From Feedstocks to Final Products

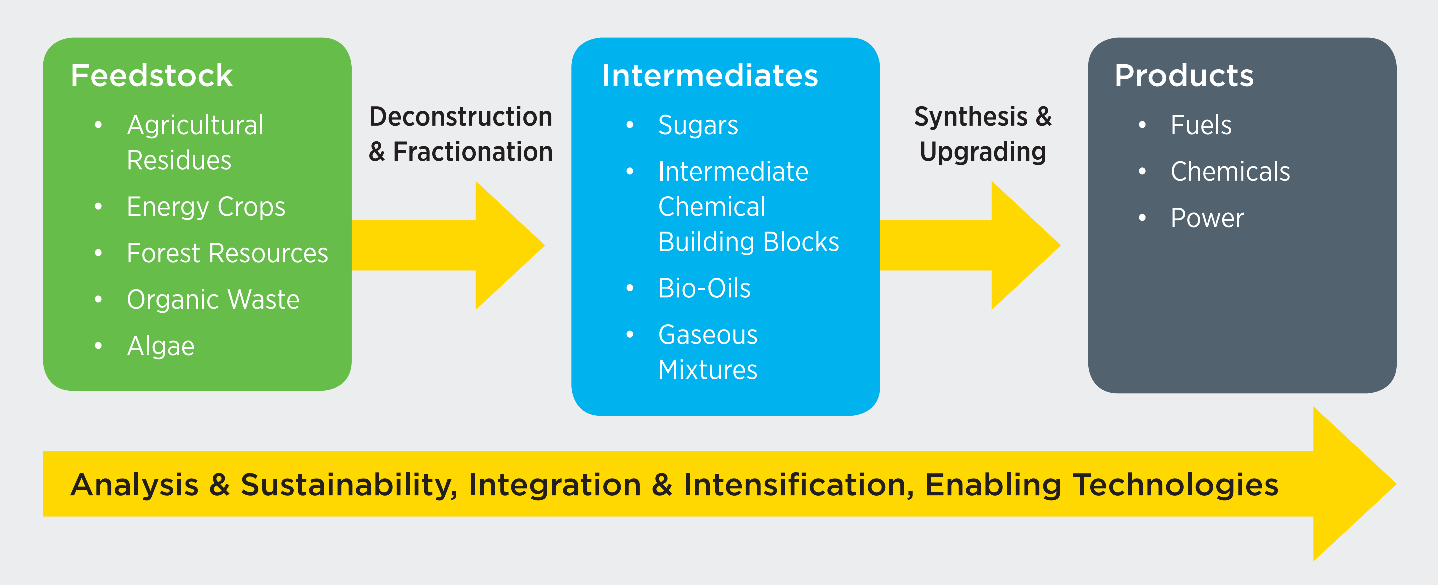
To efficiently convert algae, diverse types of cellulosic biomass, and emerging feedstocks into renewable fuels, the U.S. Department of Energy (DOE) supports research, development, and demonstration of technologies. This research will help ensure that these renewable fuels are compatible with today's vehicles and infrastructure.

Advanced biofuels are part of the United States' "all-of-the-above" energy strategy to develop domestic energy resources and win the global race for clean energy technology. Developing a sustainable, commercial-scale U.S. bioindustry will stimulate the economy, create new jobs, and substantially decrease net greenhouse gas emissions on a life-cycle basis.

Traditionally, DOE Bioenergy Technologies Office (BETO) has funded research on processes in both thermochemical (typically involving bio-oil or gaseous intermediates) and biochemical (typically involving sugar or lignin intermediates) conversion. To reflect the growing diversity of technologies, however, BETO has moved away from classifying pathways as strictly one or the other.

Instead, research and development focuses on two main areas: (1) deconstruction and fractionation and (2) synthesis and upgrading, which may contain elements of both thermochemical and biochemical conversion processes.

Integrated Biorefinery Research Facility (IBRF) includes horizontal tube pretreatment reactor systems (upper level) and high-solids enzymatic hydrolysis reactors (main level). *Photo courtesy of the National Renewable Energy Laboratory / Dennis Schroeder.*



Generalized conversion route for biomass-derived feedstocks to renewable products
Source: Bioenergy Technologies Office Multi-Year Program Plan, March 2016

Feedstocks

BETO researches a variety of feedstocks, including cellulosic biomass (the fibrous and inedible portions of plants), algae, wet waste, and biogas. The use of a specific feedstock or feedstock blend will depend on the conversion process. Feedstocks for primarily biochemical processes are selected for optimum composition, quality, and size and may include agricultural residues, woody residues, grasses, or blends of these three. Feedstock handling systems tailored to biochemical processing are essential to cost-effective, high-yield operations.

The elevated temperatures of thermochemical deconstruction (300°C to 1,000°C) expand the range of biomass feedstocks that can be used by the bioindustry. The ability to use a broad range of feedstocks helps to ensure an adequate biomass supply across seasons and spreads the economic and energy security benefits across regions.

Despite these advantages to using diverse feedstocks, researchers recognize that conversion technologies and supporting processes are sensitive to variations in feedstock characteristics (e.g., moisture content, contaminants, etc.). BETO works with industry and other partners to explore ways to pretreat and blend various types of biomass into uniform formats with consistent properties. The aim is to create commodities with predictable properties that meet established criteria for efficient conversion.

Deconstruction and Fractionation

To convert biomass into a biofuel, biomass must first be deconstructed into its component chemicals. One can generally differentiate between deconstruction processes by the temperature at which they take place. A variety of intermediates can be formed depending on the conditions used in this process.

High-Temperature Deconstruction

High-temperature deconstruction encompasses pyrolysis, hydrothermal liquefaction, and gasification.

Pyrolysis is the thermal and chemical decomposition of feedstock without the introduction of oxygen to produce a bio-oil intermediate. The bio-oil produced contains hydrocarbons of various lengths but contains more oxygenated compounds than petroleum crude oils and must undergo upgrading before it can be finished into a fuel or used in a refinery. BETO currently funds research on both fast pyrolysis and catalytic (both *in situ* and *ex situ*) fast pyrolysis.

Hydrothermal Liquefaction is a deconstruction process that utilizes a wet feedstock slurry under elevated temperature and pressure to produce a hydrothermal liquefaction bio-oil. The feedstock is treated with water before entering the reactor and is particularly applicable to algal feedstocks. Nonwater solvents may also be used.

Gasification is the thermal deconstruction of biomass at high temperature (typically >700°C) in the presence of substoichiometric air or an oxygen carrier and sometimes steam, followed by gas cleanup and conditioning.

Low-Temperature Deconstruction

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.

Low-temperature deconstruction is the breakdown of feedstock into intermediates by pretreatment followed by hydrolysis.

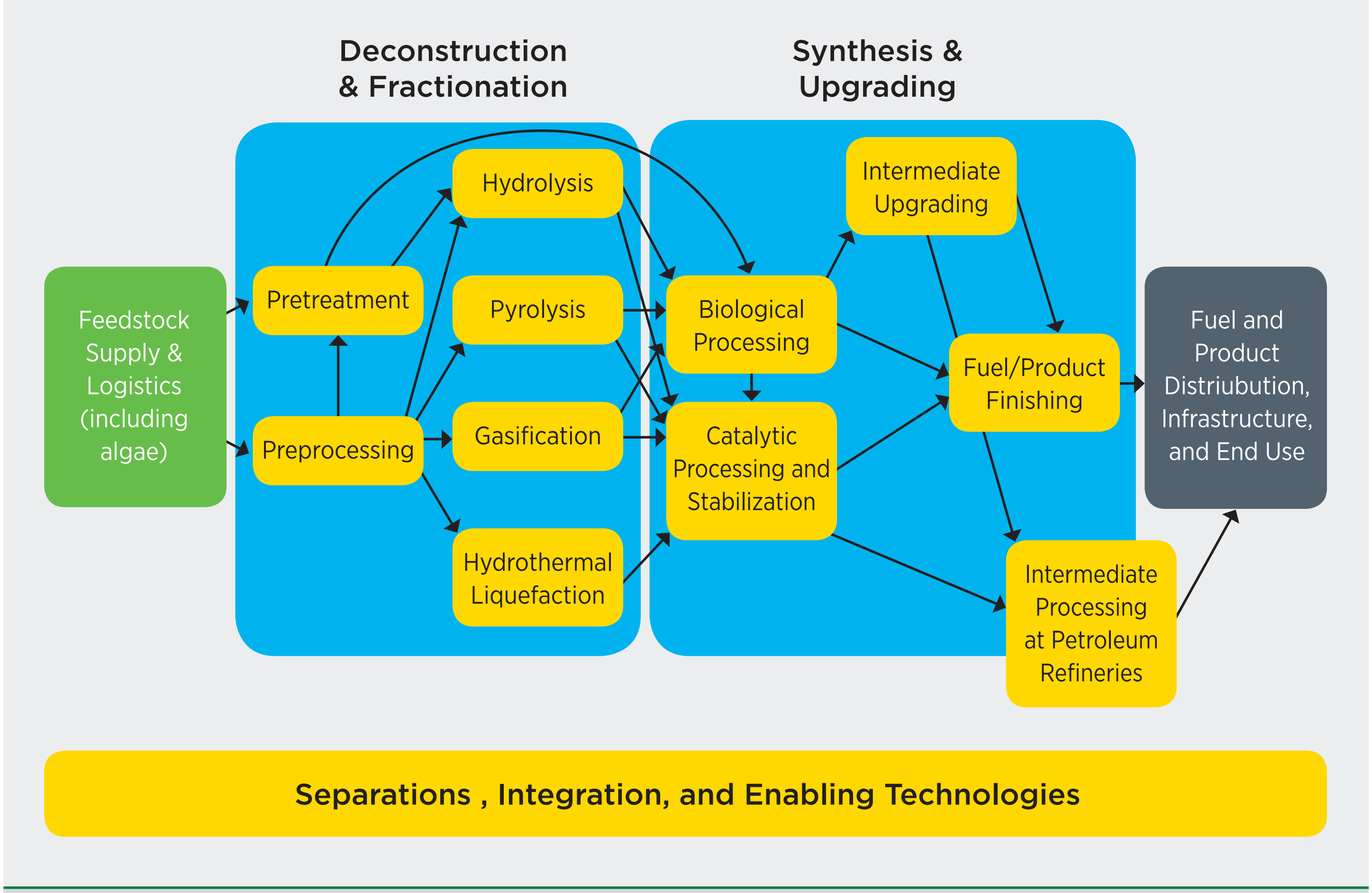
Pretreatment is the preparation of feedstock for hydrolysis via chemical or mechanical processing and separation of feedstock into soluble and insoluble components. This process opens up the physical structure of plant and algae cell walls, revealing sugar polymers and other components.

Hydrolysis is the breakdown of these polymers either enzymatically or chemically into other molecules suitable for use as fuels or building-block chemicals.

Synthesis and Upgrading

Intermediates produced following deconstruction can include crude bio-oils, sugars, gaseous mixtures, and other chemical building blocks. These intermediates are upgraded using various techniques to produce a finished product.

Actual upgrading and separations processes will vary greatly according to the identity of the intermediate streams. Streams with tight chemical distributions may require less complex processes than streams involving more varied compounds. Chemical rearrangement into the final fuel blendstock or product can involve biological or chemical processing.



Conversion pathways from feedstock to products
Source: Bioenergy Technologies Office Multi-Year Program Plan, March 2016

Microorganisms can ferment sugar or gaseous intermediates into fuel blendstocks and chemicals. Alternatively, sugars and other intermediate streams such as bio-oil and synthetic gas may be processed catalytically to minimize the effect of reactive compounds to improve storage and handling properties.

The finished products from upgrading may be fuels or bioproducts ready to sell into the commercial market or stabilized intermediates suitable for finishing in a petroleum refinery or chemical manufacturing plant.

Integration in Traditional Refineries

Successfully integrating biomass product streams for further processing in traditional petroleum refineries would provide refineries with a secure, domestic feedstock. Researchers are investigating compatibility criteria for crude bio-oils, biofuel intermediates, and finished hydrocarbon biofuels at various insertion points. The goal is to produce biomass-based feeds that are identical (at the molecular level) to products now found in the traditional petroleum-refining product chain.

For successful integration, the biomass feed streams must be able to meet rigorous criteria. More specifically, they will need to be low in oxygen, blend well with petroleum, and be free of contaminants that could poison the refinery catalysts or degrade the product.

Future Directions

Bioproducts: There are many technology pathways that could be used to produce hydrocarbon biofuels, but many of them would require the co-production of value-added chemicals and products to produce cost-competitive fuels in the near term.

For instance, the National Renewable Energy Laboratory has demonstrated that for an enzymatic hydrolysis followed by biologically upgrading the conversion pathway (the conversion pathway that was highly successful for producing cellulosic ethanol), the sale of lignin-derived coproducts (such as adipic acid) will be necessary to achieve a minimum fuel selling price of $3/gasoline gallon equivalent for a gasoline and diesel blendstock.

Synthetic Biology: Engineering biology offers the potential to dramatically reduce the lead time and cost of bringing new renewable fuels and chemicals to market. Researchers are using sophisticated metabolic engineering techniques to develop microorganisms that can more effectively ferment the variety of sugars derived from biomass. Scientists in the public and private sectors are working to develop designer strains for specific feedstocks and processes and to validate the performance of these strains in improving production economics. Development of chassis organisms on which advanced metabolic engineering can be performed will lead to rapid increases in the rate, titer, and yield of high-impact products.

Advanced Materials: Additional research into high throughput screening of catalysts, advanced computational tools, and characterization approaches to accelerate the discovery and development of new types of catalysts for conversion processes will help lead to the production of cost-competitive biofuels.

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