

# HARVEST OF ENERGY

Researchers at the  
Biomass Energy Center  
are homing in on future fuels

—By David Pacchioli, Research | Penn State



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photo Pat Little

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Three dollars got our attention. We could dispute the fact that oil reserves are dwindling. We could ignore the growing evidence that we're overheating the planet. We could somehow even disconnect an ongoing war and instability in the Middle East from our unquenchable thirst for petroleum. But when gasoline prices hit three dollars a gallon during the summer of 2005, the term "energy independence" suddenly held new urgency. Finding the energy sources of the future—clean, sustainable, reliable sources—became the task of the immediate present. For many of us, that was when the idea of growing switchgrass for fuel stopped sounding like science fiction.

Energy researchers, of course, have been taking switchgrass—and hybrid poplar, and blue-green algae, and sugar cane—seriously for much longer than that. These are just a few examples of biomass, plant matter that can be transformed into fuels and other energy products. Like petroleum and coal, biomass contains carbon taken from the atmosphere via photosynthesis: turning sunlight into energy. Unlike fossil fuels, however,

biomass is renewable, and can be grown domestically. In all its varieties, biomass is also plentiful, and has the potential to be much more environmentally friendly as fuel.

At Penn State, over 50 researchers are currently involved in researching biomass energy, in every discipline from fuel science to genetics. To help coordinate their efforts, the University has created the Biomass Energy Center, an interdisciplinary initiative housed in the College of Agricultural Sciences that also includes the Eberly College of Science, the College of Engineering, and the College of Earth and Mineral Sciences. According to biological engineer and Center director Tom Richard, none of these researchers thinks of biomass energy as a panacea. But all of them are convinced that it can be part of the solution.

**Much more than corn**

Until recently, the average American might well have been excused for equating alternative fuels exclusively with corn. After all, corn-based ethanol accounts for virtually all of the biomass-derived fuel currently



Tom Richard, Director, Biomass Energy Center

credit Gregory Angle

produced in the U.S., a projected six billion gallons in 2007. Nationwide, there are now well over 100 ethanol fuel plants processing corn grain, with another 35 or so on the way. In Pennsylvania, large corn-to-ethanol plants are under construction in Clearfield and Westmoreland counties. Corn ethanol, mixed with gasoline, now accounts for roughly three percent of this country's automobile fuel.

This rapid growth has had significant consequences, not all of them desirable. Economists and others have worried about a dramatic rise in corn prices which, while it benefits corn growers, has also inflated food prices and raised wider fears about turning over prime farmland to the production of fuel. Too, because corn is energy-intensive to grow, there is ongoing debate over the actual net gains of using corn as fuel, both in terms of energy produced and greenhouse gases emitted.

All else aside, Tom Richard says, "there's just not enough of it" for corn to be the biofuels answer over the long haul. Even if all the corn U.S. farmers now grow were to be funneled into ethanol, he notes, it would replace only 15 percent of the country's gasoline demand.

Where energy is concerned, Richard and others now agree, the chaff might actually be more important than the grain. In 2004, Richard, then at Iowa State, testified before a U.S. Senate Committee about the untapped energy potential of corn stover—the stalks and other inedible parts of the corn plant which currently go to waste.

Richard estimated that a sustainable harvest of 100 million metric dry tons per year of corn stover is available for use—a bulk that could translate into over 10 billion gallons of fuel in the U.S. “Because stover is a crop residue,” he added, “the incremental energy, nutrient and cost inputs for collection are relatively small, offering corn producers the potential for a valuable new co-product from existing acreage.”

“Transforming corn stover, wheat straw, and other crop residues into fuel can help turn the food versus fuel debate on its head,” Richard says. “Developing integrated cropping systems that provide food, fuel, and a quality environment is critical to finding win-win-win solutions that address long term societal needs.”

Crop scientist Greg Roth has been working out just such integrated cropping systems for Pennsylvania agriculture, focusing particularly on alternative winter cover crops. Roth has been studying the use of canola for biodiesel and hulless barley for ethanol production, growing these energy-rich cover crops over the winter and spring when the soil was otherwise bare.

“These cover crops allow us to get three crops out of the common corn-soybean rotation, producing 115 to 200 gallons of biofuel per acre,” Roth reports. “By covering the soil for most of the year, cover crops not



Greg Roth, Professor of Agronomy

only capture more sunlight for energy, but reduce erosion and improve water quality as well.” The starch in barley could provide a near term alternative to corn ethanol, and would be available in the summer when corn prices typically reach their annual peak. And there are even larger bioenergy resources that are yet to be tapped.

## Out of the woods

In a heavily forested state like Pennsylvania, one key bioenergy feedstock is the woody biomass of forest residue. “Pennsylvania’s forests are rich in potential bioenergy from small-diameter trees that are overcrowded, under-utilized, and inhibit the opportunity for professional management,” says Charles Ray, assistant professor of wood operations research. According to the most recent U.S. Forest Service data, Ray says, as much as 500 million tons of wood are held in these “small-diameter stems” across the state’s 16 million acres of forestland. Ray has estimated that six million dry tons of this “waste wood” per year could be harvested for bioenergy—enough raw material to produce 540 million gallons of ethanol.

Corn stover and forest residue are ready sources of cellulosic biomass—fibrous plant material made up mostly

of the structural compounds cellulose and lignin. Other potential options include fast-growing, high-yield grasses like switchgrass and miscanthus, which could be cultivated as dedicated energy crops. The cellulose in these sources can be converted to sugar, which is then fermented into ethanol. The process is not as straightforward as fermenting the starch from corn, experts say, but the net energy balance is far more favorable.

According to a study by the U.S. Department of Energy in 2006, the long-term potential for cellulosic ethanol is gigantic: some 120 billion gallons a year could be made in the U.S. by 2050. That won’t happen, though, until researchers get more efficient at cracking the lignin barrier.

## The miracle of lignin

“Nature’s plastic,” is what Ming Tien calls lignin. “It’s a polymer of phenols that helps plant tissue stay rigid,” explains Tien, professor of biochemistry. Lignin is what makes wood hard, and brown. “Aquatic plants don’t have it—it was an adaptation to the terrestrial lifestyle,” he says.

In the early 1980s, Tien, then a postdoc at Wisconsin, discovered the enzymes that fungi produce to degrade lignin. Fungi, he explains, are the predominant degraders of wood. “They have to deal with the lignin barrier to get to the cellulose, which is the carbon source that they live on.” At the time, Tien’s discovery was of great interest to the pulp and paper industry, still the major users of cellulose. “One idea was to use these enzymes instead of harsh chemicals to degrade lignin for making paper.” He pauses. “That never really panned out. While these enzymes do degrade lignin, it’s a slow process. Just think how long it takes for stumps to degrade.”

credit: Pat Little

Twenty years later, however, the chemical pretreatment required to remove the lignin barrier is a major expense in the making of cellulosic ethanol. As a result, Tien says, “There’s renewed interest in how can we use some of these fungal enzymes.” He is working with Richard on methods for adding these enzymes to biomass during ensilage, to begin breaking down lignin while biomass is still on the farm. “The trick is to enzymatically crack the lignin with a minimal loss of cellulose,” Tien says.

Another idea is genetically altering trees to make them produce less lignin. “A lot of people are working on this,” Tien says. “But if you lower the lignin content, you’re affecting the fitness of the plant. It may not be as structurally rigid. It may blow over and break if there’s a strong wind.”

Instead, Tien wondered what would happen if he engineered the tree in a slightly different way, introducing proteins into the plant’s cell walls that would block some of the cross linkages between lignin molecules and replace them with protein-lignin linkages. This would then make those molecules more accessible, easier to chemically “unzip.” “Instead of using harsh chemicals to soften the lignin, we could use proteases,” Tien says. “Protease technology is pretty well known—these are the enzymes people use to remove stains from clothing.”

He took his idea to molecular geneticist John Carlson and Haiying Liang, a postdoc working in Carlson’s lab. Carlson and Liang have since introduced the blocking proteins into hybrid poplar plants, and are currently testing the effect on lignin degradation.

“What’s nice about this,” Tien says, “is that it’s a generic strategy.

You could use it on many different plants. And it doesn’t have to be just for fuel. Tweaking the lignin content this way could make corn stover and other waste products easier for farm animals to digest. This could have impact especially in developing countries.”

## Cellulose breakdown

The lignin barrier is not the only problem that needs to be solved before cellulosic ethanol can be made commercially, however. “You can think of lignin as a layer of paint,” Daniel Cosgrove says. Once that’s scraped off, there’s the intractability of cellulose itself.

Cosgrove, who holds the Eberly chair in biology, uses a cardboard model to explain. He holds up a small white panel. “This is glucose, a nice sugar molecule, easily digested,” he says. “Cellulose is basically glucose polymerized in a particular way.” First, he demonstrates, the panels are joined end-to-end, one glucose linked to the next. Then—he pauses to fasten them—“these strips are cross-bonded together, into stiff sheets,” Cosgrove says. “Next, these sheets of glucans stack up to make something like this.” He holds out a stack several sheets deep. “That’s cellulose.”

“This is all just sugar,” Cosgrove continues. “It ought to be useful for all kinds of organisms. But cellulose is really indigestible. It’s fiber; that’s what the nutritionists call it. Converting this substance into small sugars which can then be fermented into alcohol—that’s the major technological hurdle.”

Though he wasn’t looking for it, Cosgrove happened on a possible solution over ten years ago when he discovered the family of plant proteins now known as expansins. Catalysts of cell growth, expansins have a unique

loosening effect on plant cell walls.

“In trying to figure out how expansins work,” Cosgrove says, “we discovered that if you add them to cellulose in the presence of cellulases—enzymes that break down cellulose—the cellulases become more efficient. It looks like expansins loosen up the structure of the cellulose.” He picks up the stack of sheets, and removes the top sheet. “Our hypothesis is that expansins have the ability to lift off these glucans.

“We’re continuing to try to understand how that happens—what the interaction is between expansins and cellulose—and also to explore various avenues for technological application, including biofuels,” Cosgrove says. “One way would be to throw in expansins along with the cellulases and other enzymes that are currently used for digestion of cellulosic material.

“The other way would be to use genetic technology to get the plant to produce its own expansins, just before harvest. Maybe produce cellulases too, so you don’t have to add them in,” he says. “At this point we’re testing the principle in arabidopsis and maize. If they look promising we’ll put the gene into plants that are more likely candidates to be energy crops. But that’s all a couple of years down the road.”

## On golden pond

One way to avoid the lignin problem altogether, Don Bryant suggests, would be to rely on microbial biomass as an energy feedstock. Cyanobacteria, often called blue-green algae, are hardy, fast-growing microbes found in oceans and freshwater ponds, indeed wherever there is moisture.

“You can directly ferment these organisms into ethanol,” says Bryant,

professor of biochemistry and molecular biology. “We could make big ponds out in Arizona or Nevada and grow tons of cyanobacteria if we can figure out a way to get water there.”

But cyanobacteria and the other phototrophic organisms he studies are equally important, Bryant says, as models for the ultimate in renewable energy: photosynthesis. “These things are terrifically efficient—essentially every photon that goes in is converted into chemical energy,” he says. “We’d like to be able to design man-made devices that had that kind of efficiency.”

To that end, Bryant and his team study the light-harvesting designs of nature, particularly an antenna structure some phototrophs employ called a chlorosome. “It’s literally a big sack of [light-absorbing] chlorophyll,” he says. “Each cell of the principal organism we work with contains about 200 to 250 of these sacks, and each sack contains about 250,000 chlorophyll molecules.

“We want to understand everything we can about the design principles of these structures, how the molecules are synthesized,” Bryant says. “On the surface it seems fairly simple—it’s made up of chlorophyll aggregates—but actually it’s made up of several different types of aggregates, in different proportions, under different growth conditions. There are modifications that change the size and shape and chirality of some of the side chains on these molecules.

“Turns out you these modifications provide some very important benefits for light-harvesting. We’ve worked out what several of those benefits are. But the extent to which that kind of information could be added into man-made devices is not really clear yet.”

## Grasses and trees

Back on dry land, Penn State researchers are investigating a wide variety of potential “second generation” feedstocks: crops developed and grown specifically for fuel. “Everybody talks about switchgrass as the new bioenergy crop,” Tom Richard says. “Well, we’ve been doing research on switchgrass for almost 30 years, collaborating with USDA-ARS scientists based here at Penn State. But there are other grasses we should look at as well.”

One candidate, giant miscanthus, is already being used as a biofuel in Europe. A perennial, “it grows extremely fast, and produces three times the biomass of switchgrass,” Richard says. “How does it do it? What makes it more efficient? Can that mechanism be transferred to other plants?” In addition to their energy value, he notes, perennial grasses have environmental benefits, helping with carbon sequestration, soil erosion, wildlife habitats, and water quality. And unlike corn, they can be grown on marginal land.

Another possibility is fast-growing trees. John Carlson is an expert on hybrid poplar, a tree well-studied for its value to the paper industry. As a member of the steering committee for the International Poplar Genome Consortium, Carlson helped spearhead the sequencing of the tree’s genome in 2002.

Young poplar trees grow “easily three meters a year,” Carlson says. “It is already grown in plantations.” And its small genome makes it an ideal candidate for genetic engineering. Carlson has worked for years on modifying lignin biosynthesis in poplar and other trees, first for the paper industry and now for biomass energy.

Even without genetic engineering, he says, “we can use the knowledge

of the poplar genome to improve traditional breeding for lower lignin and higher cellulose content.” Other fast-growing trees like chestnut and yellow poplar might be even better biomass species in certain habitats, he adds.

“It’s kind of a trade-off as to whether woody species are better than grasses for biomass applications,” Carlson says. “Per rotation, trees produce much more biomass than grasses do, but grasses can be harvested annually.” He has tried, unsuccessfully so far, to get funding to try alternating the two, switchgrass and hybrid poplar, on the same land.

“The idea would be to do this on mine reclamation sites in Pennsylvania,” Carlson explains. “We could reclaim these damaged sites at the same time we’re producing a crop. We could even use some of the excess cow manure from our dairy farms to supplement the soil, instead of having it end up in the Chesapeake Bay. These could be biomass plantations with ecological restoration at the same time.”

## Beyond ethanol



Glen Cauffman, Farm Operations Manager

Though ethanol has drawn most of the recent spotlight, a large number of other biofuel alternatives exist. One that is being actively researched at Penn State is biodiesel.

A renewable version of standard petroleum diesel, biodiesel can be made from vegetable oils, animal fats, even kitchen grease. In the U.S. it's made mostly from soybeans. Blended in with standard diesel at a ratio of up to 20 percent (known as "B20"), it burns well in existing diesel engines.

Five years ago, to demonstrate that fact, Glen Cauffman, manager of farms and facilities in the College of Agricultural Sciences, began a program to convert the college's farm equipment to biodiesel fuel. Cauffman also worked with Joe Perez and Wally Lloyd, emeritus faculty members in chemical engineering, who developed a program that has undergraduate students making biodiesel from leftover fryer grease donated by campus food services. By 2006, Penn State had converted all of its diesel equipment to run on B20 biodiesel.

For the past year, in collaboration with Pennsylvania-based tractor manufacturer Case New Holland, Cauffman and his staff have extended the experiment even further, running two unmodified New Holland tractors entirely on pure B100 biodiesel. "Thus far," Cauffman reports, "we have experienced no negative effects."

Though biodiesel (mostly from rapeseed or canola oil) is used widely in Europe, research continues into its combustion properties, emissions, and its effects on diesel engines. Fuel scientist Andre Boehman has studied the impact of using biodiesel on what he calls the two "classic problems" of diesel engines: soot and nitrogen oxides, or NOx.

"Biodiesel tends to lower soot emissions," Boehman reports. "It also tends to make the particulate less carcinogenic. We've been able to postulate an oxidation mechanism

for biodiesel soot that's very different from other diesel soots."

The effect on NOx (pronounced "knocks") is a trickier problem. NOx, Boehman explains, is a major contributor to smog and ground-level ozone. "What's been seen with B20 blends is a consistent two to four percent NOx increase," he says. "At high loads it can be significantly higher." Last year Boehman spent a sabbatical at Sandia National Lab trying to get a better handle on "the NOx effect." For older, hydraulic-line fuel systems, he says, "We've showed how it happens and how to get around it." Ironically, for newer electronically timed diesel engines, he says, "we still don't know."

Boehman sees clean diesel technology as a critical component in a sustainable energy future. "Diesel engines are inherently more efficient than gasoline engines," he explains. "And we won't benefit much by moving to biofuels if we don't improve the efficiency of the vehicles that use them."

One emerging problem, he says, is the uneven quality of today's biodiesel fuels. "Too much of what's being made is not in compliance with government specifications." In part, he says, this is a result of rapid expansion of the U.S. biodiesel market, from a total of 75 million gallons sold in 2005 to 225 million in 2006. "When you have that kind of explosive growth, you're going to have growing pains." But as emission standards grow more strict and engine systems more sophisticated, Boehman adds, the importance of fuel quality only increases.

Higher standards for fuel economy will "almost certainly" favor additional diesel vehicle options for U.S. consumers, Boehman predicts. He's

less sure about the role of today's biodiesel in fueling those vehicles. So-called "green diesel" takes a different approach to making fuel from soybean oil, one that may be even cleaner burning, he notes. "We can also make various synthetic fuels from renewable feedstocks."

"There's no single fuel that's going to solve all our problems," Boehman concludes. "It's much more likely that we'll have a variety of fuels, each used in the context where it works best."

## Rural electric

Jay Regan's research skips the off-site fuel part altogether. Regan, an assistant professor of environmental engineering, is interested in converting biomass directly to electricity. Since he arrived at Penn State in 2002, Regan has worked with colleague Bruce Logan on improving designs for microbial fuel cells, which exploit the energy-producing activity of microbes feeding on organic matter.

"Most living things oxidize organic matter," Logan explains. "They eat stuff and their bodies burn it to make energy." That "burning" frees up electrons, which microbial fuel cells convert into electric current. Over the last few years, Logan has attracted worldwide attention with his attempts to perfect a fuel cell that runs on wastewater, potentially taking an energy-intensive activity—sewage treatment—and turning it into an energy producer.

"More recently," Regan says, "my students have been looking at using cellulosic materials—not just wastewater, but biomass—as the substrate for running a microbial fuel cell. We're talking about farm waste materials—corn stover, or manures mixed up with their bedding materials." He

and graduate student Zhiyong Ren are studying different combinations of microbes, trying to optimize the necessary reactions. “The main constraint we have right now is the kinetics of the process,” he reports. “How fast can the organism degrade cellulose?”

Regan is also looking at improving anaerobic digesters, a related technology that holds potential for turning farm waste into energy. Digesters use anaerobic bacteria to break down manure, yielding methane that can be used to generate electricity or heat, enough to power a farm. During the energy crisis of the 1970s, Penn State researchers operated an experimental system at University Park, and several more were built around Pennsylvania, but the idea never really caught on. One problem, Regan says, is that digesters tend to be somewhat balky: the methane-producing organisms (“methanogens”) that they run on are particularly sensitive to drops in pH. “They tend to crash if the pH decreases due to high organic loading rates,” he says.

One of Regan’s graduate students, Lisa Steinberg, recently found some hardier methanogens at Bear Meadows, an acidic bog in nearby Rothrock State Forest. “Lisa noticed that these bog methanogens thrive at very low pH levels,” he says. “She’s been working on characterizing and testing them, taking bog samples and feeding them municipal sludge in an engineered digester. So far, they seem to work well.

“If they hold up, we’re hoping they will impart some needed stability to these systems.”

## The greatest challenge?

After all the talks he’s given about the future of biomass energy, Tom Richard is used to ticking down the list of technical challenges. “Then,”

he says, “there’s the big non-technical challenge: restructuring society to think and act differently.

“One thing for sure is we have to learn to be more energy-efficient. This is particularly important in the mid-term, when we’re going to have trouble filling the gaps between fossil fuels and renewables,” he says. “Our biggest opportunity right now is in conservation, both at the policy level and at the level of individual decisionmaking. It’s not sexy, but it’s vital.

“In terms of production,” he adds, “we need to develop cropping systems that provide food and fiber at levels at least equivalent to today, but also come up with energy-producing crop rotations such as cover crops to grow between food crops. We need to use land more intensively but in an environmentally sound way.”

Another important element in any large-scale transformation will be what Richard calls “buy-in” by key participants on the ground: first and foremost, farmers. “There’s been an assumption that farmers are going to jump to it, planting these new energy crops,” explains rural sociologist Clare Hinrichs. “It’s not that simple.

“Growing corn for ethanol is no big leap for U.S. farmers,” Hinrichs says. “But the shift to perennial grasses is a whole different thing. There’s not much existing commercial market for it. So the issue of what are farmers thinking about it—would they want to do it, and under what conditions—is a really important one.”

Last summer, Alissa Meyer, one of Hinrichs’ graduate students, interviewed Iowa farmers who had participated in a switchgrass demonstration project. “These farmers have a very peculiar mix of hope and skepticism

about what this transition would mean for them,” Hinrichs says. “They see a huge rush of large-scale corporate actors into this arena, and they’re not very sanguine that in the long run they’re going to be able to retain much of the value.”

This summer, Hinrichs began a similar ethnographic study in Pennsylvania. “It’s a very different agricultural environment,” she says, “a much more diverse agricultural economy. But you have some of the same restructuring going on, with farmers getting older, young people finding it difficult to get into farming, small farmers struggling to survive.

“There are lots of interrelated questions that will need to be answered in both places,” she says. “What crops should be grown? What’s the best way to grow them sustainably? How big will the refinery plants be? Where should they be located—closer to farms, or closer to consumers, in suburban areas? Who is going to be growing these energy feedstocks—will it be large-scale farmers? Small farmers? Retired farmers? Other landowners? It may be a whole different population, with a different relationship to the land, and different motivations.

“I think there’s still a big disconnect here,” Hinrichs adds at last. “People who are not associated with agriculture or with rural communities tend to think that these decisions don’t really affect them, but they do. We are more interdependent than we realize. The answers to these questions will affect all of us.”

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# BIOENERGY

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