance, waste from other production systems or even municipal garbage.

Other potential niche markets may use animal waste. One current USDA research project seeks to exploit the advantages of co-location (of an ethanol plant and poultry farms) by generating electric power and steam for ethanol production from chicken litter. Coproduction of power and steam from a waste stream is being developed in another USDA project.

Many ethanol facilities recently opened or under construction are farmer owned and dispersed across rural areas. Farmers expect the completion of an ethanol plant in the area to increase the local corn price. McNew and Griffith examined the impact on local corn prices of opening 12 ethanol plants and found that, on average, price per bushel rose 12.5 cents at the plant and that some price response was detected 68 miles from the plant.[1]

New rural ethanol plants also provide employment. Though the plants need fewer employees than they would have just a few years ago when the industry was using less labor-saving technology, the U.S. Department of Energy (DOE) estimates that ethanol production is responsible for 40,000 jobs and $1.3 billion in increased annual household income.

[1]McNew and Griffith have also established a Web site at Montana State University that shows how corn prices are impacted by the opening of an ethanol plant (*BioFuels Journal*, 2003a). The site allows the user to investigate a small, medium, or large plant and displays the results graphically in map format. The impacts are based on econometric work by the authors. The tool, called the "Ethanol Plant Analyzer: A GIS-Driven Tool for Assessing Ethanol Feasibility," can be found at http://extensionecon.msu.montana.edu/eplantanalyzer/

National Benefits from Ethanol

Ethanol produced in the United States displaces imported foreign oil and creates domestic economic activity. Gallagher et al. (2000) estimate that the current program results in a $400-million net gain in overall social welfare. More domestic production, which is likely with an MTBE phaseout, would result in additional gain.

With ethanol production of 3.41 billion gallons in 2004, 143.3 million fewer barrels of oil were needed, about 4.5 percent of annual U.S. use (Urbanchuk). A 10-percent mixture of E-10 reduces petroleum use by 6 percent, greenhouse gas emissions by 1 percent, and fossil energy use by 3 percent (Wang et al.).

Increased biomass production would also change the picture. Gallagher and Johnson focus primarily on the benefits of a developed biomass-to-ethanol industry. Assuming an industry based on corn stover, the largest single source of biomass, they conclude that U.S. welfare would increase (a) because of the expanded fuel supply and (b) because the oligopoly effects of pricing by the Organization of Petroleum Exporting Countries (OPEC) would be mitigated. A biomass-to-ethanol industry, based on something like switchgrass, could add to farmers' product line and "could significantly increase profits for the agricultural sector" (De La Torre Ugarte et al.).

Biomass: Ethanol's Future?

Though corn has been the feedstock of choice in the United States, ethanol potentially can be made from any starch, sugar, or cellulosic feedstock. In fact, ethanol has been created from a variety of grains and from grass and straw, wood fibers, and sugarcane. Though ethanol production from corn has become more efficient, some experts see it as a technology that has already matured, with any significant reduction in production costs unlikely (DiPardo). Substantial cost reductions may be possible, experts believe, if cellulose-based feedstocks are used instead of corn. One industry publication editorializes: "Ultimately, if renewable automotive fuel becomes economical in the United States it will have to be made from lignocellulosic biomass" (*Industrial Bioprocessing*).

In the end, biomass-to-ethanol production may be attractive because biomass would cost less than corn. In addition, selling the feed coproducts from corn ethanol may become burdensome. As corn ethanol production increases, an inevitable result of dry-mill expansions, more feed coproducts will find their way into the market and drive down prices for DDGS.

The vision of cellulosic conversion is not yet commercial reality, however, due to difficulties inherent in turning biomass into ethanol. Because the cellulose and fermentable portions of woody biomass are tightly bound together, researchers have had to focus on the problem of pretreatment and hydrolysis. The necessary chemical conversion can take place using acids or enzymes, but, to be commercially viable, costs must be brought down. USDA and the U.S. Department of Energy are funding projects that have this aim. Also, many of the sugars making up cellulosic feedstocks (composed of cellulose and hemicellulose) are not readily convertible to ethanol by ordinary yeast.

Researchers have not settled on the cost of producing ethanol from biomass because ethanol is not yet being produced this way. A joint project by the USDA and DOE estimated the unit cost at a 25-million-gallon per year (MMgy) plant to be $1.50 per gallon (1999 dollars) (McAloon et al.). Though some researchers put this figure lower, at $1.16-$1.44 per gallon (Wooley et al.), recent estimates of the cost of commercial cellulose collection ($40-$50 per ton) and capital outlays (over $6 per gallon of annual capacity) make the likely cost higher. A consideration for new facilities will be the one-of-a-kind expense associated with setting up the first working biomass-to-ethanol plants (e.g., scaleup and development costs). In its $1.50-per-gallon estimate, the USDA/DOE study assumed these costs had already been incurred.

Cellulose to Ethanol: The Process

In the same way that starch from corn must be hydrolyzed and saccharified (decomposed further into simple sugars) before it can be fermented, cellulose must first be converted to sugars before it is fermented and turned into ethanol. Cellulosic feedstocks are more difficult than corn to convert to sugar. Cellulose can be converted by dilute acid hydrolysis or concentrated acid hydrolysis, both of which use sulfuric acid. Hydrolysis can also be achieved with enzymes or by other new techniques, including countercurrent hydrolysis or gassification fermentation.

Cellulosic hydrolysis produces glucose and other six-carbon sugars (hexoses) from the cellulose and five-carbon sugars (pentoses) from hemicellulose. The non-glucose (carbon) sugars must be fermented to produce ethanol, but are not readily fermentable by *Saccharomyces cerevisia*, a naturally occurring yeast. However, they can be converted to ethanol by genetically engineered yeasts, though the process is not yet economically viable (DiPardo).

Supplying Biomass

Some research has centered on converting the cellulosic portion of the corn kernel. Many of the researchers in this effort initially believed that cellulosic conversion could begin with the cellulose in the current feedstock stream (corn) and proceed to corn husks, and then to corn stover, before they finally extended their research to include other sources of cellulose. A second line of research has centered on converting cellulosic biomass directly into ethanol from noncorn sources such as small-diameter trees and switchgrass. Further research has focused on converting cellulose after it has entered the waste or coproduct stream, through steam explosion, for example.

If converting biomass to ethanol can be made economically attractive, the potential feedstocks are myriad. They include agricultural waste, municipal solid waste, food processing waste, and woody biomass from small-diameter trees. Agronomic research is underway on improving dedicated-energy crops such as hybrid willow, hybrid poplar, and switchgrass (DiPardo). One project looks at genetic improvement of switchgrass to optimize its conversion. Grasses grow quickly, of course, while tree crops such as willow require a 22-year rotation, with the first harvest in year 4 and subsequent harvests every 3 years thereafter. Hybrid poplar trees require 6-10 years to reach their first harvest.

Biomass from crop residue can be a source of farm profits, and with appropriate steps, its use in ethanol conversion can be environmentally friendly. A USDA study by Gallagher et al. (2003) concluded that crop residues are the cheapest prospective source of fuel for the U.S. market, with the energy potential to displace 12.5 percent of petroleum imports or 5 percent of electricity consumption.

Biomass Byproducts: Problems with Acid and High Temperatures

The dilute acid and concentrated acid hydrolysis used in biomass-to-ethanol conversion produce byproducts that either must be disposed of or that require recycling of sulfuric acid. In addition, the high temperatures required take a toll on the sugars and thus on the ethanol yield (DiPardo).

Potential Solutions to Acid and Heat Problems

Countercurrent Hydrolysis—Advances in biotechnology could reduce conversion costs substantially. The National Renewable Energy Laboratory (NREL) presents countercurrent hydrolysis as a new pretreatment. The process uses steam to hydrolyze most of the hemicellulose. In a second, hotter, stage, dilute sulfuric acid hydrolyzes the rest of the hemicellulose and most of the cellulose. NREL researchers believe the countercurrent hydrolysis process offers more potential for reducing costs than the dilute sulfuric acid process. They estimate that it will increase glucose yields and permit a higher fermentation temperature, resulting in an increased yield of ethanol. They have achieved glucose yields of over 90 percent in experiments with hardwoods (NREL, 2004).

A New Approach—While acknowledging that a cellulose-to-ethanol industry is in its infancy, Tembo et al. attempt to determine parameters that would define a regional (Oklahoma) biorefinery industry. The authors assess alternatives for future production, positing a gassification-fermentation technique that uses neither traditional acid nor enzymatic hydrolysis. Lignocellulosic biomass can be gassified, they say, in fluidized beds to produce "synthesis gas." The gas can then be converted by anaerobic bacteria to ethanol. Advantages to such a lignocellulosic system include a theoretically lower cost than for corn ethanol and the potential to use multiple perennial feedstocks, with supposedly less environmental impact than corn use. The researchers caution that the process is at the bench level and is not yet commercially available.

Enzymatic Hydrolysis—NREL believes that the greatest potential for ethanol production from biomass lies in enzymatic hydrolysis of cellulose. Advances in biotechnology may eventually make the technique possible through the use of genetically engineered bacteria and may also permit the fermentation of the pentoses.

Reducing Enzyme Costs

The use of enzymes in biomass-to-ethanol conversion will require reductions in the cost of producing cellulase enzymes, along with an increased yield in the conversion of nonglucose sugars to ethanol. The enzyme cellulase, already used in industry, replaces sulfuric acid in the hydrolysis step. Higher sugar yields are possible because the cellulase can be used at lower temperatures (Cooper). NREL reports that recent process improvements allow simultaneous saccharification and fermentation, with cellulase and fermenting yeasts working together so that sugars are fermented as they are produced. NREL estimates that cost reductions could be four times greater for the enzyme process than for the concentrated acid process and three times greater than for the dilute acid process.

In speaking of both corn stover and forest product waste, *Industrial Bioprocessing* writes, "The big stumbling block in manufacturing ethanol from biomass is the cost of hydrolyzing cellulose into fermentable sugar." To speed the quest for cheaper ways of using enzymes to convert biomass to ethanol, DOE funded research by two commercial enzyme companies, Novozymes and Genencor International Inc. Cellulase enzymes were recently reported to cost 45 cents per gallon of finished ethanol, making them too expensive for commercial use (NREL, 1998). NREL estimated that the cost could be reduced to less than 10 cents with scaled-up production. In fact, Novozyme recently announced that its researchers have successfully completed this project and have reduced the enzyme costs to 10-18 cents per gallon of ethanol produced (Susan Reidy in *BioFuels Journal,* 2005a).

Other Biomass-to-Ethanol Improvements

NREL estimates that, in addition to reduced costs of enzyme conversion, improvements in acid recovery and sugar yield for the concentrated acid process could save 4 cents per gallon and that process improvements for the dilute acid technology could save about 19 cents per gallon.

Considerable success in cellulosic conversion has already been achieved at the experimental level. Depending on the prices of alternatives and the success of current scaleup efforts, commercial viability may be possible in the near term. A Canadian firm, Iogen Corporation, in partnership with the Canadian Government, has demonstrated a process that turns wheat straw into fermentable sugar.

Conclusions: Ethanol's Potential

In keeping with USDA's early estimates of the savings to come, the cost of ethanol production has indeed fallen. Though improvements in process optimization and technology have been important, the fluctuating prices of inputs such as corn, the price of energy alternatives, and even environmental developments such as a drop in MTBE use, play larger roles in the fortunes of the industry.

Ethanol production is becoming a mature industry, with savings in the next 10 years likely to be smaller than those of the last 10-15 years.

Some developments, such as dry fractionation technology—soon to be commercially employed—may alter the structure of the industry by giving an edge to the less capital-intensive dry-mill method. This advantage for dry milling may make it easier to build smaller plants that are cost competitive, and local farmer cooperatives could flourish as a result.

Promising areas to be exploited by new technology include coproduct development, cellulosic conversion, and niche markets. The recovery of high-value food supplements may reduce financial risk by giving the industry an outlet outside the capricious energy market. Continued high oil prices may spur the risk-taking necessary to overcome the initial scaleup and development costs of cellulose-to-ethanol production. Niche markets that take advantage of locally available feedstocks, that have local outlets for coproducts, or that produce unique coproducts may also contribute to the industry's growth.

References

BioFuels Journal. "Analyze This: Online Tool Shows Impact of Ethanol Plant on Area Corn Prices," Fourth Quarter, 2003a, p.16. McNew and Griffith's online tool, accessed at http://extensionecon.msu.montana.edu/eplantanalyzer/

BioFuels Journal "Selecting Hybrids for Dry-Mill Ethanol," Fourth Quarter, 2003b, pp. 18-19.

BioFuels Journal. "Biomass-to-Ethanol for Less: NREL, Novozymes Announce 30-Fold Reduction in Enzyme Cost," Second Quarter, 2005a, pp. 107-8.

BioFuels Journal. "Sparking CO_2 Interest: KS Oil Field Pilot Project Could Open New Market for Ethanol Plants," Second Quarter, 2005b, pp. 8-9.

BioFuels Journal. "The 10M Ton DDG Question: Speakers Explore Options for Use of Distiller's Grains," Second Quarter, 2005c, pp. 86-87.

BioFuels Journal. "Fractionating Energy: Corn Fractionation Processes Help Cut Energy Costs," Third Quarter, 2005d, pp. 31-32.

BioFuels Journal. "FWS Dry Fractionation Processes," Third Quarter, 2005e, p. 32.

Bothast, Rodney. Personal interview, September 9, 2003.

Bryan, Tom. "A Long View Approach," *Ethanol Producer Magazine,* June 2004, p. 42.

Bryan, Tom. "The Search for a Perfect Ethanol Corn," *Ethanol Producer Magazine,* September 2002, pp. 14-19.

Canadian Renewable Fuels Association, accessed at http://www.greenfuels.org/ethaques.html

Cooper, C. "A Renewed Boost for Ethanol," *Chemical Engineering* 106(2), February 1999.

"De La Torre Ugarte, G. Daniel, Marie E. Walsh, Hosein Shapouri, and Stephen P. Slinsky. *The Economic Impacts of Bioenergy Crop Production on U.S. Agriculture,* AER-816. USDA, Office of Energy Policy and New Uses, February 2003.

Dien, B.S., R.J. Bothast, L.B. Iten, L.Barrios, and S.R. Eckhoff. "Fate of Bt Protein and Influence of Corn Hybrid on Ethanol Production," *Cereal Chemistry* 79(4):582-85, March 2002.

Dien, Bruce S., Rodney J. Bothast, Nancy N. Nichols, and Michael A. Cotta. "The U.S. Corn Ethanol Industry: An Overview of Current Technology and Future Prospects," *International Sugar Journal* 104(1241):204-11, April 2002.

Dien, B.S., R.B. Hespell, L.O. Ingram, and R.J. Bothast. "Conversion of Corn Milling Fibrous Coproducts Into Ethanol by Recombinant *Escherichia coli* Strains K011 and SL40," *World Journal of Microbiology and Biotechnology* (13)6:619-25, November 1997.

DiPardo, Joseph. "Outlook for Biomass Ethanol Production and Demand." Page last modified July 30, 2002. Accessed at http://www.eia.doe.gov/oiaf/analysispaper/biomass.html, February 20, 2004.

Eckhoff, Steve. "Use the Quick Germ Method—Lower Your Ethanol Production Costs," *Seed World* 139(3):14-16, March 2001.

Eckhoff, S.R., L. Du, P. Yang, K.D. Rausch, D.L. Wang, B.H. Lin, and M.E. Tumbleson. "Comparison Between Alkali and Conventional Corn Wet-Milling: 100-g Procedure," *Cereal Chemistry* 76(1):96-99, 1999.

Escobar, J.M., K.D. Rane, and M. Cheryan. "Ethanol Production in a Membrane Bioreactor: Pilot-scale Trials in a Corn Wet Mill," *Applied Biochemistry and Biotechnology: 22nd Symposium on Biotechnology for Fuels and Chemicals* 91-93(1-9):283-96, Spring 2001.

Feed Situation and Outlook Yearbook. USDA, Economic Research Service, various years.

Gallagher, Paul, Mark Dikeman, John Fritz, Eric Wailes, Wayne Gauther, and Hosein Shapouri. *Biomass From Crop Residues: Cost and Supply Estimates,* AER-619. USDA, Office of Energy Policy and New Uses, March 2003.

Gallagher, Paul, and Donald Johnson. "Some New Ethanol Technology: Cost Competition and Adoption Effects in the Petroleum Market," *Energy Journal* 20(1999):89-120, 1999.

Gallagher, Paul W., Daniel M. Otto, and Mark Dikeman. "Effects of an Oxygen Requirement for Fuel in Midwest Ethanol Markets and Local Economies," *Review of Agricultural Economics,* 22(2):292-311, 2000.

Haefele, D., F. Owens, K. O'Bryan, and D. Sevenich. *Selection and Optimization of Corn Hybrids for Fuel Ethanol Production.* In Proceedings, ASTA 59th Annual Corn and Sorghum Research Conference, 2004. CD-ROM. Alexandria, VA, American Seed Trade Association.

Hohmann, Neil, and C. Matthew Rendleman. *Emerging Technologies in Ethanol Production.* AIB-663, USDA, Economic Research Service, January 1993.

Hojilla-Evangelista, Mila P., and Lawrence A. Johnson. "Sequential Extraction Processing of High-Oil Corn," *Cereal Chemistry* 80(6):679-83, November-December 2003.

Illinois Corn Growers Association and the Illinois Corn Marketing Board, accessed at http://www.ilcorn.org/Pages/fstintro.htm, September 14, 2000.

Industrial Bioprocessing, "Enzymes for Biomass Ethanol," 25(4), April 2003.

Johnston, David B., and Vijay Singh. "Use of Proteases to Reduce Steep Time and SO(2) Requirements in a Wet-Milling Process," *Cereal Chemistry* 78(4):405-11, 2001.

Krohn, Bradley. Former technical leader of Monsanto's High Fermentable Corn Program, personal interview, September 9, 2003.

Kwiatkowski, Jason R., and Munir Cheryan. "Recovery of Corn Oil From Ethanol Extracts of Ground Corn Using Membrane Technology," *Journal of the American Oil Chemists' Society* 82(3):221-27, 2005.

Levelton Engineering Ltd. and (S&T)2 Consulting Inc. "What Is Driving the Fuel Ethanol Industry?" available at http://www/jgpc.ca.

Madlinger, Christy. Director of Technical Services, Frazier, Barnes & Associates, personal interview, September 15, 2005.

Majumdar, S., D. Bhaumik, K.K. Sirkar, and G. Simes. "A Pilot-Scale Demonstration of a Membrane-Based Absorption-Stripping Process for Removal and Recovery of Volatile Organic Compounds," *Environmental Progress* 20(1):27-35, 2001.

McAloon, Andrew, Frank Taylor, Winnie Yee, Kelly Ibsen, and Robert Wooley. *Determining the Cost of Producing Ethanol From Corn Starch and Lignocellulosic Feedstocks*. Technical Report of National Renewable Energy Laboratory (NREL), Golden, CO, October, 2000.

McNew, Kevin, and Duane Griffith. "Measuring the Impact of Ethanol Plants on Local Grain Prices," *Review of Agricultural Economics* 27(2):164-80, June 2005.

Moniruzzaman, M., B.S. Dien, C.D. Skory, Z.D. Chen, R.B. Hespell, N.W.Y. Ho, B.E. Dale, and R.J. Bothast. "Fermentation of Corn Fibre Sugars by an Engineered Xylose Utilizing Saccharomyces Yeast Strain," *World Journal of Microbiology & Biotechnology* (13):341-46, 1997.

National Renewable Energy Laboratory (NREL). "Biofuels - Pretreatment Technology," accessed at http://www.ott.doe.gov/biofuels/current_research.html, April 15, 2004.

National Renewable Energy Laboratory (NREL), "The Cost of Cellulase Enzymes," in *Bioethanol From the Corn Industry*, DOE/GO-10097-577, Golden, CO, May 1998.

Novozymes and BBI International. *Fuel Ethanol: A Technological Evolution.* Grand Forks, ND: BBI Publishing, June 2004.

Rendleman, C. Matthew, and Neil Hohmann, "The Impact of Production Innovations in the Fuel Ethanol Industry," *Agribusiness,* 9(3):217-31, 1993.

Renewable Fuels Association. *Homegrown for the Homeland: Ethanol Industry Outlook 2005.* Washington, DC, February 2005.

Ross, Martin. "California Ethanol Dream Coming to Fruition," *FarmWeek,* April 21, 2003, p. 5.

Rutherford, Amy, Director of Monsanto's "Fuel Your Profits" program, interview August 5, 2004.

Shapouri H., J.A. Duffield, and M. Wang. *The Energy Balance of Corn Ethanol: An Update*, AER-813. USDA, Office of Energy Policy and New Uses, July 2002.

Shapouri, Hosein, and Paul Gallagher. *USDA's 2002 Ethanol Cost of Production Survey,* AER-841. USDA, Office of Energy Policy and New Uses, July 2005.

Singh,V., and S.R. Eckhoff. "Economics of Germ Preparation for Dry-Grind Ethanol Facilities," *Cereal Chemistry* 74(4):462-66, 1997.

Singh, V., and S.R. Eckhoff. "Effect of Soak Time, Soak Temperature, and Lactic Acid on Germ Recovery Parameters," *Cereal Chemistry* 73(6):716-20, 1996.

Singh, V., and J.V. Graeber. "Effect of Corn Hybrid Variability and Planting Location on Dry Grind Ethanol Production." *Transactions of the American Society of Agricultural Engineers* 48(2):709-14, 2005.

Singh, Vijay, and David B. Johnston. "Enzymatic Corn Wet Milling Process: An Update," paper presented at the 2004 Corn Utilization and Technology Conference, Indianapolis, IN, June 7-9, 2004.

Swain, R.L. Bibb. "Molecular Sieve Dehydrators: How They Became the Industry Standard and How They Work." Chapter 19 in *The Alcohol Textbook*, 3rd ed., 1999, pp. 289-93, Nottingham, England: University Press.

Taylor, Frank, James C. Craig, Jr., M.J. Kurantz, and Vijay Singh. "Corn-Milling Pretreatment with Anhydrous Ammonia," *Applied Biochemistry and Biotechnology* 104(2):41-48, February 2003.

Taylor, Frank, Andrew J. McAloon, James C. Craig, Jr., Pin Yang, Jenny Wahjudi, and Steven R. Eckhoff. "Fermentation and Costs of Fuel Ethanol from Corn with Quick-Germ Process," *Applied Biochemistry and Biotechnology* 94(1):41-50, April 2001.

Tembo, Gelson, Francis M. Epplin, and Raymond Huhnke. "Integrative Investment Appraisal of a Lignocellulosic Biomass-to-Ethanol Industry," *Journal of Agricultural and Resource Economics* 28(3):611-33, December 2003.

Urbanchuk, John M. "Contribution of the Ethanol Industry to the Economy of the United States," paper prepared for the Renewable Fuels Association, January 10, 2005.

Walker, Devona. "New Technology May Converge Biodiesel, Ethanol Markets." Associated Press, June 28, 2005, accessed at http://www.aberdeennews.com. September 19, 2005.

Wang, M.Q. *GREET 1.5 – Transportation Fuel-Cycle Model: Volume 1: Methodology, Development, Use, and Results*, Center for Transportation Research, Argonne National Laboratory, Argonne, IL, August 1999.

Wang, M., C. Saricks, and D. Santini. *Effects of Fuel Ethanol Use on Fuel-Cycle Energy and Greenhouse Gas Emissions*. Center for Transportation Research, Argonne National Laboratory, Argonne, IL, January 1999.

Wooley, Robert, Mark Ruth, David Glassner, and John Sheehan. "Process Design and Costing of Bioethanol Technology: A Tool for Determining the Status and Direction of Research and Development," *Biotechnology Progress* 15(5):794–803, September-October 1999.