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Science News Online

Week of Oct. 1, 2005; Vol. 168, No. 14

Growing Expectations

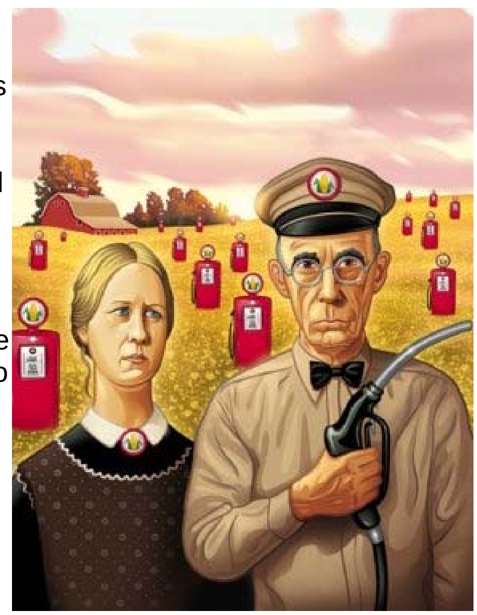
New technology could turn fuel into a bumper crop

Naila Moreira

Word on the street is that the days of petroleum are numbered. Industry giants run full-page newspaper ads with slogans such as "Think outside of the barrel." Even though it could take decades or more before the oil pipeline dries up, researchers in industry, government, and academe are preparing for the inevitable.

Tom Blades is one of them. In July, at the First International Biorefinery Workshop in Washington, D.C., he handed Paul Grabowski of the Department of Energy (DOE) a vial with clear liquid in it. "It's water," the DOE official joked. But instead, the innocuous-looking stuff could go straight into a diesel engine to run a car.

Called SunFuel and made from waste plant matter, this new diesel was developed at the Freiburg pilot plant of Choren Industries in Hamburg, Germany, where Blades is chief executive officer. Grabowski and Blades were among 300 participants at the workshop, which was convened by the DOE to discuss the potential for replacing petroleum fuels in the United States and Europe with renewable, environmentally friendly liquid fuels made from plant matter, municipal solid waste, and other sources of biomass.



Thanks to new technologies, many scientists foresee greener passenger cars running on ethanol and diesel fuel made from crop waste. Ethanol from corn is currently only a marginal gasoline additive.
Dean MacAdam

As gasoline prices have skyrocketed to around $2.75 a gallon and the United States grapples with energy-security concerns, "green fuels" have become more attractive. Made by converting crops or waste material into combustible liquid, these fuels include ethanol and biodiesel, both of which can be used as substitutes for petroleum fuels.

The Energy Policy Act of 2005, signed by President Bush in August, requires 7.5 billion gallons of ethanol and biodiesel to enter the nation's fuel supply by 2012, providing 5.75 percent of the nation's transportation-fuel needs. Because ethanol can be readily blended with gasoline, U.S. politicians have touted this alcohol as an important contributor to the nation's future energy supply. In contrast, hydrogen fuels, another alternative-fuel technology, would require new engine designs and transportation infrastructure.

Made in vast amounts from corn kernels in the United States and sugarcane in Brazil, ethanol is the most common plant-to-fuel product, or biofuel, currently available. Standard gasoline engines can run on blends of gasoline containing up to 15 percent ethanol. Flexible-fuel vehicles can use blends with up to 85 percent ethanol.

Green fuels produce lower emissions of greenhouse gases and atmospheric pollutants than does gasoline. But corn grain–derived biofuel has its downsides. Its critics point to the high energy costs associated with corn farming and environmental impacts such as fertilizer pollution and soil erosion (see "But Is It Green?", below).

Using waste plant material instead of corn grain to produce ethanol and other green fuels may sidestep these problems. Annual U.S. accumulation of agricultural detritus such as cornhusks, switchgrass, and wood chips—collectively known as cellulosic biomass—measures nearly a billion tons per year. A study of biofuels released by the National Resources Defense Council (NRDC) last July reports that biomass fuels from such sources could supply as much as 30 percent of the nation's fuel needs by 2050.

"Cellulosic biofuels are at least as likely as hydrogen to be a future sustainable transportation fuel of choice," says Yerina Mugica of NRDC.

Champions of biofuels still have technical, economic, and political barriers to overcome. For one thing, no one has yet found a commercially viable process for making large amounts of cellulosic biofuel. But with a host of cost-cutting advances now working their way through the pipeline, many researchers say biofuels from both cellulosic feedstocks and corn grain are fated to play vital roles in the world's energy equation.

Plant payoff

Most players in the transportation debate, including politicians, industry representatives, environmentalists, and researchers, agree that fuels from plant waste offer promise. However, it takes chemistry to turn solid biomass into liquid fuels.

Researchers seeking to make ethanol must first unlock sugars from the plant polymer called cellulose and other plant carbohydrates. "Cellulose looks like a long string of pearls," explains Charles Wyman of Dartmouth College in Hanover, N.H. "The individual pearls are the sugar-monomer units." Yeast and bacterial cells can ferment those individual sugar monomers into alcohol.

DRIVING ON FUMES. Corn and the ethanol produced from it have fueled both cars and a debate over whether corn farming offers an environmentally sound replacement for petroleum drilling.
USDA

Unlike starch from corn grains, cellulose is difficult to break up into its constituent sugars. The recalcitrance of cellulose poses the biggest challenge facing biomass-to-fuel technology. "Cellulose is in plants to give the plants rigidity," says Joel Cherry of Novozymes in Davis, Calif. "Starch is in plants to feed seeds when they grow. It's made by nature to be broken down."

Making ethanol from cellulose requires, first, mechanical and chemical pretreatments of the plant matter and biochemical treatments with enzymes to break the polymer into its single-sugar pearls. Next, the sugars must be fermented into ethanol. Finally, the ethanol is distilled from the fermentation solution. Each stage adds expense and consumes energy, but new technologies promise to improve efficiency and lower costs.

This past January, Novozymes and a competing firm, Genencore in Palo Alto, Calif., announced major advances in reducing the cost of cellulases, which are the types of enzymes that break cellulose into sugars. The two companies already produce commercial cellulases for the textile industry, for such applications as weathering blue jeans.

In 2000, the companies projected the cost of the microbially produced enzymes at $5.40 per gallon of ethanol produced. That's a prohibitive price tag. In collaboration with DOE, the two companies have since discovered new microbial cellulases by using genetic techniques and have streamlined production of those enzymes.

Novozymes has brought down enzyme costs to 20 cents per gallon of ethanol, Cherry says. Genencore reports a similar achievement.

"The cost of enzymes for this process was a showstopper 5 years ago," says James MacMillan of DOE's National Renewable Energy Laboratory (NREL) in Golden, Colo. "It no longer is."

Combining steps in the ethanol-production process that are now separated could reduce costs even more, says Lee R. Lynd of Dartmouth College. Most biomass operations enzymatically break down cellulose into sugars in an oxygen-rich environment and then use yeast or bacteria to ferment the sugars under oxygen-poor, or anaerobic, conditions.

However, Lynd argues that a single anaerobic microorganism can do both jobs. Many researchers had previously suspected that anaerobic microbes generate too little cellular energy, in the form of the molecule ATP, to efficiently break down cellulose. But in the May 17 *Proceedings of the National Academy of Sciences*, Lynd and his Dartmouth colleague Yi-Heng Percival Zhang reported observations of an anaerobic microbe that, by growing on cellulose, generates plenty of ATP. In fact, the microbe produces even more cellular energy by breaking down cellulose than it does by growing on simple sugars such as glucose.

Using existing technology, Lynd intends to bioengineer such organisms to also take the next step: producing ethanol.

"Lynd's work offers promise for really reducing the cost of processing," says Bruce Dale of Michigan State University in East Lansing. It shows that no theoretical obstacle remains to achieving "consolidated bioprocessing," in which both cellulose breakdown and ethanol production are done by a single microorganism, he says.

Dale himself is working on improvements in preparing plant waste for enzymatic treatment. His research uses liquid ammonia to "literally blow the plant apart," he says. Through recent advances, for which he has applied for patents, he has cut in half the cost of this pretreatment process.

Despite such process improvements, ethanol production still requires an energy-intensive distillation step. That's why George Huber and his colleagues at the University of Wisconsin–Madison, are working to develop biodiesel instead of ethanol from cellulose-derived sugars.

Most biodiesel is produced from soybean oil, sunflower oil, or waste vegetable grease. But oils aren't nearly as plentiful as carbohydrates in plant matter, says Huber.

His new process runs biomass carbohydrates through a four-phase catalytic reactor to produce liquid alkanes, which are molecules made entirely of hydrogen and carbon. Like oil, these alkanes spontaneously separate from water and can be blended with diesel fuel, Huber's research team reported in the June 3 *Science*.

So far, the researchers have made only small, laboratory-scale batches of the alkanes. Scaling up the process in a cost-effective way may be difficult, especially since alkane production requires many steps. "We're currently looking at ways to combine the steps to make it a simpler process overall," says James Dumesic, who led the University of Wisconsin study.

Wyman says that although such biodiesels may prove practical in Europe, where more cars run on diesel, ethanol will likely remain the transportation biofuel of choice in the United States, given this country's gasoline-based infrastructure.

John Sheehan, a senior engineer at NREL, notes that there is no one solution to keeping the future fuel pipeline filled and running. "What we really need is a broad approach that looks at every strategy that makes sense," he says.

Fields to wheels

Of these strategies, so-called thermochemical pathways for biofuel may be the first to overcome technical and commercial hurdles. Most thermochemical processes burn biomass into a gaseous mixture of carbon dioxide, carbon monoxide, and hydrogen.

Any type of biomass, including wood, grass, animal manure, and municipal solid waste, can be gasified. The resulting gas can then be converted into liquid fuel by chemical pathways, including the well-known Fischer-Tropsch synthesis, which produces diesel.

SAWDUST TO DIESEL. Wood chips may someday power automobiles, now that emerging technologies can cheaply turn them into fuels such as Choren Industries' diesel-like SunFuel, shown in the flask.
Choren Industries

Currently, thermochemically produced biofuels can't compete with petroleum on the open market. Thermochemical processing must be done at a larger scale than biochemical processing is to be economic, says Lynd, but it's expensive to build a huge refinery. Transporting large amounts of dry biomass adds to the cost. Also, biomass gasification produces contaminants such as tar, which must be removed for the Fischer-Tropsch process to work.

Thermochemical production of biofuel may soon overcome those problems, at least in Europe. To create its SunFuel, Choren relied on new technology that simplifies thermochemical processing by creating a liquid stream from biomass. This stream feeds more easily into the gasification system, permitting the plant to run at the high temperatures that eliminate tar, says Blades.

Both Daimler Chrysler and Volkswagen have used Choren's SunFuel in test runs. "We are supporting their technology, and together we are developing new specifications for [these] fuels," says Wolfgang Steiger of Volkswagen in Wolfsburg, Germany.

At their SunFuel pilot plant, Choren engineers are working out the best operating conditions for a larger plant, currently under construction in Freiburg and slated to produce biodiesel by the end of next year. Blades estimates that the plant should produce fuel at 0.90 Euro per liter. At the pump, European diesel fuel costs about 1.05 Euro per liter, or about $5 per gallon.

Future's fuel

In the United States, the quickest route to commercially competitive biofuels may lie in combining biochemical- and thermochemical-biofuel pathways, says Lynd. A combined plant could produce ethanol or other products by biochemical pathways, then thermochemically convert recalcitrant materials into electricity or additional fuels.

In a 2004 NRDC study, "Growing Energy," Lynd and his colleagues assessed biofuels' potential. "Our forward-looking analysis seems to show that biochemical and thermochemical [processes] together have greater potential for cost-effectiveness and energy efficiency than either separately," Lynd says.

Increased vehicle efficiency would amplify the impact of biofuel in replacing petroleum as well as ease land-area requirements for biofuel production, notes Brian Davison, director of the Bioprocessing Research and Development Center at Oak Ridge (Tenn.) National Laboratory. In fact, according to "Growing Energy," biofuels, coupled with improved vehicle efficiency, could meet all the transportation-fuel needs of the United States by 2050.

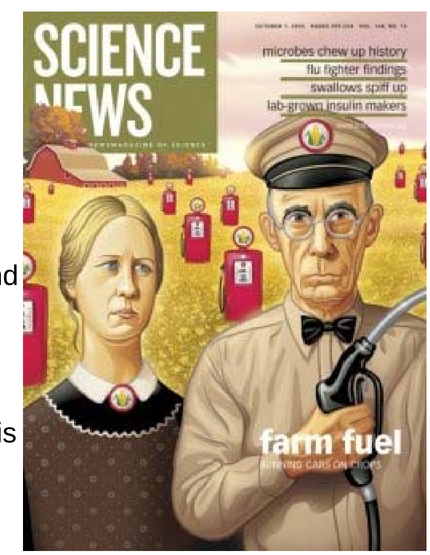
Says Larry Russo of the DOE Office of the Biomass Program, "Agriculture in the 21st century will become our oil wells."

But Is It Green?

Scientists disagree over the benefits of tomorrow's fuels

Not everyone's on board when it comes to driving cars on biofuel. Ethanol production from biomass requires the consumption of more fossil fuel–derived energy than it saves, says David Pimentel of Cornell University. "Ethanol is not helping us. It's encouraging the importation of oil from Saudi Arabia and elsewhere," he says.

For instance, ethanol production from corn consumes 29 percent more energy than it returns as fuel, Pimentel and Tad Patzek of the University of California, Berkeley calculated in the March *Natural Resources Research*.



Dean MacAdam

Heavy use of fossil fuel is intrinsic to the farming of corn, Pimentel says. Manufacture of plows, combines, and other farm machinery takes lots of energy, and they guzzle fuel.

Producing nitrogen fertilizers also consumes large amounts of energy, he and Patzek argue. It takes yet more energy and fuel to extract the ethanol from the 8 percent ethanol solution that forms once the corn is fully fermented.

Other researchers, among them Bruce Dale of Michigan State University in East Lansing, dispute Pimentel's numbers. Dale says that Pimentel's analysis relies on outdated energy data for ethanol processing and on exaggerated irrigation and fertilizer requirements for farming. Also, Dale says, future ethanol plants will burn unfermentable portions of their feed material to fuel the plant's power needs, further reducing fossil fuel use.

"The responsible, reliable analyses done well show that both corn [kernel] ethanol and cellulosic ethanol can replace petroleum," Dale says. He points to a 2004 study by the U.S.

Department of Agriculture that reported that ethanol production returns 67 percent more energy than it consumes.

"In recent years, more studies have shown a positive energy balance," says Michael Wang of Argonne (Ill.) National Laboratory, an author of the USDA study.

Energy balance is just one important factor when considering the pros and cons of fuel technologies, says Erich Pica of Friends of the Earth in Washington, D.C. Growing large areas of corn or any other single crop requires pesticides and fertilizers that can find their way into the environment in water runoff from the fields, he says.

Replacing the entire U.S. fuel supply with corn ethanol would require at least 60 percent of the nation's available cropland, according to calculations by Marcelo Diaz de Oliveira of the University of Florida in Gainesville and his colleagues.

Use of plant waste, called cellulosic biomass, rather than corn for making fuels would eliminate the need for large, dedicated agricultural areas. "We are supportive of cellulosic ethanol," says David Hamilton of the Sierra Club in Washington, D.C. "It's more environmentally friendly and more competitive as a fuel."

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From *Science News*, Vol. 168, No. 14, Oct. 1, 2005, p. 218.