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NREL National Renewable Energy Laboratory

Innovation for Our Energy Future

The Biomass Economy

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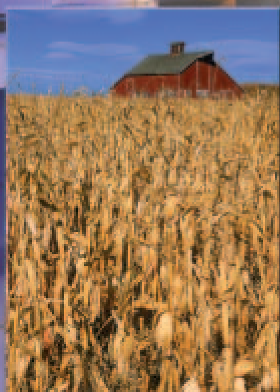
The 20th century was the century of the petrochemical economy. Gasoline and diesel (made from petroleum) power almost all our vehicles. Myriad plastics made from petroleum or natural gas are used to make our clothes, carpets, food packaging, and increasingly, our car parts and building materials. Most of our chemicals and even toiletries and pharmaceuticals are petrochemically derived.

Unfortunately for the United States, most of the world's petroleum is located elsewhere, so we import more than half of what we use, creating heavy economic and security burdens. And unfortunately for the world, whenever gasoline, diesel, and other fossil fuels are burned, they release carbon dioxide that had been locked up underground for millions of years, increasing greenhouse gas levels.

In the 21st century, use of biomass—plants and plant-based materials, produced by photosynthesis within biological rather than geologic time—will offset this petrochemical dependence.



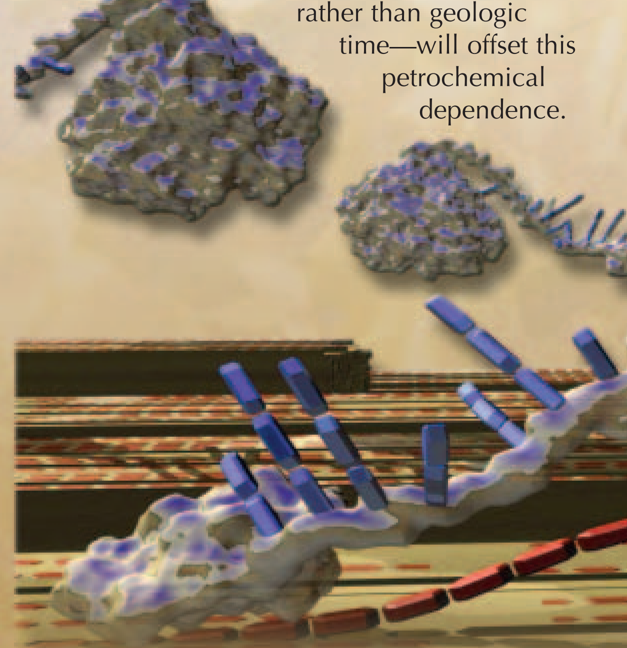
Current ethanol production is primarily from the starch in kernels of field corn. NREL researchers are developing technology to also produce ethanol from the fibrous material (cellulose and hemicellulose) in the corn husks and stalks or in other agricultural or forestry residues.

Biomass Conversion Facilities

NREL has world-class facilities for testing technologies that would be used for biorefineries. These facilities are available to NREL researchers as well as to NREL's research partners, under a variety of agreements.

On the biological side, NREL has a one-ton-per-day-feedstock bioethanol pilot plant that can take cellulosic biomass all the way from feedstock preparation through pretreatment, hydrolysis, and fermentation to distillation of fuel ethanol. The plant is certified to handle metabolically engineered fermentation organisms such as NREL's *Zymomonas mobilis*, can use any of several pretreatment options, and includes complete process monitoring.

On the thermochemical side, the Thermochemical Users Facility simulates thermochemical processes such as gasification, combustion, and pyrolysis. The facility includes cyclonic and fluidized bed reactors for pyrolysis or gasification and can easily accommodate research partners' reactors. A variety of secondary reactor and condensation equipment is available, and conversion products can be analyzed online with molecular beam mass spectrometry, fourier transform infrared spectrometry, infrared spectrometry, or gas chromatography.



Artistic rendition of a cellulase enzyme breaking cellulose down to component sugars. NREL's understanding and continuing research of the basic biochemistry underlying biorefinery processes are key to major technology advances.

Biomass can't fully replace the huge volumes of petroleum and other fossil fuels that we now use, but it can provide fuels and chemicals comparable to those derived from petroleum. American farmers and foresters can fuel as well as feed and house America—in a sustainable fashion.

During the past 25 years, NREL researchers have developed an impressive slate of core biological, physical, chemical, and engineering skills for biomass technologies. With primary responsibility for carrying out U.S. Department of Energy Biomass Programs, NREL's National Bioenergy Center is at the forefront of efforts to develop the biological and thermochemical technologies that will allow economically and environmentally responsible production of fuels, chemicals, and power from biomass to meet modern-day needs—the biomass economy.

Six Biomass Platforms

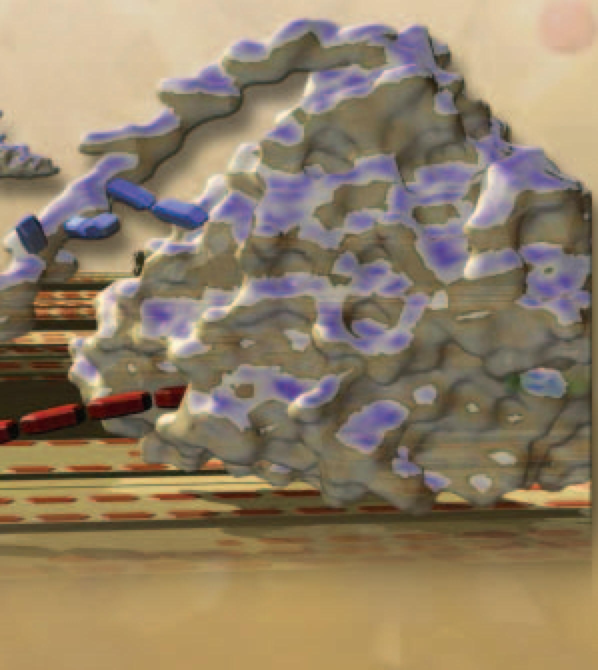
In 2000 and 2001, biomass, largely because of biomass power—combustion of materials such as timber industry scrap or municipal solid waste to generate electricity—surpassed hydroelectric power as the largest U.S. source of renewable energy. And in 2002, U.S. production of fuel ethanol, made from corn grain (starch), will surpass 2 billion gallons per year, displacing a modest but significant amount of imported oil. Also in 2002, a collaborative venture of two major companies began production of polylactic acid plastic made from biomass for clothing and packaging.

NREL researchers, who have made important contributions to each of these developments, are working to improve and greatly expand these technologies through six different core technologies or "platforms" for building the biomass economy. Just as oil refineries break down petroleum and natural gas into numerous materials that then serve as commodity or platform chemicals that the petrochemical industry can use to make a multitude of final products, these six biomass technology platforms will provide the base chemicals for making biobased fuels and products.

The Sugar-Lignin Platform. One out of eight gallons of gasoline sold in the United States already includes ethanol as an additive. Ethanol is made by fermenting sugar, most of which is derived from starch in corn kernels. In contrast, instead of starting with sugar, NREL's advanced bioethanol technology starts with cellulose and hemicellulose, two of the three main components of most plant material—vastly expanding potential feedstocks—breaking them down to sugars for fermentation. In addition to ethanol, the sugars, or intermediate breakdown products, can be fermented, polymerized, or otherwise processed into any number of products. Lignin, the third main component of biomass, can fuel the process or be used to produce a slate of different chemicals, expanding the number of products for the sugar-lignin platform biorefinery. (See sidebar "Lignocellulosic Bioethanol.")

The Syngas Platform. If biomass is heated with limited oxygen (about one-third that needed

Switchgrass, which can be easily grown throughout much of the United States, represents a huge future resource of lignocellulosic biomass for use in biorefineries.



Biomass Characterization Technology

One reason NREL is so effective in biomass technology research and development is because of its capabilities to analyze biomass and intermediates from its processing. Biomass gasification and pyrolysis both require precise characterization of the breakdown products being generated, so that processes can be fine-tuned to produce optimal end products.

NREL uses sophisticated molecular beam mass spectrometry and has developed a portable system that could have great value for syngas and bio-oil platform industries.

NREL's R&D 100 Award-winning Rapid Biomass Analysis system quickly and inexpensively characterizes chemical and mechanical properties of raw or processed biomass. Using near-infrared spectrometry correlated by multivariate analysis, it characterizes in minutes what would otherwise require three or four days and cost far more. Opportunities for use in the lumber and paper industries, let alone biorefineries, are almost limitless. NREL researchers are currently using this approach to analyze variations in corn stover composition and their implications for ethanol production.

for ideal combustion), it gasifies to a "syngas" composed mostly of hydrogen and carbon monoxide. That syngas inherently burns cleaner and more efficiently than the raw biomass. NREL scientists are using gasification technology to improve a large innovative biomass power plant in Vermont (see sidebar "Vermont Gasifier") and to provide electricity for the first time to isolated Philippine villages with small electric generators. The syngas also can be used to produce hydrogen (see "Hydrogen Economy" on pages 10–13) which, in turn, can be used as a fuel or to make plastics, fertilizers, and a wide variety of other products. Syngas can also be converted to sulfur-free liquid transportation fuels using a catalytic process (known as the Fischer-Tropsch Process), or provide base chemicals for producing biobased products.

The Bio-Oil Platform. If biomass is heated to high temperatures in the total absence of oxygen, it pyrolyzes to a liquid that is oxygenated, but otherwise has similar characteristics to petroleum. This pyrolysis- or "bio-" oil can be burned to generate electricity or it can be used to provide base chemicals for biobased products. As an example, NREL researchers have extracted phenolics from bio-oil to make adhesives and plastic resins. NREL uses several thermochemical reactor systems—available for use by outside researchers—to efficiently pyrolyze and control the bio-oil components. NREL scientists have also used pyrolysis for "true recycling" of plastics such as nylon carpeting, selectively regenerating the base chemicals from which the plastics were made.

The Vermont gasifier, one of the first large-scale demonstrations of biomass gasification, supplies clean, renewable fuel from biomass to the McNeil Biomass Power Generating Station in Burlington, Vermont.

Vermont Gasifier

At the McNeil Biomass Power Generating Station in Burlington, Vermont, NREL researchers helped design and install an R&D 100 Award-winning gasification system. The project is one of two major DOE projects to develop technology to dramatically improve the efficiency and air emissions quality of biomass power systems. The McNeil Station already is successfully burning up to 200 tons per day of gasified wood chips in its normal steam generator. Once the gas is hooked up to a planned gas turbine, efficiency should be double that of a combustion-boiler generation system.

A researcher examines a beaker containing cellulase enzymes, a key element in producing ethanol from lignocellulosic biomass.

The Biogas Platform. Another way to convert "waste" biomass into useful fuels and products is to have natural consortiums of anaerobic microorganisms decompose the material in closed systems. Anaerobic microorganisms break down or "digest" organic material in the absence of oxygen and produce biogas as a waste product. Biogas produced in closed tanks, or anaerobic digesters, consists of 50% to 80% methane, 20% to 50% carbon dioxide, and trace levels of other gases such as hydrogen, carbon monoxide, oxygen, and nitrogen. NREL has developed an anaerobic digestion system that handles much higher solids loading than typical digesters. This system effectively converts cellulosic waste (such as municipal solid waste) and fatty waste (such as tuna cannery sludge) to a methane-rich biogas suitable for power generation (or as a starting material for biobased products) and usable compost material. Anaerobic digesters are currently getting considerable attention as a way to turn swine and cattle manure into useful fuel and chemicals.

The Carbon-Rich Chains Platform. Plant and animal fats and oils are long hydrocarbon chains, as are their fossil-fuel counterparts. Some are directly usable as fuels, but they can also be modified to better meet current needs. Fatty acid methyl ester—fat or oil "transesterified" by combination with methanol—substitutes directly for petroleum diesel. Known as biodiesel, it differs primarily in containing oxygen, so it burns cleaner, either by itself or as an additive. Biodiesel use is small but growing rapidly. In the United States, it is made mostly from soybean oil and used cooking oil. Soybean meal, the coproduct of oil extraction is now used primarily as animal feed, but also could be a base for making biobased products. Glycerin, the coproduct of making biodiesel, is already used to make a variety of products, but has potential for many more. And the fatty acids are used for detergents and other products. So carbon-rich chains are already well on their way as a platform for the biorefinery.

The Plant Products Platform. Modern biotechnology not only can transform materials extracted from plants, but can transform the plants to produce more valuable materials. Selective breeding and genetic engineering can be used to improve production of chemical, as well as food, fiber, and structural products. Plants can be developed to produce high-value chemicals in greater quantity than they do naturally, or even to produce compounds they do not naturally produce. With its genetic engineering, material and economic analysis, and general biotechnology expertise, NREL could make major contributions in this exciting arena. For example, NREL researchers exploring variation in composition of stover for various strains of corn are analyzing the impact this makes on producing ethanol from stover.

Moving to Biorefineries

As exciting as these six platforms are, biorefineries will not happen overnight. The oil refineries, and the corn wet-mills and pulp and paper plants (the biorefineries of today) that they would parallel, are highly complex and very expensive. No new U.S. oil refineries have been built in the past 30 years. Corn wet-mills produce a variety of food products—as well as ethanol—from starch, but most new ethanol plants are smaller dry mills producing just ethanol and animal feed. To overcome the challenge and complexity of producing a slate of products starting with lignocellulosic material instead of oil or starch will require enhanced technology development. NREL is providing the foundation for this to occur.

Two important concepts are guiding NREL's efforts to create novel, successful biorefineries—taking maximum advantage of intermediate products and balancing high-value/low-volume products with high-volume/low-value fuels. High-value bioproducts may meet special needs and generate market excitement, but high-volume fuels are what America needs to reduce its dependence on foreign oil and to improve the environment.

Biorefineries will not eliminate the need for petrochemicals. But they will play a key role in reducing our level of dependence on imported petroleum and making the 21st century one of an increasingly sustainable, domestic, and environmentally responsible biomass economy.

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Lignocellulosic Bioethanol

NREL and the corn-starch-to-fuel-ethanol industry have grown up together during the past 25 years. NREL has contributed significantly to the industry maturing to one utilizing energy-efficient technologies.

NREL researchers are focusing on the challenge of producing bioethanol from lignocellulosic biomass instead of corn starch. Toward this end, NREL researchers already have developed effective technology to thermochemically pretreat biomass; to hydrolyze hemicellulose to break it down into its component sugars and open up the cellulose to treatment; to enzymatically hydrolyze cellulose to break it down to sugars; and to ferment both five-carbon sugars from hemicellulose and six-carbon sugars from cellulose. This entire process has been integrated using an NREL-patented R&D 100 Award-winning metabolically engineered bacteria—*Zymomonas mobilis*. Using a one-ton-feedstock-per-day bioethanol pilot plant, NREL researchers are testing and improving these technologies under conditions that simulate industrial production.

Bioethanol and the biorefinery concept are closely linked. The cellulosic ethanol technology developed by NREL will open the door to making a wealth of other products. Just as cellulose and hemicellulose are polymers of sugars, new polymers can be made from those sugars. Biodegradable plastics and natural, nontoxic herbicides are just some of the possibilities NREL researchers are exploring.

NREL uses a one-ton-per-day pilot plant to test bioethanol technologies, including NREL's metabolically engineered bacteria, Zymomonas mobilis, *which enables the cofermentation of cellulose and hemicellulose.*