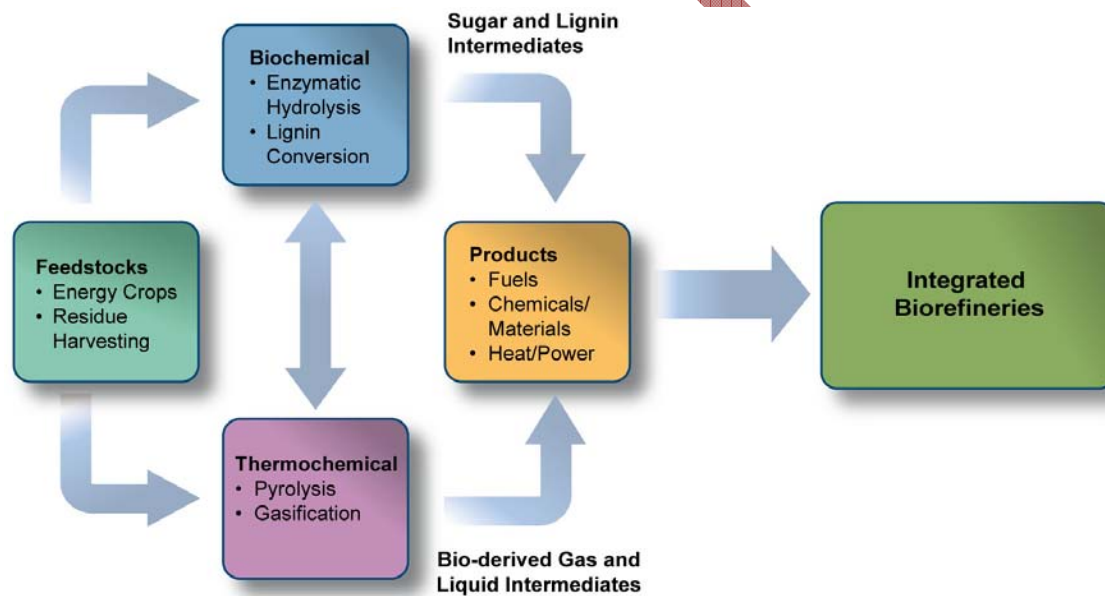


2.2 Conversion Platforms

The strategic goal of the conversion element is to **develop technologies for converting feedstocks into cost-competitive commodity liquid fuels, like ethanol, as well as bioproducts and biopower**. The diversity of the biomass resource leads to the need to develop multiple conversion technologies that can efficiently deal with the broad range of feedstock physical and chemical characteristics. OBP In this section, the two primary conversion platforms under investigation by OBP are described; the biochemical and thermochemical conversion platforms. Within each platform there are many possible variations, but the main differences are in the primary catalytic system employed, and the intermediate building blocks produced.

While the two platforms are described separately, it is envisioned that the combined use of technologies from both conversion platforms offers the greatest opportunity for optimizing biomass conversion into a variety of different fuel, chemicals and energy products. Not all biorefineries will be this complex, especially in the early years of the industry, but some may have added complexity.



2.2.1 Biochemical Conversion Platform

The Biochemical platform is focused on reducing the cost of converting lignocellulosic biomass to mixed, dilute sugars and their further conversion to liquid fuels, like ethanol, to enable successful integrated biorefineries. Biochemical conversion uses biocatalysts, such as enzymes and microorganisms, in addition to heat and chemical catalysts to convert the carbohydrate portion of the biomass (hemicellulose and cellulose) into an intermediate sugar stream. The biomass sugars act as intermediate building blocks which are then fermented to ethanol and other products. The remaining lignin portion of

the biomass can be used for heat and power, or alternatively used to produce additional fuels and chemicals via thermochemical processing.

Biochemical platform R&D will make further improvements to feedstock interface, pretreatment and conditioning, enzymes and fermentation processes, in addition to process integration in order to reduce sugar costs; these economically viable technologies will act as the springboard to launching the next generation of cellulosic ethanol technology from a wide range of feedstocks.

Biochemical Platform Unit Operations

The conceptual block flow diagram in Figure 2.2-1 outlines the main technologies/unit operations of the baseline biochemical biomass-to-ethanol process. Process details are available in the most recent design report.¹

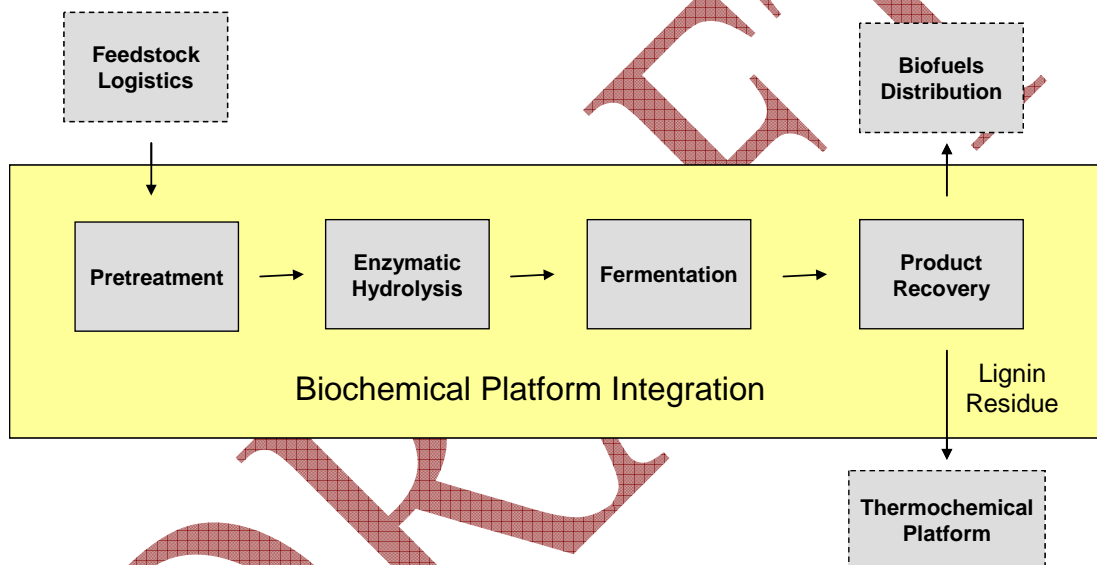


Figure 2.2-1. Biochemical Conversion Route for Biomass to Biofuels

Pretreatment (Prehydrolysis): In this step, biomass feedstock undergoes a thermochemical process to break down the hemicellulose fraction of the feedstock into a mixture of soluble five-carbon sugars – xylose and arabinose, and soluble six-carbon sugars – mannose, galactose, and glucose. This partial solubilization makes the remaining solid cellulose fraction more accessible for enzyme saccharification later in the process. A small portion of the cellulose is often converted to additional glucose in this step, and a portion of the lignin fraction may also be solubilized. The specific mix of sugars released depends on the feedstock used and pretreatment.

¹ "Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover," NREL TP-510-32438, June 2002.

Conditioning (Optional): In some process configurations, the pretreated material goes through a hydrolyzate conditioning process which removes undesirable byproducts from the pretreatment process that are toxic to the fermenting organism.

Enzymatic Hydrolysis: In the enzymatic hydrolysis step, the pretreated material, with the remaining solid carbohydrate fraction being primarily cellulose, is saccharified with cellulase enzymes, releasing glucose. Addition of other enzymes, such as xylanases, in this step may allow for less severe pretreatment, resulting in a reduced overall pretreatment and hydrolysis cost. Enzymatic hydrolysis requires several days, after which the mixture of sugars and any unreacted cellulose is transferred to the fermenter. The process concept under development assumes that the cellulase enzymes are purchased from enzyme companies, like other consumable catalysts and chemicals. The current concept may also combine the enzymatic hydrolysis and fermentation steps.

Fermentation: In the fermentation step, an inoculum of a fermenting organism is added and fermentation of all sugars to ethanol is carried out while continuing to utilize the enzymes for further glucose production from any remaining solid cellulose. After a few days of fermentation and continued saccharification, nearly all of the sugars are converted to ethanol. The resulting beer (low-concentration ethanol) is sent to product recovery.

Product Recovery: Product recovery involves distilling the beer to separate the ethanol from the water and residual solids. A final dehydration step removes any remaining water from the ethanol. Residual solids are composed primarily of lignin which can be burned for combined heat and power generation or thermochemically converted to synthesis gas or pyrolysis oil intermediates for other uses. This process is part of the Thermochemical platform focus.

Biochemical Platform Interfaces

Feedstock Logistics Interface: The Feedstock platform provides preprocessed feedstock that meets the requirements (composition, quality, size, etc.) as defined by the specific biochemical conversion process configuration. Close coordination between the Feedstock and Biochemical Conversion platforms is required to ensure that the feedstock and the process are optimized together for the lowest overall cost and highest conversion efficiency of the biomass.

Thermochemical Platform Interface: Lignin and other byproducts/residues of the biochemical conversion process can be used to produce the electricity required for the production process. Lignin can also be thermochemically converted to fuels and chemicals.

Biofuels Distribution Interface: The next step in the biomass-to-biofuels supply chain is the biofuels distribution step. Biofuels leaving a biorefinery must meet all applicable federal, state and local codes and standards.

2.2.2.1 Biochemical Platform Support of Program Strategic Goals

The Biochemical platform's strategic goal is to *develop technology for converting lignocellulosic feedstocks into inexpensive sugar streams that can be used to produce cost-competitive commodity fuels, like ethanol, as well as bioproducts.*

The Biochemical platform directly addresses and supports production of sugars and fuels in the Agricultural Residues Processing and the Energy Crops Processing pathways. It also indirectly supports the production of bioproducts from both these pathways and any pathway conversion where biochemical processing can be considered as an option.

2.2.1.2 Biochemical Platform Support of Program Performance Goals

The overall performance goal of the Biochemical platform is to reduce the estimated mature technology processing cost² for converting cellulosic feedstocks to ethanol to \$0.82 per gallon in 2012 (see Figure 2.2-4 for additional information) and \$0.60 per gallon in 2017 (2007\$) based on data at the integrated pilot scale. The baseline processing cost for dry corn stover to ethanol was \$1.59 per gallon (2007\$) in FY 2005 based on data at the bench scale.

The performance goals for the pathways under investigation are as follows:

Agricultural Residues Pathway

- M.4.5.5: By 2012, validate integrated pretreatment and enzymatic hydrolysis of corn stover (dry and wet) at pilot scale
- M.4.6.3: By 2012, validate/optimize integrated production of ethanol from corn-stover-derived sugars at pilot scale

Energy Crops Pathway

- M.5.4.5: By 2017, validate integrated pretreatment and enzymatic hydrolysis of switchgrass at pilot scale
- M.5.6.3: By 2017, validate integrated production of ethanol from switchgrass-derived sugars at pilot scale

2.2.1.3 Biochemical Platform Technical Challenges and Barriers

Bt-A. Biomass Fractionation: Fractionation can be used to increase the value of the individual components in biomass prior to their subsequent conversion to products. Currently, the interactions between chemical, biological, solvation (ability to go into solution), and mechanical processes to ultimately allow biomass to be more efficiently fractionated at high yield into high-purity components is insufficiently understood to implement commercially.

² Estimated mature technology processing cost means that the capital and operating costs are assumed to be for an "nth plant" where several plants have been built and are operating successfully so that additional costs for risk financing, longer startups, under performance, and other costs associated with pioneer plants are not included.

Bt-B. Biomass Variability: The characteristics of biomass can vary widely in terms of physical and chemical composition, size, shape, moisture content, and bulk density. These variations can make it difficult (or costly) to supply biorefineries with feedstocks of consistent, acceptable quality year-round, and also feedstock variability affects overall conversion rate and product yield of biomass conversion processes.

Bt-C. Biomass Recalcitrance. Lignocellulosic biomass feedstocks are naturally resistant to chemical and/or biological degradation. The fundamental role of biomass structure and composition and the critical physical and chemical properties that determine the susceptibility of cellulosic substrates to hydrolysis are not well understood. This lack of understanding of the root causes of the recalcitrance of biomass limits the ability to focus efforts to improve the cost-effectiveness and efficiency of pretreatment and other fractionation processes.

Bt-D. Pretreatment Chemistry. Thermochemical prehydrolysis of biomass, typically referred to as pretreatment, is required to break down the structure of biomass and increase its susceptibility to subsequent enzymatic hydrolysis by cellulase enzymes. The critical physical and chemical properties that determine the susceptibility of cellulosic substrates to hydrolysis and the role that lignin and other pretreatment products play in impeding access to cellulose are not well enough understood. Continued significant cost reductions in pretreatment technologies via improved sugar yields and quality require developing a better understanding of pretreatment process chemistries, including the kinetics of hemicellulose and cellulose hydrolysis.

Bt-E. Pretreatment Costs. Pretreatment reactors typically require expensive materials of construction to resist acid or alkali attack at elevated temperatures. In addition, the impact of reaction configuration and reactor design on thermochemical cellulose prehydrolysis is not well understood. Developing lower-cost pretreatments depends on the ability to process the biomass in reactors designed for maximum solid levels and fabricated out of cost-effective materials.

Bt-F. Cellulase Enzyme Production Cost. Cellulase enzymes remain a significant portion of the projected production cost of sugars from cellulosic biomass. Cost-effective enzyme production technologies are not currently available, although significant progress has been made through concerted efforts with industrial enzyme producers.

Bt-G. Cellulase Enzyme Loading. Reducing the cost of enzymatic hydrolysis depends on identifying more efficient enzyme preparations and enzyme hydrolysis regimes that permit more cost-effective and lower ratios of enzyme to substrate to be used.

Bt-H. Enzyme Biochemistry. Currently available enzymes do not exhibit the high thermostability and substantial resistance to sugar end-product inhibition. Developing enzymes that enable low-cost enzymatic hydrolysis technology requires more understanding of the fundamental mechanisms underlying the biochemistry of enzymatic cellulose hydrolysis, including the impact of biomass structure on enzymatic cellulose decrystallization. Additional efforts aimed at understanding the role of cellulases and their interaction not only with cellulose but also the process environment is needed to affect further reductions in cellulase cost.

Bt-I. Cleanup/Separation. Sugar solutions resulting from thermochemical pretreatment are impure, containing a mixture of sugars and a variety of non-sugar components. Potential impurities include acetic acid liberated upon hydrolysis of hemicellulose, lignin-derived phenolics solubilized during pretreatment, inorganic acids or alkalis or other compounds introduced during pretreatment, various salts, and hexose and pentose sugar degradation or transglycosylation products. The presence of some of the non-sugar components can be inhibitory to microbial fermentation or biocatalysis or can poison chemical catalysts. Low-cost purification technologies need to be developed that can remove impurities from hydrolysates and provide concentrated, clean sugar feedstocks to manufacture biofuels and biobased products.

Bt-J. Fuels Organism Development

Fermentation organisms used today have not been optimized for production of liquid fuels (ethanol, butanol and other alcohols) from the sugar mixture in the hydrolyzate broth produced during biomass pretreatment and enzymatic hydrolysis. For example, current organisms are not capable of utilizing the five-carbon sugar components, xylose and arabinose, in the biomass hydrolyzate as efficiently as glucose. In addition, impurities generated during pretreatment inhibit the organism, resulting in slow fermentations and incomplete utilization of sugars; this can lead to the need for costly purification. Improvements in fermentative organisms to perform in hydrolysate broths can significantly lower capital costs.

Bt-K. Biological Process Integration. Process integration remains a key technical barrier hindering development and deployment of biochemical conversion technologies. Biochemical conversion technologies currently present large scale-up risks because of lack of high-quality performance data on integrated processes carried out at the high solids conditions required for industrial operations. The effect of feed and process variations throughout the process must be understood to ensure robust, efficient biorefineries. Process integration work is essential for characterizing the complex interactions that exist between many of the processing steps, identifying unrecognized separation requirements, addressing bottlenecks and knowledge gaps, and generating the integrated performance data necessary to develop predictive mathematical models that can guide process optimization and scale-up.

Bt-L. Biochemical/Thermochemical Processing Integration. Integration of the entire biorefinery is the final conversion barrier and overcoming it will require successful integration at the interfaces between the biochemical and thermochemical processes. For example, the lignin residue can be used as a feedstock for syngas or bio-oil production and for subsequent conversion to combined heat and power, fuels, or chemicals. Without planned and managed integration, the complete picture of biomass conversion to fuels and chemicals will not be clear enough to attract potential developers because the risks of commercialization will be too high for financiers. As conversion technologies mature, higher levels of integration will be feasible and second generation biorefineries are envisioned to be closely coupled biochemical/thermochemical facilities enabling the most efficient use of a wide range of feedstocks.

2.2.1.4 Biochemical Platform Approach for Overcoming Challenges and Barriers

The approach for overcoming biomass conversion technical challenges and barriers is outlined in the Biochemical platform's work breakdown structure (WBS), as shown in Figure 2.2-2. The platform has four key activities which are further broken down into tasks. One of the major organizational goals within the platform is to better coordinate and align tasks to make sure all R&D efforts are directed toward achieving the same programmatic goal.

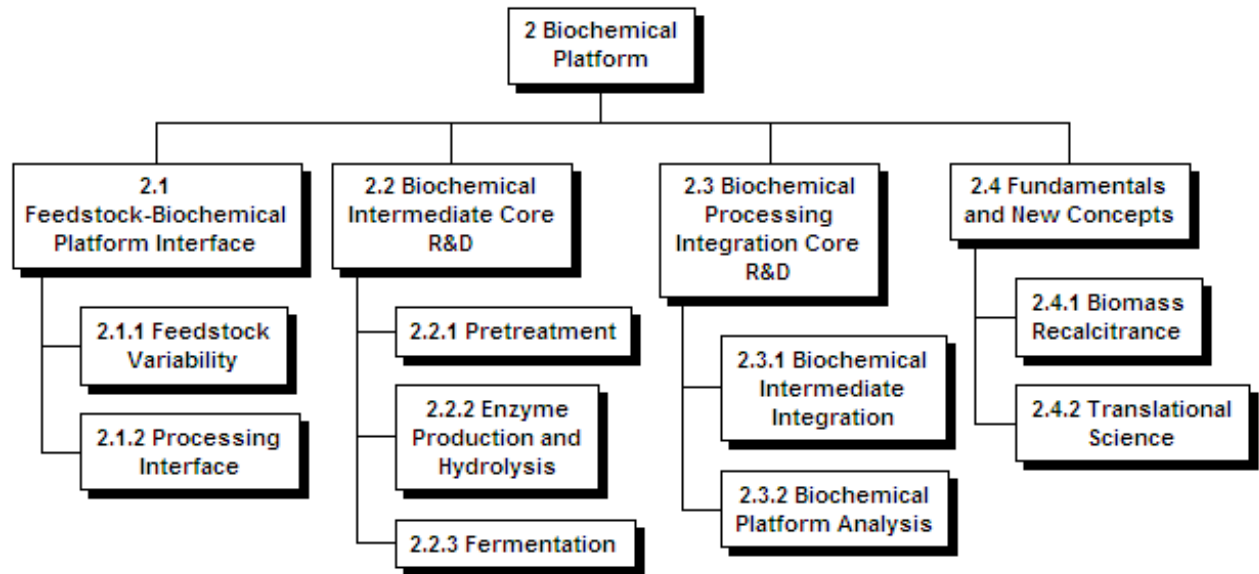


Figure 2.2-2. Work Breakdown Structure for Biochemical Platform Core R&D

The current platform efforts are focused on overcoming the recalcitrance of biomass (when compared to starch, cellulose is not easily broken down into sugars); validating advanced conversion enhancements such as increased solids loadings, improved separations and milder conditions; more robust fermentation organisms; and integrating conversion technologies both within the Biochemical platform with upstream feedstock collection/transport processes and downstream thermochemical conversion processes. Core research, which addresses the key technical barriers, is performed by national laboratories, industry and universities. Relevance to industrial and commercial applications to foster transfer of technology will be ensured via stage gate reviews by industry, partnering with industry as appropriate, and patenting and publishing the results.

Biochemical Platform WBS Task Areas

WBS 2.1 Feedstock-Biochemical Interface R&D

Establishing the value of and requirements for feedstock assembly processes to feed bioconversion processes are necessary for the development of biorefineries. Linking feedstock collection/transport processes with conversion processes allows evaluation of technology options and trade-offs on both sides of the processing interface. Activities will develop cost and quality specifications for feedstock assembly technologies that are

compatible with biochemical conversion technologies. *The key technical target is to maintain or even improve feedstock yield potential through targeted logistics operations between the field or forest and the biorefinery.*

WBS 2.2 Biochemical Intermediate Core R&D

Overcoming the barriers associated with high capital and operating cost and sub-optimal sugar yields is key to developing an integrated pretreatment, enzymatic hydrolysis and fermentation process. The investigation and evaluation of pretreatment approaches are aimed at reducing the cost of pretreatment and increasing the enzymatic digestibility of residual cellulose and hemicellulose in pretreated biomass. Fundamental research is focused on improving existing fermentation organisms and improving understanding of and developing advanced technologies to overcome the key rate limiting steps in the conversion of biomass to fermentable sugars. *The key technical targets involve achieving high sugar and ethanol conversion rates and yields in the core processing steps of pretreatment, enzymatic hydrolysis and fermentation.*

WBS 2.3 Biochemical Processing Integration Core R&D

Investigating pretreatment and enzymatic hydrolysis technologies together with downstream synthesis identifies the issues and opportunities of integration. Integration of biomass pretreatment, saccharification and fermentation steps can improve overall efficiency and reduce cost. In addition, the effect of feed and process variations throughout the process must be understood to ensure robust, efficient biorefineries. *The key technical target is to maintain high conversion rates from the individual operations in an integrated processing configuration, ideally at high solids loadings.*

WBS 2.4 Fundamentals and New Concepts

A fundamental understanding of the factors and causes underlying the recalcitrance of biomass to biological and chemical degradation is needed to make processing more specific and less costly. The development of tools such as molecular modeling and cell wall microscopy is enabling a more complete understanding of biomass structure and the most appropriate methods to convert it. With this knowledge, advanced energy crops can be developed that require minimal processing. R&D efforts outlined in the Office of Science and EERE's recently developed joint roadmap³ will directly feed this R&D area, providing basic science groundwork to develop applied and ultimately integrated process solutions for biomass conversion. *The key technical target is developing basic knowledge of biomass and biological systems that can ultimately be used to develop new or improved technologies that increase the conversion efficiency and/or reduce the conversion cost.* As feedstock prices increase with supply and demand, decreased conversion costs will allow the industry to utilize a wider range of feedstocks at varying costs.

Major activities for each of the above task areas are outlined in Table 2.2-1.

Table 2.2-1. Biochemical Platform Core R&D Task Summary

³ "Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda," DOE/SC-0095, June 2006.

WBS Element	Description	Barriers Addressed	Pathway(s) Addressed
2.1 Feedstock-Biochemical Platform Interface			
2.1.1 Feedstock Variability	<p>Understanding feedstock variability and options for mitigating impacts on downstream processing 2007-2012</p> <ul style="list-style-type: none"> • Characterize/optimize lignocellulosic biomass feedstocks • Assess/mitigate impacts of biomass characteristics on downstream unit operations • Determine process sensitivity to differences in feedstock type and quality • Identify required process modifications to accommodate feedstock differences <p>2013-2017</p> <ul style="list-style-type: none"> • Design and manipulate plant cell wall composition and structure to maximize yield of fermentable sugars 	Bt-B	4,5
2.1.2 Processing Interface	<p>Defining and coordinating the interface between feedstock logistics and biochemical conversion processes 2007-2012</p> <ul style="list-style-type: none"> • Evaluate technology options and trade-offs with respect to feedstock assembly and preprocessing processes with biochemical conversion processes • Validate feedstocks as received from feedstock logistics systems at pilot scale <p>2013-2017</p> <ul style="list-style-type: none"> • Continue efforts with new or emerging feedstocks 	Ft-M	4,5
2.2 Biochemical Intermediate Core R&D			
2.2.1 Pretreatment	<p>Identifying cost-effective, feedstock-specific pretreatment options with respect to chemistry and reactor design 2007-2012</p> <ul style="list-style-type: none"> • Evaluate and compare lignocellulosic biomass pretreatment options (chemistry, reactor design and pretreatment process) with respect to hemicellulose conversion, cellulose digestibility and ethanol production. • Select and further develop most promising pretreatment options • Validate targeted performance in pilot-scale pretreatment reactor systems <p>2013-2017</p> <ul style="list-style-type: none"> • Map structures and chemistries of native and prehydrolyzed plant cell walls to better understand cell wall deconstruction 	Bt-D, Bt-E	4,5

2.2.2 Enzyme Production and Hydrolysis	<p>Increasing fundamental understanding of mechanics of enzymatic hydrolysis to improve efficiency and performance of enzymes and developing optimized enzymatic hydrolysis processes</p> <p>2007-2012</p> <ul style="list-style-type: none"> • Reduce cost of enzymes by developing high-activity enzyme mixtures and low-cost production processes • Define optimum enzymatic hydrolysis conditions/reactor design (for specific feedstocks and process conditions) to reduce enzyme utilization requirements • Quantify effects of enzyme loading, strain inoculation time and inoculum charge on integrated hydrolysis/fermentation process performance • Validate targeted enzymatic hydrolysis performance of pretreated biomass in scalable system configuration <p>2013-2017</p> <ul style="list-style-type: none"> • Develop improved (engineered) enzymes for advanced biochemical conversion technologies 	Bt-F, Bt-G, Bt-H, Bt-I	4,5
2.2.3 Fermentation	<p>Developing robust ethanol fermentation organisms capable of converting all biomass sugars to ethanol at high yields and rates</p> <p>2007-2012</p> <ul style="list-style-type: none"> • Develop multi-sugar fermenting organisms that can tolerate impurities in biomass hydrolysate • Validate targeted organism performance on pretreated hydrolysate in scalable system configuration <p>2013-2017</p> <ul style="list-style-type: none"> • Develop organism for single-step processing that compares with commercial fermentative organisms and enzymes (at lab scale) 	Bt-J	4,5
2.3 Biochemical Processing Integration Core R&D			
2.3.1 Biochemical Intermediate Integration	<p>Defining/coordinating/consolidating the interfaces within biochemical conversion platform</p> <p>2007-2012</p> <ul style="list-style-type: none"> • Integrate pretreatment and enzymatic hydrolysis with biomass sugar fermentation to maximize cellulose hydrolysis and sugar fermentation rates and yields • Validate targeted integrated process performance in pilot-plant-scale system. <p>2013-2017</p> <ul style="list-style-type: none"> • Identify optimized pretreatment technology for use with single-step biological processing 	Bt-K	4,5

2.3.2 Biochemical Platform Analysis	<p>Developing and employing conceptual models to demonstrate the feasibility of various process design concepts and identify integration issues</p> <p>2007-2012</p> <ul style="list-style-type: none"> • Prepare annual State of Technology estimates to show progress to the 2012 performance target • Develop conceptual process design and mature technology cost estimates for other feedstocks, including wet corn stover and switchgrass, based on the dry corn stover baseline model • Validate 2012 performance target using pilot plant data and baseline process design and mature technology cost estimate <p>2013-2017</p> <ul style="list-style-type: none"> • Complete conceptual design reports on advanced conversion technology configurations including significant process consolidation (e.g. single step biological processing) 	Bt-K, Bt-L	4,5,6 ?
2.4 Fundamentals and New Concepts			
2.4.1 Biomass Recalcitrance	<p>Determining the factors that contribute to biomass recalcitrance and how best to deconstruct plant cell walls</p> <p>2007-2012</p> <ul style="list-style-type: none"> • Define the relationships between pretreatment conditions and biomass structural changes to selectively remove sugars • Determine how cellulase enzymes move along cellulose chains • Define how cellulases and other enzymes interact with plant structure • Investigate the basic mechanisms that will provide the framework for next generation deconstruction technologies <p>2013-2017</p> <ul style="list-style-type: none"> • Continue to investigate the basic mechanisms of deconstructing plant cell walls in the broad diversity of bioenergy feedstocks 	Bt-A, Bt-C, Bt-D, Bt-G, Bt-H	4, 5, 6
2.4.2 Translational Science	<p>Developing and applying systems biology methods for enhanced understanding of the basic mechanisms in biomass conversion</p> <p>2007-2017</p> <ul style="list-style-type: none"> • Develop systems biology methods for strain improvement of enzyme producing and fermentative microorganisms <p>2013-2017</p> <ul style="list-style-type: none"> • Apply systems biology methods to 	Bt-J	4,5,6

	identify and improve enzyme producing and fermentative microorganisms for use with a wide range of feedstocks		
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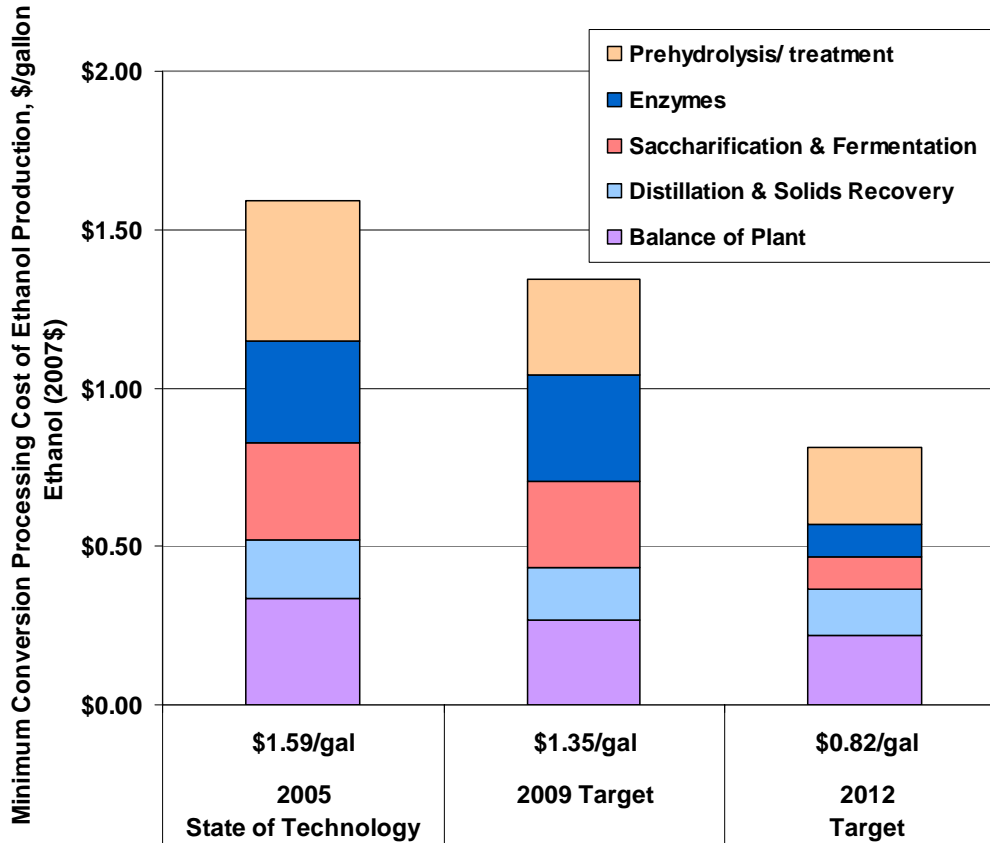
General Plans Beyond 2017

Progress in understanding the scientific basis for biomass conversion, and figuring out how to exploit that knowledge will play key roles in the evolution of the Biochemical Conversion platform. Beyond 2017, the identification of new conversion options is expected to lead to a series of improved generations of technology that will be developed, demonstrated and ultimately deployed. Process consolidation is a common theme envisioned in the future of biochemical conversion where advanced technology will combine several unit operations and improve the pretreatment operation. Enzyme production and fermentation will be combined in a single organism, combining three processes (enzyme production, saccharification and fermentation) into one.

Prioritizing Biochemical Platform Barriers

Biochemical platform has prioritized its R&D efforts in overcoming the identified technical barriers based on the analysis results illustrated in Figure 2.2-3.⁴ The figure shows that the largest potential reduction in the cost of sugars can be obtained with bioconversion technology development in enzymes and fermentation areas. OBP-funded research and development are therefore focused to impact this cost.

⁴ Corn Stover to Ethanol State of Technology and 2012 Targets, NREL Technical Memorandum, March 2007.



Process Area	2005 State of Technology	2009 Target	2012 Target
Processing Total	\$1.59	\$1.35	\$0.82
Prehydrolysis/ treatment	\$0.44	\$0.31	\$0.25
Enzymes	\$0.32	\$0.33	\$0.10
Saccharification & Fermentation	\$0.31	\$0.27	\$0.10
Distillation & Solids Recovery	\$0.18	\$0.17	\$0.15
Balance of Plant	\$0.34	\$0.27	\$0.22

Figure 2.2-3. Biochemical Conversion of Corn Stover to Ethanol (\$/gal in 2007\$s)
(Unit operation cost contribution estimates are based on process concept targets)

Detailed information on the technical performance targets that form the basis for the conceptual biochemical conversion systems designs and cost estimates in Figure 2.3-3 are provided in Appendix B, Table B-4.⁵ The targets are for the baseline ethanol concept which includes dry corn stover conversion via dilute acid pretreatment, enzymatic hydrolysis, ethanol fermentation and recovery, with lignin combustion for combined heat and power production.

2.2.1.5 Biochemical Platform Milestones and Decision Points

⁵ "Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover," NREL/TP-510-32438, 2002.

The key Biochemical platform milestones, inputs/outputs and decision points to complete the tasks described in section 2.2.1.4 are summarized in the chart in Figure 2.2-4. Detailed tables of the milestones, inputs, outputs and decision points are provided in Appendix C, Table C-2.

Figure 2.2-4. Biochemical Core R&D Gantt Chart

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