New metabolic pathways will enable energy-efficient biochemical conversion of woody (lignocellulosic) biomass into biofuels that are compatible with today's vehicles and infrastructure. *Photos (clockwise from upper left): iStock/4373820, NREL/15040, Energetics Inc., iStock/6091090.*

Biochemical Conversion:

Using Hydrolysis, Fermentation, and Catalysis to Make Fuels and Chemicals

Advanced biofuels are part of America's all-of-the-above strategy to develop all domestic energy resources and win the global race in clean energy technology. The Biomass Program works with the emerging U.S. bioindustry to sustainably convert non-food biomass resources into cost-competitive biofuels, biopower, and bioproducts.

Cellulosic biomass—the fibrous, non-edible part of plants—is an abundant domestic resource that can potentially provide a renewable feedstock for next-generation biofuels and bioproducts. The Energy Department's Biomass Program conducts collaborative research, development, and demonstration (RD&D) projects to improve several processing routes for the conversion of cellulosic biomass.

Biochemical conversion entails breaking down biomass to make the carbohydrates available for processing into sugars, which can then be converted into biofuels and bioproducts through fermentation and use of microorganisms and other catalysts. Potential fuel blend stocks and other bioproducts include the following:

- Renewable gasoline
- Ethanol and other alcohols
- Alkanes
- Renewable diesel

Key challenges for biochemical conversion include the considerable cost and difficulty involved in breaking down the tough, complex structures of the cell walls in cellulosic biomass. The Biomass Program is exploring more efficient and cost-effective ways to gain access to these useful sugars for conversion processing.

Another key challenge is to more efficiently convert the sugars into biofuels and purify them. The Program is exploring new metabolic pathways to achieve this efficiency.

> The scientists have reprogrammed yeast and bacteria, introduced entire metabolic pathways so that the yeast and bacteria, when fed simple sugars, would convert those sugars…into diesel-like gasoline, jet-plane-like fuel.
>
> *—Energy Secretary Steven Chu*

Biochemical Conversion Step by Step

Biochemical conversion uses biocatalysts, such as enzymes, in addition to heat and other chemicals, to convert the carbohydrate portion of the biomass (hemicellulose and cellulose) into an intermediate sugar stream. These sugars are intermediate building blocks that can then be fermented or chemically catalyzed into a range of advanced biofuels and value-added chemicals. The overall process can be broken into the following essential steps:

A. Feedstock Supply: Feedstocks for biochemical processes are selected for optimum composition, quality, and size. Feedstock handling systems tailored to biochemical processing are essential to cost-effective, high-yield operations.

B. Pretreatment: Biomass is heated (often combined with an acid or base) to break the tough, fibrous cell walls down and make the cellulose easier to hydrolyze (see next step).

C. Hydrolysis: Enzymes (or other catalysts) enable the sugars in the pretreated material to be separated and released over a period of several days.

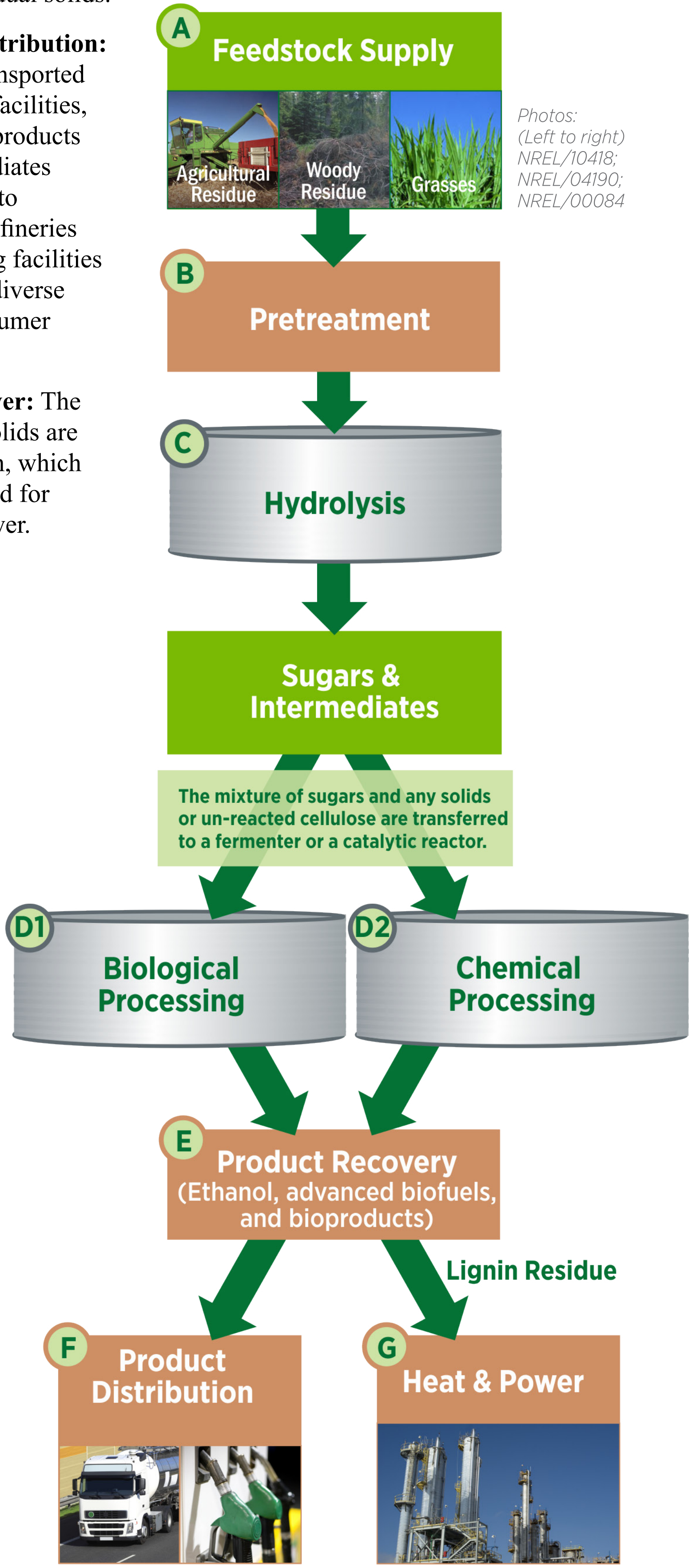
D1. Biological Processing: Microorganisms are added to the mixture to ferment the sugars or otherwise convert them into biofuels.

D2. Chemical Processing: Alternatively, the sugars can be converted to fuels or an entire suite of other useful products using chemical catalysis.

E. Product Recovery: Products are separated from water, solvents, and any residual solids.

F. Product Distribution: Fuels are transported to blending facilities, while other products and intermediates may be sent to traditional refineries or processing facilities for use in a diverse slate of consumer products.

G. Heat & Power: The remaining solids are mostly lignin, which can be burned for heat and power.



Photos: Istock/10732999; Istock/4556166

Photo: Istock/8894376

Improving Conversion Efficiency

To improve the economics of biofuels production, the Biomass Program is developing technologies for integrated biorefineries that can convert diverse feedstocks into cost-competitive liquid transportation fuels, bioproducts, and biopower. To optimize the role of biochemical conversion within this flexible production scenario, researchers are developing technologies needed throughout the process. A few examples are provided below.

Researcher examines a transgenic yeast strain capable of cofermenting ethanol from glucose and xylose. *Photo: NREL/16374*

Sample Research Areas:

- **Enzymes for Hydrolysis.** A new generation of enzymes and enzyme production technologies are needed to cost-effectively hydrolyze the cellulose and hemicellulose in biomass to free the sugars for conversion. The program is working to identify the most productive, naturally occurring enzymes and then use molecular biology to increase their efficiency. Research objectives also include lowering the cost of the enzyme unit operation in the sugar extraction process (saccharification).

Enzyme Primer

- Enzymes are proteins that naturally enable chemical reactions in living organisms.
- Many of these reactions break down larger molecules into smaller ones.
- Enzymes act as catalysts to dramatically increase reaction times. Reactions that might otherwise take a year may take only a few seconds in the presence of the right enzyme!

- **Microorganisms for Fermentation.** Our researchers use sophisticated metabolic engineering techniques to develop microorganisms that can more effectively ferment the variety of sugars derived from biomass. Specifically, they are developing microorganisms that can coferment both the five-carbon sugars (such as xylose from the hemicellulose) and the more common six-carbon sugars (such as glucose) in cellulosic biomass. With our industrial partners, we are working to develop designer strains for specific feedstocks, feedstreams, and processes and to validate the performance of these strains in improving production economics. Future investments will focus on microorganisms that produce longer chain molecules that can be used as biofuel blend stocks (or biofuel intermediates), biochemicals, or other bioproducts.

- **Advanced Catalytic Conversions.** A promising future area of research is the development of chemical catalytic processes for transforming sugars into chemical intermediates that can be further processed into a range of biofuel blend stocks and chemicals.

Scientist bioprospecting for microbes at Yellowstone National Park. *Photo: INL*

Public-Private Research Partnerships

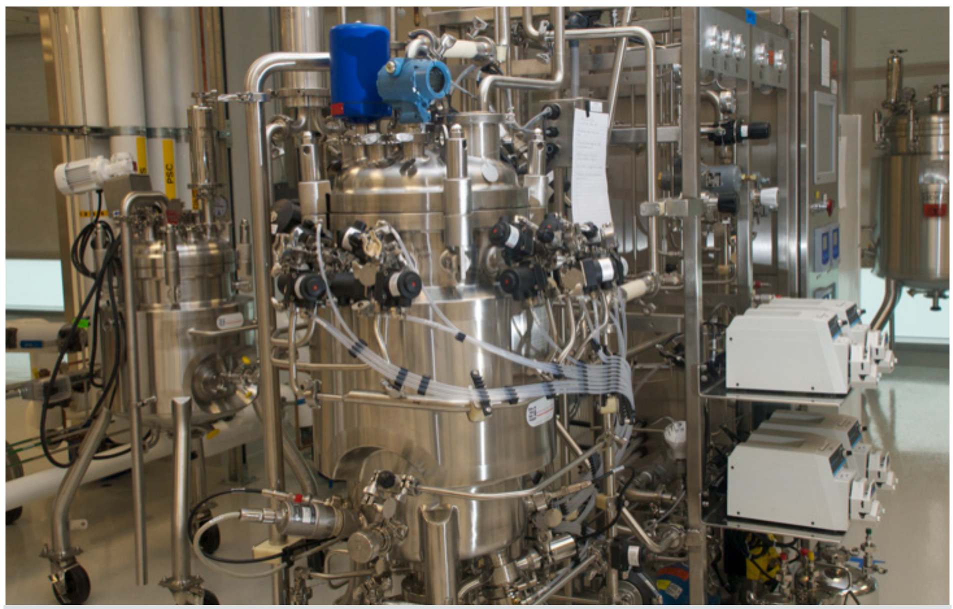
Our research partners in the National Laboratories, universities, and industry are actively exploring and demonstrating novel biochemical conversion processes at bench, pilot, demonstration, and commercial scales. As conversion technologies mature, higher levels of integration will become feasible. Second-generation biorefineries are envisioned to integrate biochemical and thermochemical processes, enabling the most efficient use of a wide range of feedstocks.

Process Demonstration Units (PDUs)

The Energy Department is expanding its capability to demonstrate and evaluate bioprocessing technologies for the production of biofuels and chemicals. The Biomass Program has established two such facilities for use by industry and others:

- The Advanced Biofuels PDU at Lawrence Berkeley National Laboratory accepts diverse feedstocks to demonstrate the efficiency of novel biofuels production processes.
- The Integrated Biorefinery Research Facility at the National Renewable Energy Laboratory evaluates the efficiency and fuel yields of different feedstock compositions and process designs and conditions.

Researchers at NREL's Alternative Fuels User Facility study biochemical processes for the conversion of lignocellulosic biomass. *Photo: NREL/16330*



Berkeley Lab's Advanced Biofuels PDU can convert biomass into advanced biofuels in sufficient quantities for engine testing. *Photo: LBNL*

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