Appendix D: 2012 Cellulosic Ethanol Success

The Bioenergy Technologies Office has supported research, development, demonstration, and deployment for the production of cellulosic ethanol, focusing on three key areas: feedstock logistics, biochemical conversion, and thermochemical conversion. In September 2012, after 10 years of dedicated research and development (R&D) at the lab/bench and pilot[1] scales, the Office's research, development, and demonstration (RD&D) activities resulted in a four-fold reduction in cost and ultimately demonstrated two biofuels pathways that can produce cellulosic ethanol at a modeled nth plant cost of approximately $2 per gallon. This equates to a 77% reduction in the minimum ethanol selling price (MESP) from an estimated $9.16 (2007$US) in 2001.

This achievement marks a critical milestone for the industry that was accomplished with strong bipartisan federal support across two presidential administrations. This milestone was achieved through U.S. Department of Energy (DOE) support of R&D at DOE national laboratories, academic institutions, and industry. RD&D was specifically focused on improving the efficiency and economics around biomass harvesting and feedstock supply system logistics, developing techno-economically viable process steps for both biochemical and thermochemical conversion processes, and through process integration. Reduced costs, technology improvements, and progress in scale-up and integration of processes represent major successes in cost-competitive cellulosic ethanol production. With conservative economic assumptions and proven process parameters, the technologies demonstrated at pilot scale[1] are modeled to produce cellulosic ethanol at commercial-scale costs that are competitive with gasoline production at $110/barrel of crude oil.

Many industry partners are also demonstrating their proprietary technology pathways to produce biofuel at pilot, demonstration, and commercial scales. Some of these technologies are similar to those demonstrated in the recent R&D accomplishment, while others demonstrate or commercialize newly developed technologies for cellulosic ethanol production.

Feedstock Logistics

Improvements in biomass harvesting and feedstock supply system logistics are crucial to meeting modeled 2,200 U.S. tons (2,000 tonne) per day refinery input/uptake/requirement for commercial-scale production costs of cellulosic ethanol. For 2012, research focused on corn stover as a model agricultural residue feedstock and purpose-grown trees as a model woody feedstock for biochemical and gasification routes, respectively.

Key advances in sustainable harvesting and collection include using the Residue Removal Tool[2] for accurate area assessments, improved storage strategies for preservation of biomass quantity and quality, and more energy- and cost-efficient mechanisms for preprocessing of biomass appropriate for introduction into the conversion processing system. Additional improvements included increased harvest efficiency, which contributes to higher sustainable yields, and improved biomass quality through ash content reduction. Higher bale density and reduced losses

[1] Pilot throughput is defined as ½ to ≥ 1 dry ton per day.
[2] D. Muth, K.M. Bryden. (2012). "An Integrated Model for Assessment of Sustainable Agricultural Residue Removal Limits for Bioenergy Systems." *Environmental Modelling and Software*. 39(1).

during handling and storage further contributed to meeting cost targets by lowering the cost of transporting feedstocks. Other contributions to cost reduction include lower-cost storage methods, reduced uncertainty associated with storage losses through meeting a 59% carbohydrate preservation target, and direct improvements in grinder efficiency and capacity. These feedstock advancements, paired with increases in conversion yield/efficiency, resulted in a \$0.42 and \$0.67[3] per gallon reduction in biochemical and thermochemical cellulosic ethanol production costs, respectively.

Biochemical Conversion

Biochemical conversion route costs were significantly impacted through an approximate 90% reduction in enzyme cost (enabled by development of new enzymes and enzyme cocktails) and the engineering of microorganisms that can more effectively utilize multiple sugars produced from hydrolyzed plant cell wall cellulose and hemicellulose (i.e., glucose, xylose, and arabinose). A biochemical conversion pilot plant demonstrated a fully integrated suite of technologies capable of producing cellulosic ethanol from corn stover at a cost of \$2.15 per gallon ethanol (\$3.20 gasoline gallon equivalent [GGE]) when modeled at commercial scale.

Biochemical conversion of biomass to cellulosic ethanol can involve many steps, including pretreatment, conditioning, and enzymatic hydrolysis, followed by fermentation. Key breakthroughs in these process steps included the development of more efficient pretreatment processes, resulting in increased sugar yields; improved enzyme production method and enzymes that reduced enzyme loading and associated enzyme costs; and more robust fermentation organisms that were able to utilize 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 reduction in enzyme costs by 20-fold. 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 gram/liter.

[3] Reductions in feedstock costs resulted in cost/ton of \$58.50 for corn stover and \$61.57 for white oak chips.

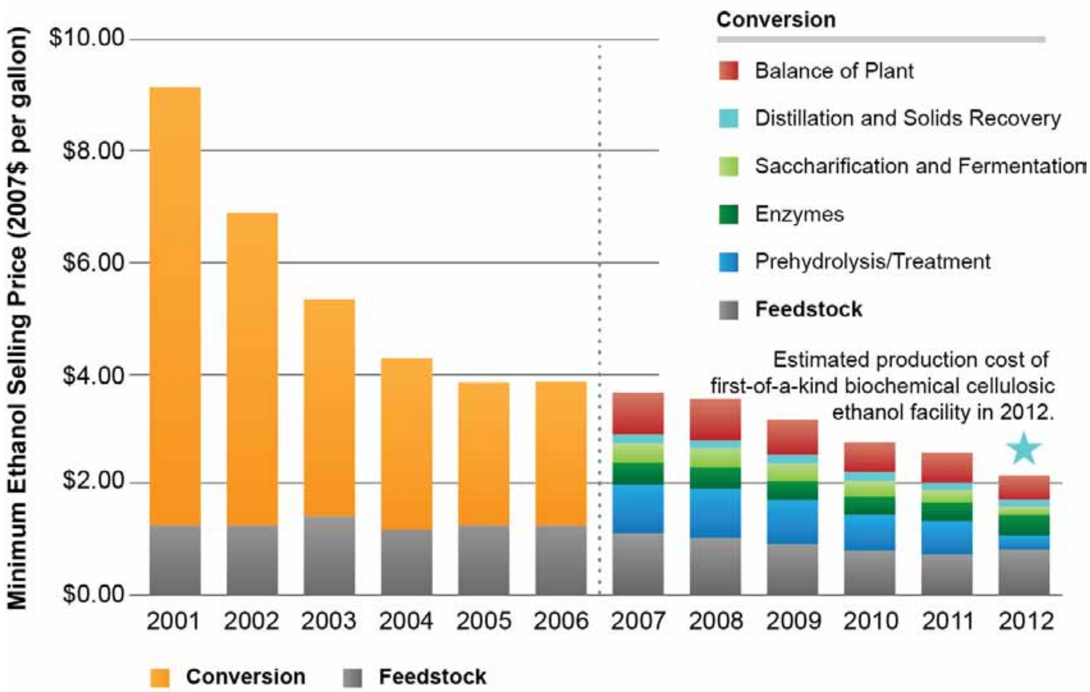

Figure D-1: Biochemical R&D impact on MESP from corn stover

Figure D-1 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[4] expected at one of the first cellulosic ethanol facilities to come online.

Thermochemical Conversion

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.

After developing, improving, and down-selecting a variety of technologies for each process step, the Office demonstrated a 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 (using the pilot plant at its Thermochemical Users Facility). The Office's notable technical breakthroughs included the optimization of its indirectly heated fluidized bed gasifier; the development of tar- and methane-reforming catalysts that increased 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 D-2 illustrates the R&D successes contributing to the decrease in MESP for a gasification process between 2007 and 2012.

[4] Chris Standlee. “Advanced Ethanol: Coming Online.” National Ethanol Conference. February 18, 2014. Orlando, FL.

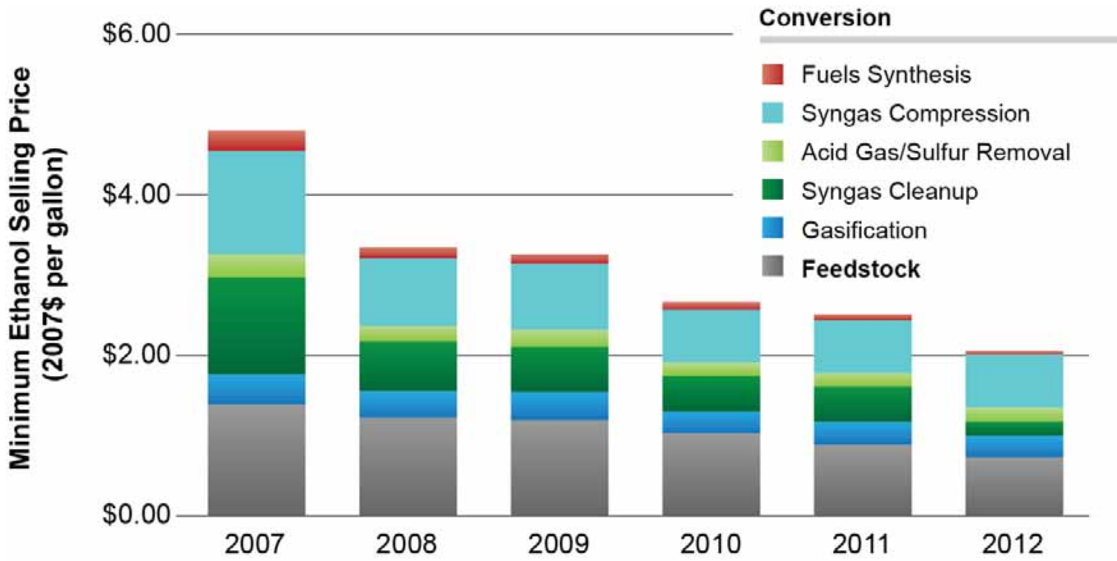

Figure D-2: Thermochemical R&D impact on MESP from woody feedstock

Figure D-2 illustrates the R&D impact on MESP of woody feedstocks to ethanol via thermochemical conversion, from 2007 to 2012.

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 greenhouse gas emissions compared to petroleum gasoline (roughly 80% and roughly 90% for fermentation and gasification pathways, respectively).[5] This does not suggest that these processes cannot be further improved. Updated design cases have shown that the escalation of costs to 2011 U.S. dollar bases increased the MESP and helps to identify further process efficiencies that could be addressed through additional R&D.

These R&D achievements demonstrated in 2012 and since 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. These breakthroughs will be repurposed and leveraged to accelerate the commercialization of new, renewable fuels and chemicals from biomass.

[5] Jennifer B. Dunn, Michael Johnson, Michael Wang. "Supply Chain Sustainability Analysis of SOT Pathways." BETO Quarterly Meeting. January 17, 2013. Washington, D.C.