Quadrennial Technology Review 2015

Chapter 7: Advancing Systems and Technologies to Produce Cleaner Fuels

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U.S. DEPARTMENT OF ENERGY

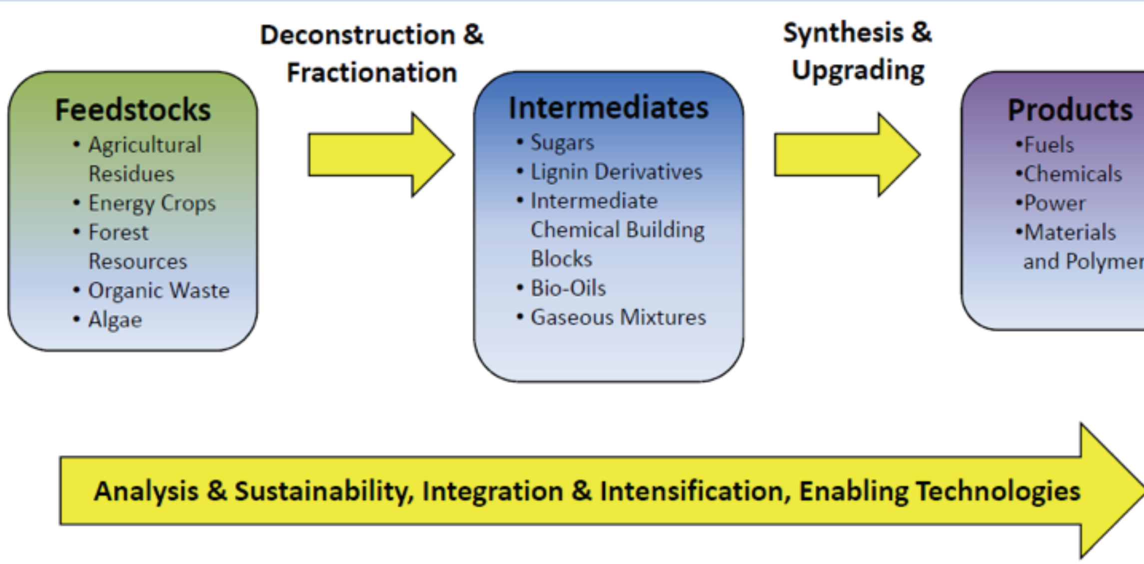
Bioenergy Conversion

Chapter 7: Technology Assessments

Bioenergy conversion research and development (R&D) seeks to develop commercially viable technologies for converting biomass feedstocks into energy-dense, fungible, liquid transportation fuels as well as bioproducts, chemical intermediates, and biopower. To achieve this goal, a variety of conversion technologies are being explored that can be combined into pathways from feedstock to product. Historically, these pathways have been classified as either biochemical or thermochemical to reflect the primary catalytic conversion system employed as well as the intermediate building blocks produced. Generally, biochemical conversion technologies involve pathways that produce sugars and lignin intermediates, while thermochemical conversion technologies involve pathways that produce bio-oil and gaseous intermediates. Moving forward, as evidenced by a variety of hybrid processes in industry, the traditional division between biochemical and thermochemical conversion technologies will not encompass the diversity of innovative conversion technologies, and focus has shifted to a simpler process flow in which the bio-derived polymeric feedstock is deconstructed into simpler intermediates that are then upgraded into products (Figure 7.A.1).

The conceptual block flow diagram in Figure 7.A.1 outlines the main process steps and materials in the feedstock-to-end-products process. This figure depicts a high-level view of the primary unit operations within the scope of conversion R&D to create desired biomass-derived products. Each conversion technology involves at least two main steps: deconstruction and fractionation of feedstock into relatively stable intermediates through the breaking of chemical bonds followed by the controlled upgrading of those building blocks into a slate of desired products (synthesis and upgrading).

Figure 7.A.1 Generalized Conversion Route for Biomass-Derived Feedstocks to Renewable Products[1]

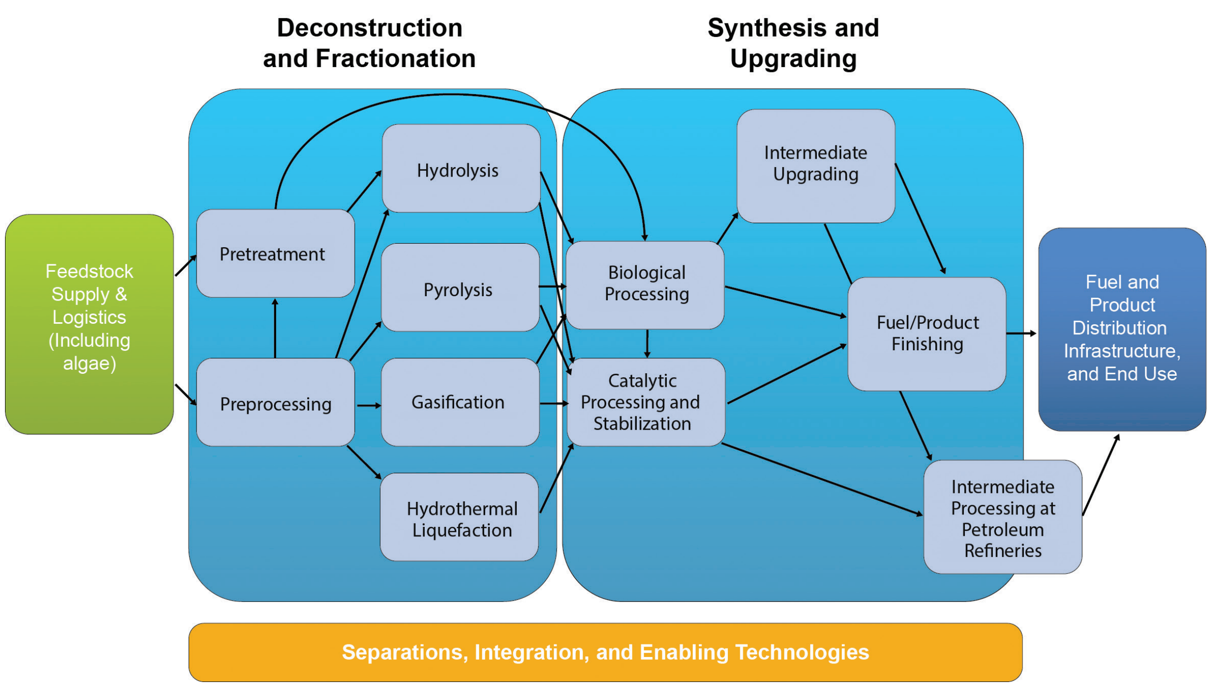


These renewable products can include finished fuels, fuel precursors, chemicals, or high-quality intermediates, such as sugars, lignin derivatives, synthesis gas (syngas), or stabilized bio-oils. Specific process operating conditions, inputs, and outputs vary within and between each step. These process variations impact key performance outcomes (such as titer [a method of expressing concentration], rate, selectivity, and yield) that in turn determine the overall economic viability of the process. Potential environmental impacts are also assessed for conversion pathways by evaluating sustainability metrics (water use, soil quality, etc.) and conducting life-cycle assessments (LCAs) to determine greenhouse gas (GHG) and other emissions.

Conversion Process Steps

Conversion can be broken down into two major areas: deconstruction and fractionation; and synthesis and upgrading. Figure 7.A.2 highlights key technologies within deconstruction and fractionation as well as synthesis and upgrading, which can be linked to form a complete conversion pathway from feedstock to products. The arrows represent the transition of organic matter from feedstock to intermediates to end products, showing the diversity of accessible conversion options. Multiple technologies along several pathways are under development to address the broad range of physical and chemical characteristics of various feedstocks and to reduce the risk that any specific technology could fail to reach commercial viability. One advantage of the numerous paths between key technologies for R&D is that an advancement in one area can potentially impact several unique final pathways. Additionally, each linked set of conversion technologies results in the production of a unique product slate whose value will vary, depending on market size and demand.

Figure 7.A.2 Conversion Pathways from Feedstock to Products[2]



The following section provides a high-level overview of current conversion technologies. More information on each process step related to individual pathways can be found in specific design cases (see the Cost Projections and Sustainability Analysis section below).

Deconstruction and fractionation: Deconstruction and fractionation processes break biomass-derived polymeric feedstock down into tractable intermediate streams suitable for conversion into targeted products. After preprocessing and/or pretreatment, deconstruction processes can be divided into two categories: high-temperature deconstruction and low-temperature deconstruction. High-temperature deconstruction refers to processes performed at or above 100°C and includes processes such as pyrolysis, hydrothermal and solvent liquefaction, and gasification. Low-temperature deconstruction refers to processes performed below 100°C and includes processes such as enzymatic and acid hydrolysis.

- *Preprocessing:* Development of a variety of conversion technologies is necessary to address the broad range of physical and chemical characteristics of various biomass feedstocks as discussed in the preceding section. Depending on the conversion strategy, a variety of feedstock preprocessing and handling steps may be employed. Linking feedstock logistics with conversion processes allows for the evaluation of technology options and trade-offs on both sides of the processing interface, ensuring a fully integrated supply chain from stump or field to fuel. R&D is ongoing for preprocessing options (e.g., densification, blending of an expanded pool of feedstocks, and physical formats, such as pellets, shredded material, and slurries) and simultaneously assessing the impact on conversion efficiency when such preprocessed feedstocks are introduced into a conversion process.
- *Low-temperature deconstruction:* Low-temperature deconstruction is the breakdown of the physical structure of the feedstock by pretreatment followed by hydrolysis with the intent of producing high quality, low cost sugar streams. R&D is ongoing to develop technologies to create more efficient hydrolysis and cleaner separation of the resulting intermediate streams at lower cost. Specific areas of interest include developing better pretreatment conditions, creating lower cost hydrolytic enzymes, developing new hydrolytic enzymes with improved substrate scope, limiting the formation of contaminants, improving separation efficiency, and creating a tractable lignin stream for higher value uses of the non-sugar portion of the feedstock.
  - Pretreatment is the preparation of feedstock for hydrolysis via chemical and/or mechanical processing and separation of feedstock into soluble and insoluble components. This process opens up the physical structure of plant cell walls, revealing the more recalcitrant cellulosic, hemicellulosic and lignin polymers for subsequent hydrolysis while solubilizing some of the lower molecular weight compounds.
  - Hydrolysis is the breakdown of these polymers either enzymatically or chemically into their component sugars and/or aromatic monomers and/or low molecular weight oligomers.
- *High-temperature deconstruction:* High-temperature deconstruction encompasses pyrolysis, gasification, and hydrothermal and solvent liquefaction. The primary focus of R&D for high-temperature deconstruction is on improving technologies for thermochemical deconstruction of biomass to form a gaseous or bio-oil intermediate. Key focus areas include developing a better understanding of the fundamentals of pyrolysis, hydrothermal liquefaction, and gasification processes, including reaction mechanisms; improved reactor designs; improved quality and stability of deconstructed intermediates; more robust catalysts and catalyst regeneration processes; and catalysts with improved specificity.
  - Hydrothermal and solvent liquefaction is a deconstruction process that utilizes a wet feedstock slurry under elevated temperature and pressure (generally 250-500°C and 5-25 MPa) that produces a bio-oil similar to pyrolysis oil. The feedstock is treated with water before entering the reactor, and therefore hydrothermal liquefaction is particularly applicable to algae feedstocks. Other variations

include solvent liquefaction where a non-water solvent, such as methanol, is used to make the feedstock slurry prior to liquefaction.

- Pyrolysis is the thermal and chemical decomposition of feedstock (at temperatures typically <700°C), without the introduction of oxygen, to produce a bio-oil intermediate. The bio-oil produced contains various length hydrocarbons but contains more oxygenated compounds than most petroleum crude oils and must undergo upgrading before it can be finished into a fuel or used in a refinery. There are several variations of pyrolysis that require different catalysts and reaction conditions.
- Gasification is thermal deconstruction of biomass at higher temperature (typically >700°C) in the presence of sub-stoichiometric oxygen, air, or an oxygen carrier such as steam followed by gas cleanup and conditioning. In these processes, feedstock is partially oxidized to form a syngas that contains a mixture of light gases, predominantly CO and H_2, along with some CO_2 and CH_4 and other light gases.

Synthesis and upgrading: Synthesis and upgrading converts tractable intermediate streams from deconstruction and fractionation of biomass into finished fuels, chemicals, and materials. These intermediates can include crude bio-oils, sugars, gaseous mixtures such as syngas, and other chemical building blocks as outlined in Figure 7.A.2, and are upgraded using either biological, chemical, or hybrid processing techniques. These upgraded streams could be finished fuels or bio-derived chemicals ready to sell into the commercial market or they could also be stabilized intermediates suitable for final finishing in a petroleum refinery or chemical manufacturing plant. Processes include:

- *Biological processing*: Microorganisms have the ability to convert sugar, lignin, or gaseous intermediates into fuel blend stocks and chemicals. R&D in this area focuses on identification and development of robust microorganisms capable of converting complex intermediates to desired target molecules in the presence of inhibitors at high rates, titers, selectivity, and yields. To accomplish this, advanced metabolic engineering methods are being developed allowing these microbes to achieve maximum intermediate utilization, robustness, and selection of the product slate with minimal perturbation of other critical cellular functions. To accomplish this, genetic tools such as CRISPR-Cas9 need to be deployed in a wider variety of industrially relevant host organisms. These new genetic tools combined with machine learning for design of biological systems as well as research into process conditions can greatly open the space in which biologically derived chemicals and fuels can compete.
- *Catalytic processing and stabilization*: Intermediate streams such as bio-oil, syngas, and mixed sugars must be upgraded to minimize the effect of reactive compounds to improve storage and handling properties and ease downstream upgrading. This is accomplished through removal of water, char, and ash particulates as well as destabilizing components, such as metals and oxygenated species.
  - For bio-oil, catalytic processing and stabilization may involve hydro-processing, such as hydro-deoxygenation, to transform oxygen-rich biomass into a mix of compounds more similar to hydrocarbon-rich petroleum. It may also involve separation and fractionation steps to remove water, coke (ash made of carbon fragments that can drop out of a process stream), catalyst, char, and ash particulates or metals and oxygenated species. Research on bio-oils focuses on hydro-processing and similar thermal-catalytic processing techniques to reduce total oxygen and acid content, thereby increasing stability and enabling easier downstream conversion.
  - For syngas streams, stabilization and preparation for fuel synthesis involves removal of contaminants from crude biomass-derived syngas and adjusting gas ratios. Gas cleanup and conditioning involves the removal of problematic heteroatom compounds, metals, and particulates as well as adjusting the hydrogen-carbon monoxide ratio. Research on syngas cleanup and conditioning has historically focused on removing or reforming tars and methane, capturing alkali metals, and removing particulates.

- For mixed sugar streams, catalytic processing and stabilization may involve four types of catalytic processes: hydrogenation, aqueous phase reforming, condensation and oligomerization, and hydrotreating. Each stage consists of packed-bed reactor vessels. Hydrogen is added to the reactors in each stage that operate at varying process conditions and have varying catalyst composition. The goal of these successive catalytic steps is to remove oxygen or "de-functionalize" carbohydrates and other carbon components and oligomerize them to primarily diesel or jet-range hydrocarbons.

- *Intermediate upgrading*: Intermediate upgrading involves a variety of technologies to transform intermediate streams into preliminary product streams. Actual upgrading and separations processes will vary greatly according to the identity and composition of the intermediate streams and the purity requirements for the finished fuel or product. Streams with tight chemical distributions, such as algal lipids, fatty acids, or other products from biological processing, may require less complex processes than streams involving more varied compounds. Chemical rearrangement into the final fuel blend stock or product can involve biological or chemical processing.
- *Fuel/product finishing:* After upgrading, final product streams must conform to standards for off-take agreements. This may involve removing problematic contaminant compounds and further finishing to attain correct product specifications. For complex bio-oil mixtures, the finishing process may involve balancing various hydrocarbon components, whereas for single molecule products this may involve removing impurities.
- *Intermediate processing at petroleum refineries:* Certain product streams may be transported to refineries at a more crude stage for upgrading. Placement of this box on the edge of synthesis and upgrading and products in Figure 7.A.2 represents the interface of conversion technologies with refiners. Conversion R&D is working to establish clear product specifications that will enable bio-oil, bio-intermediates, fuel-blend stocks, finished fuels, and products to seamlessly integrate with existing infrastructure and will encourage acceptance of bio-based replacements in industry. This activity involves R&D in coordination with refiners to understand how a bio-oil blend will perform when integrated into their existing operations and ultimately seeking to provide additional value to refineries.

Emerging Opportunities

The technologies areas discussed above are not exhaustive of research efforts into biofuels and bio-derived chemicals. Many emerging technology areas could help to complement or replace elements of the unit operations described. These opportunities include:

1. **Synthetic Biology**: The use of synthetic biology tools to create new biological pathways to fuels and chemicals could open up new product slates and greatly improve the efficiency of conversion.
2. **Optima**: The co-optimization of engines and fuels to achieve maximum efficiency could take advantage of the unique properties of biomass-derived fuels to increase engine performance.
3. **Ionic liquids**: Deconstruction of biomass into tractable intermediate streams could be accomplished using ionic liquids, which offer unique upgrading opportunities and have steadily decreased in price.
4. **Functional replacements**: The chemical space easily accessible from petroleum and biomass are different, creating an opportunity to use some of the unique functionality of biomass-derived chemicals to create alternatives to fossil-derived chemicals. These bio-derived chemicals could function as replacements with superior properties for applications from plastics to lubricants.

Cost Projections and Sustainability Analysis

The National Laboratories in consultation with engineering contractors and industry have published several design cases that use techno-economic modeling to quantify the economic feasibility of process designs to convert biomass into biofuels. These rigorous models are based on the best available engineering configurations for a hypothetical commercially mature plant combined with data on the state of technology for each step in a given pathway. The overall model gives cost estimates in $/gasoline gallon equivalent (gge) at the plant-gate for the current year and projections for likely improvements in future years. These estimates are shown as minimum fuel selling price (MFSP) that essentially represents a plant-gate wholesale price and does not included cost of transport to the retailer, retailer markup, taxes, etc.

These design cases include a wide range of technologies at various levels of technology readiness. In addition to the two cellulosic ethanol design reports published in 2011,[3,4] seven design reports on new technologies to produce drop-in hydro carbons have been included: fast pyrolysis and hydrotreating, in situ and ex situ catalytic fast pyrolysis, syngas upgrading to hydrocarbon fuels, biological conversion of sugars to hydrocarbons, catalytic conversion of sugars to hydrocarbons, whole algae hydrothermal liquefaction, and algal lipid upgrading. All of these design cases can be found on the Bioenergy Technologies Office design case webpage[5] as well as through each of the national labs. In each of these new design cases, the product is a hydrocarbon fuel blend-stock amenable to blending into gasoline, diesel, and/or jet fuel. Some design cases also include the production of co-products, such as commodity chemicals from lignin, which increase the cost-competitiveness of the fuel component in a manner analogous to the petroleum industry.

Cellulosic Ethanol Pathway

In September 2012, after more than a decade of dedicated work, RD&D activities at the lab/bench and pilot[6] scales, supported by the Bioenergy Technologies Office, resulted in a four-fold reduction in cost of cellulosic ethanol. This cost reduction was demonstrated for two biofuels pathways that can produce cellulosic ethanol at a modeled mature plant cost of approximately $2 per gallon (2007 U.S. dollars). This equates to a 77% reduction in the minimum ethanol selling price (MESP) from an estimated $9.16 (2007 U.S. dollars) in 2001. The reduction in cost achieved by this RD&D has enabled the opening of several new commercial-scale integrated biorefineries since 2012, including POET-DSM, DuPont, and INEOS (see the Integrated Biorefinery Section below). Even with crude oil prices very low, cellulosic ethanol (particularly when agricultural residues are used as a feedstock) provides unique benefits such as large GHG reductions, additional income for farmers, domestic energy security, and other benefits (see the Bioeconomy Initiative section below). As the cellulosic ethanol technology has transitioned to industry, government sponsored RD&D in the area has shifted to a focus on hydrocarbon fuels and other drop-in replacements.

Biochemical Conversion

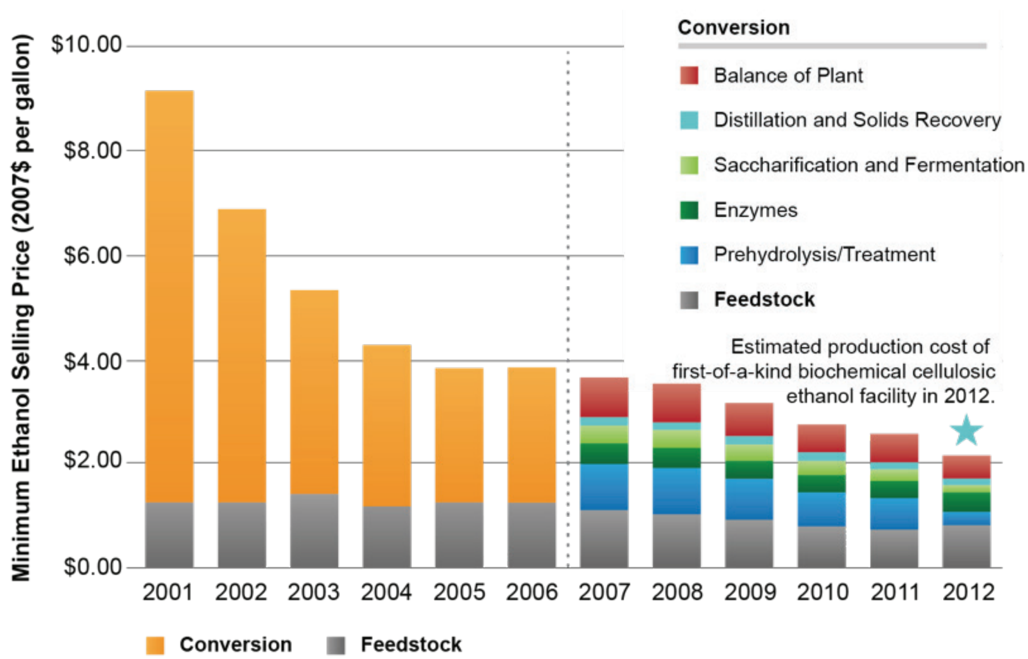
A 2011 design report[7] detailing the biochemical production of ethanol from dilute-acid pretreated corn stover was validated in 2012 at a biochemical conversion pilot plant with a fully integrated suite of technologies. This demonstration showcased a process capable of producing cellulosic ethanol from corn stover at a cost of $2.15 per gallon ethanol ($3.20 gge) when modeled at commercial scale.

Key breakthroughs that enabled this demonstration included the development of more efficient pretreatment processes, resulting in increased sugar yields; improved enzyme production method and enzymes that reduce enzyme loading and associated enzyme costs by approximately 90%; and more robust fermentation organisms that are able to utilize multiple sugars in the presence of biomass-derived inhibitors, ultimately achieving significantly higher ethanol yields. The deconstruction strategy, tested at bench and pilot scales, resulted in greater than 80%

conversion of the xylan to desired xylose monomer in whole slurry mode while simultaneously lowering acid usage from 3.0% to 0.3%. An improved neutralization step reduced conditioning-related sugar losses from 13% to undetectable amounts. Increased enzyme efficiency resulted in reduced enzyme loading and cellulose-to-glucose yields of nearly 80%, contributing to an overall 20-fold reduction in enzyme costs. Improvements in fermentation and microbial strain development resulted in the industrially relevant strains capable of converting cellulosic sugars at total conversion yields greater than 95% and tolerant of ethanol titers of approximately 72 grams/liter.

Figure 7.A.3 illustrates the R&D impact on MESP of corn stover to ethanol via biochemical conversion, from 2001 to 2012. The dotted line denotes success at varying scales: bench scale prior to 2007, and pilot and modeled nth plant scale thereafter, until 2012. The star represents the published production cost[8] expected at one of the first cellulosic ethanol facilities to come online. The facilities that have come online to this point (discussed in the integrated biorefineries section below) are not yet operating at full capacity as of 2015 and the actual costs of ethanol production from these facilities has not been published.

Figure 7.A.3 Biochemical R&D Impact on MESP from Corn Stover[9]



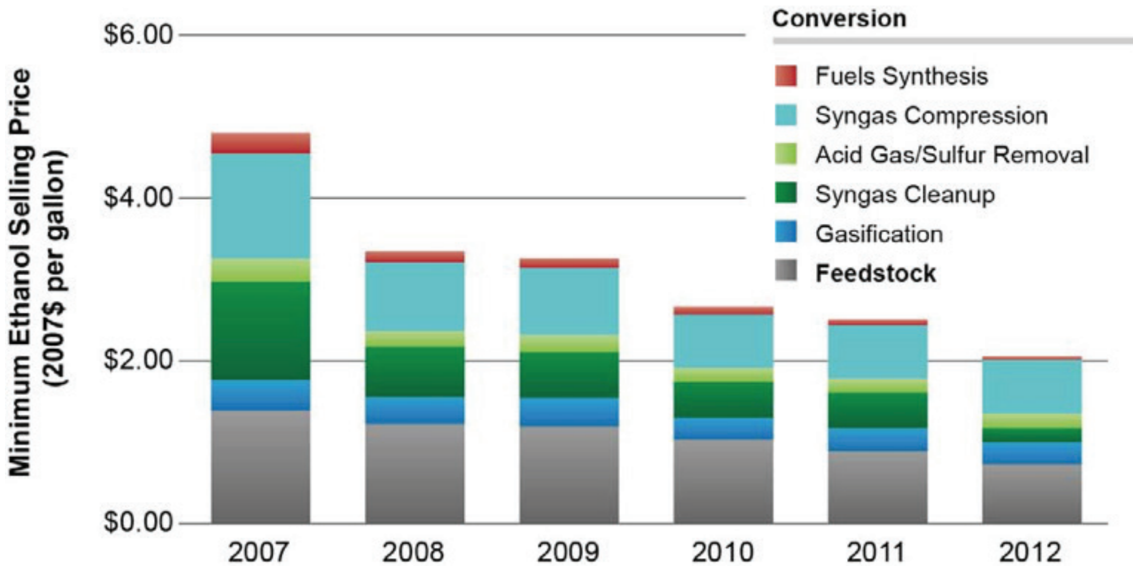
Thermochemical Conversion

A 2011 design report[10] detailing the thermochemical production of ethanol from a woody feedstock was validated in 2012 at the Thermochemical Users Facility. This demonstration showcased a process configuration capable of producing cellulosic ethanol from a woody feedstock at a cost of $2.05 per gallon ethanol ($3.06 gge) when modeled at commercial scale.

The thermochemical conversion process used for cellulosic ethanol production included a gasifier, syngas cleanup, and catalytic fuel synthesis reactors. Significant process engineering improvements were achieved within the gasifier and fuel synthesis steps, and technical improvements were achieved in the syngas cleanup and catalytic fuels synthesis steps. The notable technical breakthroughs include the optimization of an indirectly heated fluidized bed gasifier; the development of tar- and methane-reforming catalysts that increase methane conversion to syngas from 20% to more than 80%; and development of catalysts and operational strategies for the conversion of syngas to mixed alcohols production. These key improvements resulted in an increase in ethanol yield from 62 gallons to greater than 84 gallons per ton of biomass. Figure 7.A.4 illustrates the R&D successes contributing to the decrease in MESP for a gasification process between 2007 and 2012.

Figure 7.A.4 Thermochemical R&D Impact on MESP from Woody Feedstock[11]

Credit: National Renewable Energy Laboratory (NREL)



Leveraging Success

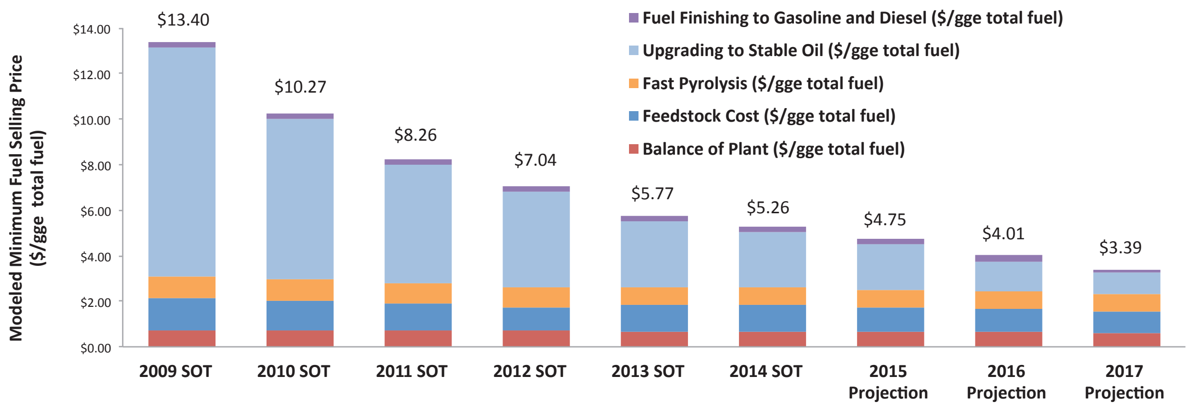
More than 10 years of dedicated RD&D enabled the breakthroughs necessary for the production of cost-competitive cellulosic ethanol. Meeting cost-competitive production targets is important because cellulosic ethanol represents a very significant life-cycle reduction in GHG emissions compared to petroleum gasoline (roughly 80% and roughly 90% for fermentation and gasification pathways, respectively).[12] These very large and significant GHG reductions from cellulosic ethanol are distinct from the smaller GHG reductions estimated for traditional corn-based ethanol (~34%).[13]

These R&D achievements, formally demonstrated in 2012 for cellulosic ethanol production, provide the groundwork for the development and optimization of biomass conversion technologies and techniques capable of producing hydrocarbon liquids that are virtually indistinguishable from gasoline, diesel, jet fuel, and other petroleum products, and that are fully compatible with existing fuel handling and distribution infrastructures. One example of a new hydrocarbon pathway, Fast Pyrolysis, is shown below.

Fast Pyrolysis and Hydrotreating Pathway

One illustrative design case is the updated fast pyrolysis and hydrotreating design case, which uses a blended, formatted woody feedstock to produce gasoline and diesel blend stock fuel in 2017,[14] and serves as an example of how the $3/gge plant-gate cost goal could be achieved by 2017. The cost, when shown in gge, represents a weighted average of gasoline and diesel blendstocks produced in a roughly 1:1 ratio. Cost projections for the fast pyrolysis design case are shown in Figure 7.A.5 and Table 7.A.1.

Figure 7.A.5 Cost Projection Breakdown for the Fast Pyrolysis Design Case at the plant gate[15] (SOT = state of technology)



Based on the 2013 design case for fast pyrolysis, Figure 7.A.5 shows that a total potential cost reduction of 75% can be achieved between 2009 and 2017, with improvements in all four conversion R&D areas shown in the legend. The feedstock cost is listed here as $/gge fuel which can be calculated from the $/dry ton feedstock cost from Tech Assessment 7B and the efficiency of the conversion process in gge/dry ton. Total fuel yield is estimated at 78 gge/dry ton feedstock in 2009-2012 and rose to 87 gge/dry ton feedstock in 2013-2017 due to process improvements. This equates to a carbon-fuel efficiency (C in fuel/C in feedstock) of 38% and 47% respectively.

Table 7.A.1 Cost Projection Breakdown for the Fast Pyrolysis Design Case[16]

	2009 SOT	2010 SOT	2011 SOT	2012 SOT	2013 SOT	2014 SOT	2015 Projection	2016 Projection	2017 Projection
Fast Pyrolysis ($/gge total fuel)	$0.97	$0.93	$0.91	$0.90	$0.78	$0.78	$0.77	$0.76	$0.76
Upgrading to Stable Oil ($/gge total fuel)	$10.07	$7.05	$5.23	$4.17	$2.88	$2.40	$2.01	$1.35	$0.95
Fuel Finishing to Gasoline and Diesel ($/gge total fuel)	$0.25	$0.24	$0.24	$0.24	$0.25	$0.24	$0.24	$0.24	$0.14
Balance of Plant ($/gge total fuel)	$0.74	$0.72	$0.71	$0.71	$0.68	$0.68	$0.67	$0.66	$0.63
Conversion Contribution ($/gge total fuel)	$12.02	$8.94	$7.10	$6.02	$4.60	$4.09	$3.69	$3.01	$2.47
Feedstock Cost ($/gge total fuel)	$1.38	$1.33	$1.17	$1.03	$1.17	$1.17	$1.06	$0.99	$0.92
MFSP ($/gge total fuel)	**$13.40**	**$10.27**	**$8.26**	**$7.04**	**$5.77**	**$5.26**	**$4.75**	**$4.01**	**$3.39**

The value of biofuels to the U.S. extends beyond their role as a cost-competitive replacement for fossil fuels, including societal and economic factors. One important component of the environmental benefits of biofuels are their potential for greenhouse gas (GHG) emissions reductions. Tools, including the GREET model, have been developed to estimate these GHG reductions as well as other environmental factors. Supply chain sustainability analysis for the Fast Pyrolysis Design Case indicates that, on a life-cycle basis, pyrolysis-derived gasoline and diesel produced from pine or forest residue offer between a 64% and 70% reduction in GHG emissions compared to conventional gasoline and diesel in the 2017-projected scenario.[17] These life-cycle GHG reductions include those associated with growing, harvesting, and transporting the feedstock, indirect land use change, as well as the conversion process. For the 2014 state of technology (SOT) case, reductions are estimated to be 45% because of significant energy consumption in feedstock drying which will be mitigated through ongoing R&D.

Integrated Biorefineries

The United States consumes 283 billion gallons/year of fuels, petrochemical products, and other commodities manufactured from crude oil. Table 7.A.2 shows the current composition of this market and anticipated future changes as projected by the Energy Information Administration (EIA).

Table 7.A.2 U.S. Liquid Fuels and Products Market Size (billion gallons/year)[18]

	2013	2040	Growth 2013 – 2040 (%/year)
Gasoline	136	108	-0.8%
Diesel	55	64	0.6%
LPGa	38	49	1%
Otherb	31	37	0.7%
Jet fuel	22	29	1%
Residual fuel oil	5	4	-.4%
Total	**291**	**296**	

Notes:
a. LPG =Liquid Petroleum Gas. Includes ethane, natural gas, and refinery olefins.
b. Includes kerosene, petrochemical feedstocks, lubricants, waxes, asphalt, and other commodities.

Alternative fuels are being developed in the United States and worldwide that can replace a portion of the market currently being supplied by oil-based products. RD&D projects have focused on the conversion of lignocellulosic biomass into ethanol, renewable diesel/jet/gasoline, and bioproducts. Algae-derived feedstocks are being investigated for production of fuels, products, and power. Additional feedstocks of interest include methane from waste sources (such as landfill gas, wastewater treatment facilities, and on-farm anaerobic digesters) and carbon dioxide from waste streams (e.g., steel mill flue gas and ethanol production facilities [see also the Technology Assessment 4.D *Carbon Dioxide Capture for Natural Gas and Industrial Applications*]). A conversion facility can be constructed as a stand-alone integrated biorefinery that produces a blend stock or a near finished fuel. Another approach is the production of a bio-crude that becomes a feed into a petroleum refinery at a suitable insertion point. In the second approach, the refinery continues to produce its normal slate of products with a specific bio-derived content.

Ethanol from corn continues to be consumed in the light duty vehicle fleet as blends of ethanol/gasoline (e.g., E10 is 10% ethanol and 90% gasoline). Approved blends in the U.S. market are E10 (suitable for most vehicles on the road today), E15 (for 2001 and newer light duty vehicles), and E85 (for flex-fuel vehicles). Biodiesel from soybean and waste oils is also being used in heavy duty vehicles at blends up to B20. Renewable diesel, jet, and gasoline are indistinguishable from their fossil counterparts and can serve the aviation (civilian and military), marine, rail, and heavy duty vehicle markets in addition to light duty vehicles. Bio-products (e.g., succinic acid, polymers, adhesives, lubricants, animal feed, fish feed, and soil supplements) have similar but not identical characteristics as their fossil-derived counterparts.

Four commercial-scale facilities have been constructed (Abengoa—25 million gallons/year, Dupont—30 million gallons/year, INEOS—8 million gallons/year, and Poet—25 million gallons/year)[19,20] that can produce ethanol from lignocellulosic ethanol. These facilities will use corn stover, citrus waste, and other types of agricultural residues as feedstocks, which will be converted via biochemical and thermochemical processes into ethanol. In addition to these commercial scale facilities a large number of pilot and demonstration scale integrated biorefineries have been constructed building on key technologies developed in this area.

In order to produce commercial-scale volumes of renewable jet and diesel, an initiative has been launched with funding from three agencies (U.S. Navy, U.S. Department of Agriculture, and U.S. Department of Energy [DOE]), with matching funds from the private sector. The objective of this initiative is to construct multiple integrated biorefineries that are capable of producing at least 10 million gallons/year of renewable diesel or jet fuel for use by the Navy, civil aviation, marine, or other sectors. Three projects (Emerald, Fulcrum, and Red Rock)[21] have been selected for funding under this initiative that use fats, oils, and greases; municipal solid waste; and woody biomass as feedstocks. Conversion technologies being used by these projects include hydro-treatment and upgrading of waste oils and gasification, followed by Fischer-Tropsch (FT) conversion. Innovative aspects of these projects include separation of municipal solid waste into organic and recyclable fractions, new gasifiers, new catalysts, and scale-up of process technologies to commercial-scale operation. The Defense Logistics Agency has issued a solicitation that signals the intent of the Department of Defense to purchase alternative fuels at up to a 10% blend as long as the finished fuel is price competitive, has lower GHG emissions than conventional fuels, and meets other applicable criteria. Growing interest for alternative fuels from the civil aviation and marine sectors will encourage market growth beyond military use.

Fuel has become the largest cost element in the civil aviation sector, accounting for about 30% of an average airline ticket in the United States. Fuel price volatility remains a challenge that airlines manage on a daily basis. The civil aviation sector has established a goal of carbon neutral growth by 2020, despite growing demand for aviation services worldwide. Owing to the long life of aviation assets, the near- to mid-term strategy requires the use of advanced biofuels and other alternative fuels that can be used without engine or delivery infrastructure modifications. The aviation industry has taken active steps in this direction by approving the use of three types of alternative fuels: hydro-treated esters and fatty acids at up to 50/50 blend, FT at up to 50/50 blend, and sugar-based iso-paraffins at up to 10/90 blend. Five additional pathways are in the pipeline for the American Society of Testing and Materials (ASTM) approval process.

R&D is needed to reduce the cost of bio-derived jet fuels to competitive levels using multiple feedstocks and conversion technologies. The aviation industry will be an early adopter of biofuels as long as prices are competitive and the fuels are approved by ASTM. Jet fuel consumption in the United States is 21 billion gallons/year and is expected to grow to 24 billion gallons/year by 2040. A workshop was held on techno-economic analysis of alternative jet fuel pathways.[22] The workshop highlighted the need for detailed techno-economic analysis of new pathways that are being explored. DOE has joined a multiagency initiative called Farm-to-Fly 2.0. This is an agreement among the U.S. Department of Agriculture, Federal Aviation Administration, and civil aviation sector to collaborate and help develop biomass-derived alternative jet fuels. There is similar interest from the marine community for renewable diesel due to vessels having to meet low sulfur requirements in future years.

Bioeconomy Initiative

The goal of the Biomass Research & Development Board's Billion Ton Bioeconomy Initiative is to develop and provide innovative ways to remove barriers to expanding the sustainable use of the United States' abundant biomass resources, such as renewable plant material and waste feedstocks for biofuels, bioproducts, and biopower.[23] The bioeconomy has the potential to provide more jobs and economic opportunities; support a secure, renewable energy future; and contribute to improved environmental quality.

The Initiative will coordinate and enhance federal efforts, as well as garner collaboration from the government and its stakeholders, in an accelerated, systematic effort to expand the bioeconomy. The proposed vision is to expand today's bioeconomy five-fold in the next 15 years, as measured by biomass tonnage sustainably produced and used. To achieve this vision, considerable efforts must focus on overcoming natural resource and environmental concerns, as well as optimizing economic, environmental, and social outcomes through the efficient scale-up of production and use of large amounts of biomass. Fulfilling this vision entails aligning the diverse goals and roles of many stakeholders across both the public and private sectors, thus allowing for coordinated action.

While the United States has always maintained a bioeconomy that contributes to its overall economy, there is the potential to expand the bioeconomy and utilize up to one billion dry tons of biomass annually, particularly for producing renewable energy and products. This effort will increase the sustainable production of biomass feedstocks; construction of more biorefineries and manufacturing facilities; growth in the market for biofuels, biochemical, and other biomass-derived products; and development of feedstock production to support the industry. Table 7.A.3 shows the current and anticipated outcomes from a fully mature bioeconomy.

Table 7.A.3 Estimates of Current and 2030 Potential Bioeconomy[24]

Bioeconomy Parameter	2014 Current	~2030 Potential
Biomass Utilization	406 million dry tons*	1130 million dry tons**
Total requirement (including supply chain losses)	439 million dry tons	1228 million dry tons
Biofuels Production	16 billion gallons (128 million dry tons)	52 billion gallons (701 million dry tons)
Biopower Production (EIA)	53 billion kWh 1363 TBtu (257 million dry tons)	78 billion kWh 1376 TBtu (292 million dry tons)
Livestock Anaerobic Digestion	3 billion kWh 11 TBtu (10 million dry tons)	27 billion kWh 90 TBtu (88 million dry tons)
Biochemicals Production	1.1 billion pounds (3 million dry tons)	13.1 billion pounds (34 million dry tons)
Wood Pellet Production	15 billion pounds (8 million dry tons)	31 billion pounds (15 million dry tons)

* Current biomass utilization is derived from uses in 2014 using various sources: EIA, EPA RFS, USDA
** 2030 potential utilization is derived from projections using various sources: EIA, EPA RFS, USDA

Endnotes

[1] Bioenergy Technologies Office. "Multi-Year Program Plan, March 2015." 2015. Available at: http://www.energy.gov/sites/prod/files/2015/04/f22/mypp_beto_march2015.pdf.

[2] Ibid.

[3] Humbird, D. et al., 2011 "Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol". National Renewable Energy Laboratory and Harris Group Inc. Available at http://www.nrel.gov/biomass/pdfs/47764.pdf

[4] Dutta, A. et al. "Process Design and Economics for Conversion of Lignocellulosic Biomass to Ethanol: Thermochemical Pathway by Indirect Gasification and Mixed Alcohol Synthesis". Available at http://www.nrel.gov/biomass/pdfs/51400.pdf

[5] Bioenergy Technologies Office Design Case Webpage: Available at http://energy.gov/eere/bioenergy/technology-pathways

[6] Pilot throughput is defined as ½ to ≥1 dry ton per day.

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[15] Bioenergy Technologies Office. "Multi-Year Program Plan, March 2015." 2015. Available at: http://www.energy.gov/sites/prod/files/2015/04/f22/mypp_beto_march2015.pdf.

[16] Ibid.

[17] Dunn, J. B., et al. "Supply Chain Sustainability Analysis of Fast Pyrolysis and Hydrotreating Bio-Oil to Produce Hydrocarbon Fuels." Argonne National Laboratory, ANL/ESD -15/2, 2015. Available at: https://greet.es.anl.gov/publication-fast-pyrolysis-SCSA.

[18] Energy Information Administration. "Annual Energy Outlook 2015." Reference case table A11. Available at http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

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[21] "Departments of Energy, Navy, and Agriculture Invest $210 million in Three Commercial Biorefineries to Produce Drop-in Biofuel for the Military", January 30, 2015. Available at: http://energy.gov/eere/success-stories/articles/departments-energy-navy-and-agriculture-invest-210-million-three.

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[23] "The Biomass Research and Development Board" involves a number of agencies and was established under the Biomass Research and Development Act of 2000. Details can be found at http://biomassboard.gov/index.html including discussion of the Biomass Research and Development Initiative.

[24] Preliminary analyses, Analysis Subgroup, Biomass Research and Development Board

Acronyms

ASTM	American Society of Testing and Materials
EIA	Energy Information Administration
FT	Fischer-Tropsch
GHG	Greenhouse gas
Coke	Ash made of carbon fragments that can drop out of a process stream
MESP	Minimum Ethanol Selling Price
SCSA	Supply Chain Sustainability Analysis
SOT	State of Technology
Titer	A method of expressing concentration
$/gge	Dollars/gallon of gasoline equivalent

Glossary

Deconstruction	Breakdown of biomass into intermediate streams
Gasification	Deconstruction of biomass into a syngas intermediate
Hydrothermal Liquefaction	Deconstruction of wet biomass into a liquid intermediate stream at increased temperature and pressure
Upgrading	The transformation of intermediate streams into crude product streams usually involving chemical transformations
Pyrolysis	The thermal and chemical decomposition of feedstock (at temperatures typically <700°C), without the introduction of oxygen, to produce a bio-oil intermediate
Syngas	A mixture of light gases, such as CO_2, CO, H_2, and CH_4 as well as heavier, more complex species.
Intermediates	Relatively stable chemical building blocks such as bio-oil, sugars, or syngas produced through the deconstruction of biomass
Fuel finishing	Removal of problematic compounds to allow final product streams to conform to standards for off-take agreements