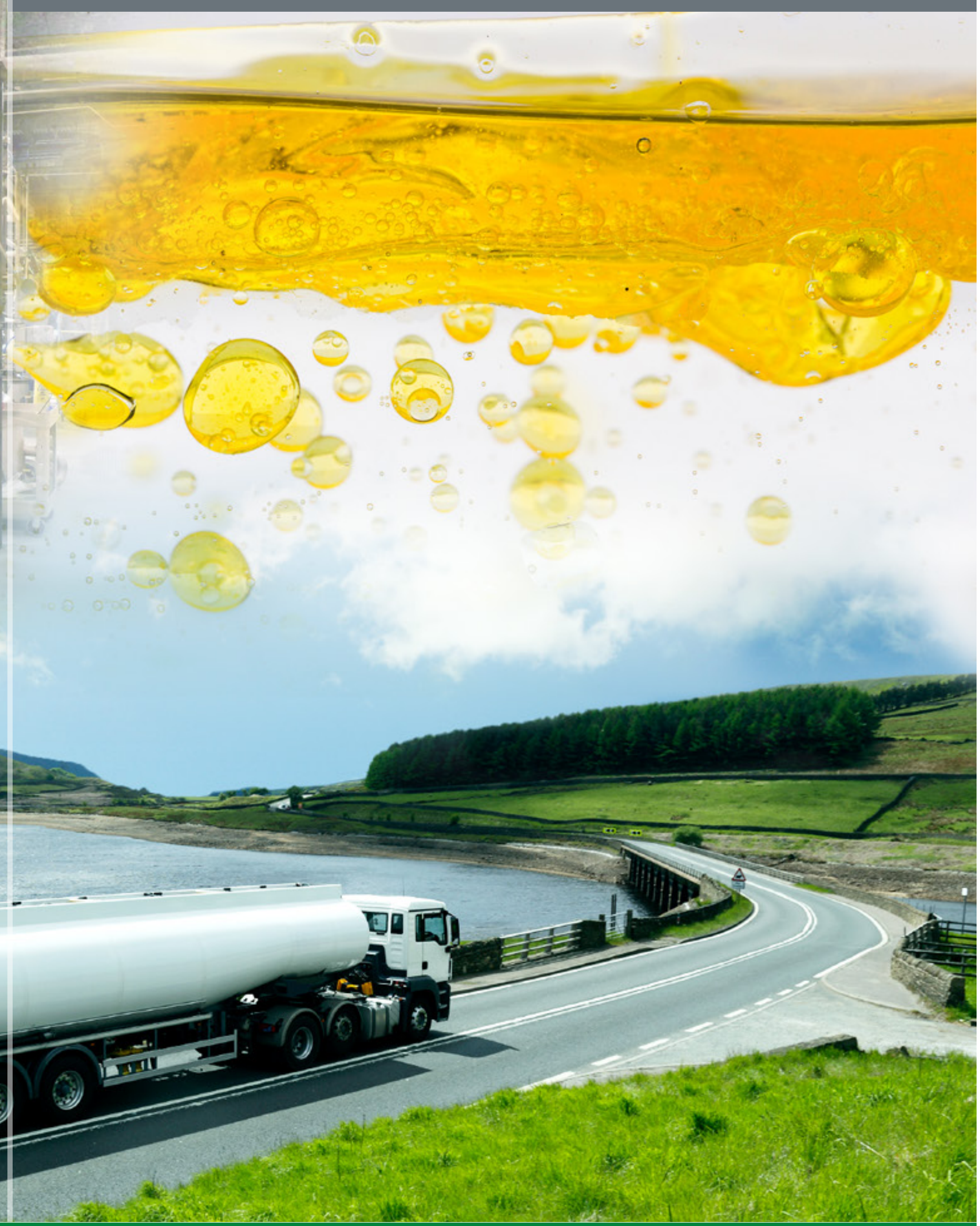
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Process Integration and Carbon Efficiency Workshop Summary Report

Summary Report from the June 11–12, 2014, Workshop in Lakewood, Colorado

December 2014



Workshop and summary report sponsored by the U.S. Department of Energy

Office of Energy Efficiency and Renewable Energy

Bioenergy Technologies Office

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Preface

The U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) invests in a diverse portfolio of energy technologies to achieve a stronger economy, a cleaner environment, and a more secure energy future for America.

This report summarizes the results of a public workshop sponsored by DOE/EERE in Lakewood, Colorado, on June 11–12, 2014. The views and opinions of the workshop attendees, as summarized in this document, do not necessarily reflect those of the United States government or any agency thereof, nor do their employees make any warranty, expressed or implied, or assume any liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe upon privately owned rights.

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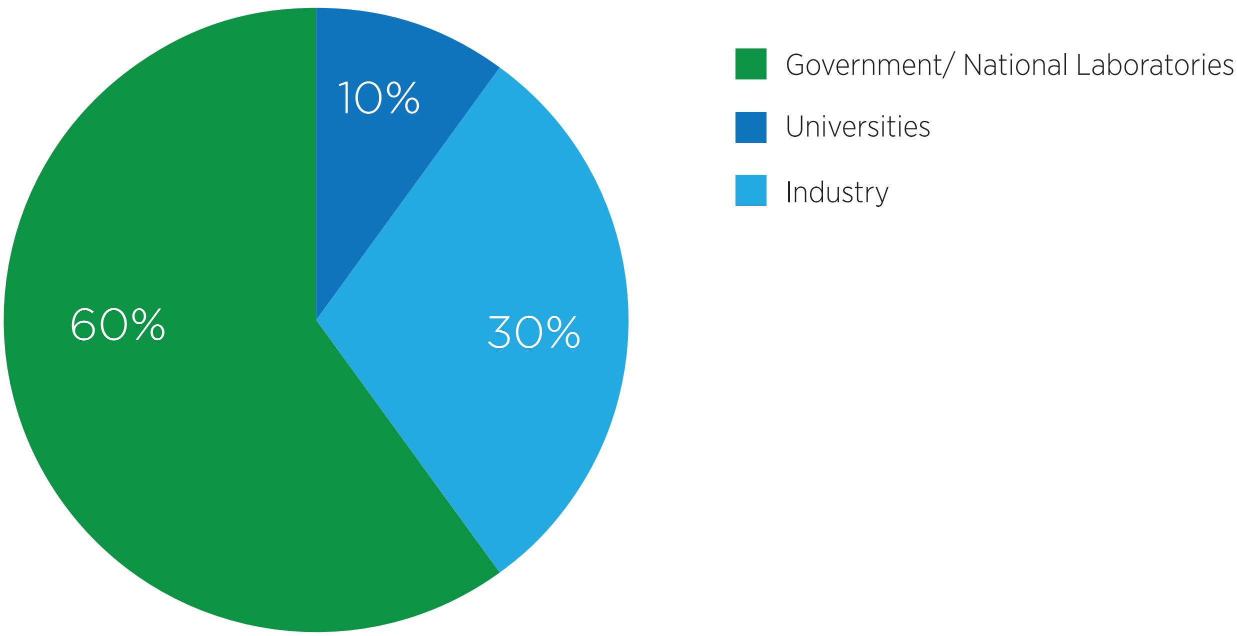
Introduction

On June 11–12, 2014, the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) Bioenergy Technologies Office (BETO) hosted a workshop in Lakewood, Colorado, to discuss research and development (R&D) opportunities related to the efficient production of biofuels and bio-based chemicals from lignocellulosic biomass. The workshop was entitled, the Process Integration and Carbon Efficiency (PRINCE) Workshop. Fifty two stakeholders from industry, national laboratories, and universities provided information on biological and chemical conversion processes, separations technologies, and integration of unit operations (Fig. 1).

Figure 1. Breakdown by sector of session attendees at the PRINCE Workshop: 31 from government/national laboratories, 5 from universities, and 16 from industry.



Purpose of the Workshop

BETO funds research, development, and demonstration of a variety of technologies and processes to support domestic production of biofuels, bio-based chemicals, and biopower. The Office focuses on reducing technology risks from feedstock supply and logistics through biorefinery technologies to enable industry investment in technology deployment at scale. BETO has a successful track record of supporting R&D in technologies for cellulosic ethanol, many of which are currently being deployed and commercialized. As cellulosic ethanol technologies mature, BETO has shifted its R&D support towards advancing technologies that create products that serve as drop-in replacements for fuels (such as gasoline, diesel, and jet fuel), and chemicals that can be substituted for their petroleum counterparts.

Abundant lignocellulosic biomass resources in the United States could potentially supply one billion tons of feedstock, potentially allowing for the production of 70 billion gallons of biofuels by 2022.[1] BETO's current strategic goals include enabling the production of 36 billion gallons per year of sustainable transportation fuels at $3 per gallon gasoline equivalent (gge) by 2022.[2] Despite these resources, many challenges remain for cost-competitive production of fuels and bio-based products, including lack of uniform distribution of biomass and inefficient conversion processes. To address some of these issues, BETO's Conversion Program has set a target of achieving an nth-plant modeled conversion cost of $3.30 gge by 2017 through a biological or chemical conversion pathway. This conversion cost would be achieved by supporting R&D projects that improve efficiency and productivity of a variety of processes. Federally funded R&D efforts spanning more than ten years succeeded in lowering the modeled selling price of cellulosic ethanol production from $9.16 (2007$) to about $2 in 2011.[3] BETO intends to build upon the successes realized from these efforts through the identification of critical R&D barriers that can be overcome to realize cost-competitive biofuels and bio-based products.

Technologies that deconstruct lignocellulosic biomass feedstocks into intermediates, convert those intermediates into fuels or chemicals precursors, upgrade precursors to final products, and separate components into useful streams are a key R&D focus for BETO. Significant resources and investment is needed to overcome R&D barriers and challenges for current and future technologies to become commercially viable. To understand what these challenges are and what is needed to overcome them, BETO held the PRINCE Workshop.

Technologies to produce biofuels and bio-based chemicals from lignocellulosic biomass are still in a relatively nascent stage. The few successful technologies that are moving towards commercial implementation are specific processes tailored for specific end products, such as Myriant's work to develop a process for production of succinic acid and Amyris's development of organisms to produce hydrocarbon fuels. While future methods for producing fuels and chemicals will also be tailored for the various end products, the current lack of established and integrated processes mean that numerous R&D challenges remain.

The pathways of interest (Fig. 2) for this workshop can be generally described as consisting of the deconstruction of biomass feedstocks to usable intermediates that can be upgraded to various fuels and chemicals through biological or chemical means.

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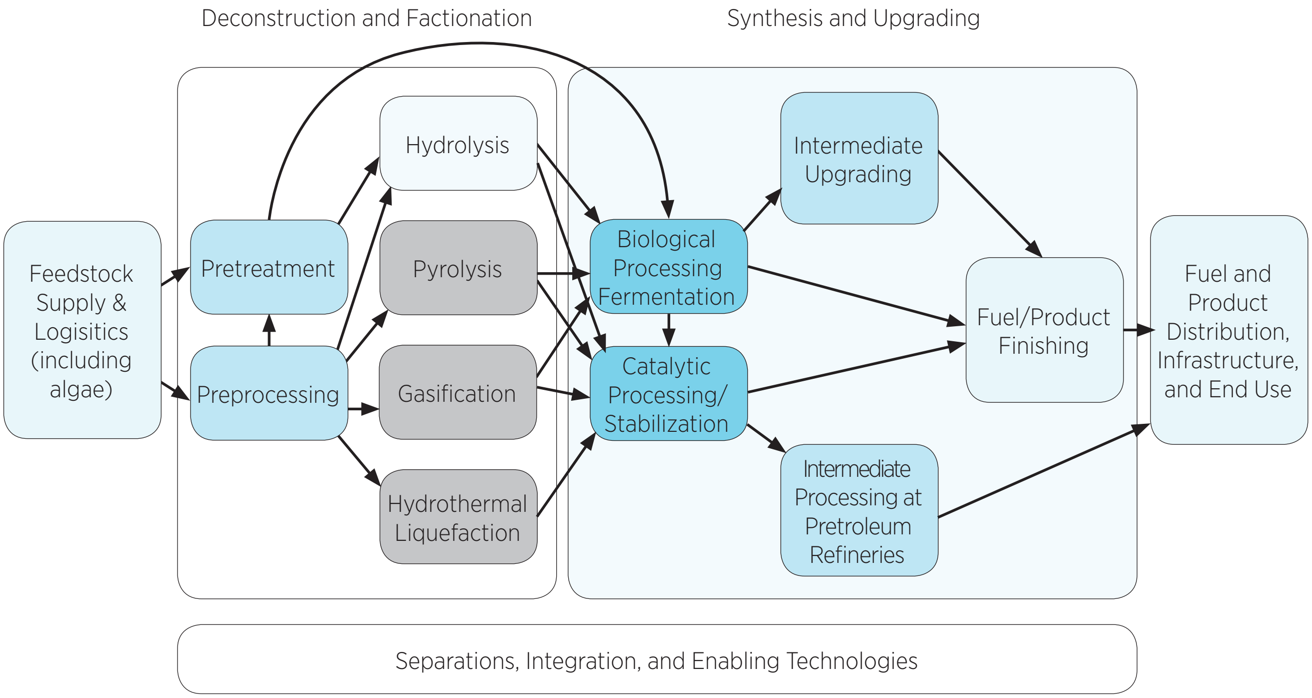
[1] U.S. Department of Energy (2011). U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. DOE/EE-0363. R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN. 227p. http://www1.eere.energy.gov/bioenergy/pdfs/billion_ton_update.pdf.

[2] U.S. Department of Energy (2014). Bioenergy Technologies Office Multi-Year Program Plan, July 2014, DOE/EE-1108, 214 pp., http://www.energy.gov/sites/prod/files/2014/07/f17/mypp_july_2014.pdf.

[3] Ibid.

Figure 2. Conversion Processes. Boxes in gray were not of interest for the purposes of this workshop.



Workshop Concept and Process

The Process Integration and Carbon Efficiency Workshop gathered knowledgeable stakeholders for a day and a half of discussion on the current state of technology and barriers to commercialization of biological and chemical processes that convert lignocellulosic biomass to biofuels and bioproducts. Three speakers from BETO began the workshop by presenting the Office's vision and priorities for executing that vision. Jonathan Male, BETO Director, spoke on the overall purpose for the Office and his vision for the bioeconomy. The Conversion Program Manager, Kevin Craig, gave an overview of the program and the technologies it supports through R&D efforts. Finally, Jim Spaeth, the Demonstration and Deployment Program Manager, spoke about scaling technologies from the lab bench to pilot, demonstration, and commercial scales, including recent projects that are demonstrating technologies with the assistance of DOE funds.

Participants were split into two breakout groups to discuss topics pertaining to the four outlined sessions (Appendix A). The sessions were as follows:

- Challenges and barriers to efficient biological conversion
- Challenges and barriers to efficient chemical conversion
- Challenges and barriers to efficient integration of unit operations
- Challenges and barriers not addressed in previous sessions.

Each breakout session lasted two hours. Participants were asked to brainstorm on specific technologies and challenges. Their answers were gathered using notecards and sorted based upon technology. Each technology was discussed, including identification of current barriers, the R&D needed to overcome those barriers, and the impact if the technology were to succeed. The discussions were captured in spreadsheets and notes, and the input of participants is reflected in the session summaries below. At the end of each day, selected members of the breakout groups reported out highlights of that day's sessions to the group at large.

Breakout Session Summaries

Session 1: Challenges and Barriers to Efficient Biological Conversion

Participants were asked to identify biological conversion technologies, including enzymatic hydrolysis and biological conversion of biomass-derived intermediates to fuels and chemicals,and to discuss R&D barriers that must be overcome for cost-competitive production.

Enzymatic Hydrolysis

Enzymatic hydrolysis was identified as a key technology for deconstruction of biomass to sugars and other intermediates. Previous work to optimize the process for production of ethanol from corn stover could be leveraged for hydrocarbon fuels and products, particularly enzyme development. Hydrolysis will likely be a stand-alone unit operation decoupled from fermentation, unlike processes such as simulanteous saccharification and fermentation or consolidated bioprocessing.

Participants identified some of the current barriers for enzymatic hydrolysis as the following:

- Poor feedstock flexibility for commercialized enzymes
- Lack of enzymes for a broad range of feedstocks and processes
- Poor efficiency of sugar release for some types of biomass-derived sugars
- Cation loads from pH neutralization
- High costs associated with high levels for enzyme loading.

Additionally, there are new enzymes being discovered that may be useful for enzymatic hydrolysis, but the current lack of knowledge about how they can be best applied is a barrier to their use. These newly-discovered enzymes include those that degrade lignin, which could be valuable for recovering biomass carbon for conversion, but little is known about their application for commercial processes.

Participants identified R&D needs to improve enzymatic hydrolysis, including the following:

- Enzymatic hydrolysis that is tailored for the complete end-to-end process being developed, including feedstock(s), pretreatment technology, and downstream processes
- High-throughput discovery of new enzymes and process conditions
- Specifications for hydrolysis inputs and outputs
- Development of modeling tools for enzyme behavior and parameters
- Enzyme recycling
- Utilization of by-products of enzymatic hydrolysis, including unfermentable sugars.

R&D progress for enzymatic hydrolysis was also discussed. Most participants said DOE and others have invested significant money and time to develop enzymes and cocktails. However, participants disagreed as to whether the fundamental knowledge regarding enzymatic mechanisms and process conditions is sufficient; some believe understanding is still lacking, while others believe that a solid basis has been established and that enzymatic hydrolysis processes should not be the target for R&D.

Organism Development

Participants also discussed the use of organisms to convert the intermediates produced during deconstruction into fuels and chemicals. While there are many groups pursuing R&D to develop organisms to convert sugars to fuels and products, the known technologies are relatively new and small in scale.

There are many barriers and challenges to the efficient conversion of intermediates, including the following:

- Poor carbon efficiency through metabolic pathways
- Lack of understanding of an organism's tolerance to inhibitors in the fermentation broth
- Relatively few genetic tools for industrially relevant organisms
- Relatively few industrial strains for fuels and chemicals production
- Method of product extraction (i.e., secretion vs. extraction).

R&D needs were identified for organism development many of which reflect the immaturity of the state of technology. These needs include the following:

- Commercially relevant product rates, titers, and yields that are competitive with products derived from conventional feedstocks
- Organism and product choice that corresponds with recovery methods and other process parameters
- Greater understanding of organisms and their corresponding genetic tools
- Optimization focused on industrially relevant organisms
- Integration and engineering around using hydrolysate or other inputs
- Engineering tolerance to inhibitors
- Specifications for inputs and outputs
- Modeling tools for pathways of interest.

Participants also noted that better understanding of the technical and economic drivers for producing fuels and chemicals was a critical need. Development of techno-economic analyses (TEAs) that can inform and guide process development was identified as a key aspect to address this need. Participants said that organism development for conversion of intermediates is an area in which targeted R&D can have a large impact and would be crucial for reducing the cost of lignocellulosic hydrocarbon fuels and chemicals.

Session 2: Challenges and Barriers to Efficient Chemical Conversion

In the second breakout session, participants were asked to provide input regarding chemical conversion technologies and related challenges and barriers. Technologies that were discussed included chemical pretreatments, catalytic upgrading of intermediates, and lignin utilization.

Chemical Pretreaments

Chemical pretreatments have been studied and used for many years, including for deconstruction of biomass prior to conversion to cellulosic ethanol, and in pulp and paper mills. However, there are many existing R&D barriers, especially for processes to produce hydrocarbon fuels and chemicals.

Current challenges include the following:

- Lack of feedstock flexibility
- Relatively low solids loading for the pretreatment slurries
- Pretreatments that are currently focused on breaking down biomass to five- and six-carbon sugars
- Carry-over of poisons from the pretreatment slurry to downstream unit operations.

Many of these current barriers contribute to sub-optimal carbon release from the biomass and lower the overall carbon efficiency of conversion processes.

The challenges can be overcome through R&D that accomplishes the following:

- Addresses and defines the specifications for feedstock inputs and the products of pretreatment
- Improves the design pretreatment reactors
- Enables recycling of reagents that allow for better pretreatments that are matched with their downstream processes, including use of slip streams
- Increases pretreatment efficiencies through development of integrated processes
- Addresses process conditions by matching temperatures and pressures as well as helps to understand the impacts of impurities.

Catalytic Upgrading of Intermediates

The workshop participants also discussed catalytic upgrading of biomass-derived intermediates. Current barriers to effective catalytic conversion were identified as the following:

- Short catalyst lifetimes
- Lack of multifunctional catalysts
- Current high costs of catalysts
- Lack of engagement with catalyst developers
- Mismatch of the scale of catalyst production with the available amounts of hydrolysate.

Additionally, the use of catalysts is challenging because catalyst fouling or coking can occur due to residual impurities in the input stream. Similar to biological conversion of hydrolysate, catalytic upgrading is a relatively immature technology, and most R&D is performed at lab scale on model intermediates.

To address the challenges with catalytic conversion and improve upon the state of the art, R&D is needed for the following:

- Whole process integration with real hydrolysates
- Better catalyst performance
- Improved understanding of catalyst needs and specifications for hydrolysates
- Fundamental modeling of catalysts on real hydrolysates
- Reactor design, including designs for aqueous solutions and better understanding of mass transfer.

Lignin Utilization

Lignin utilization was discussed as an emerging area of interest. Currently, lignin is often used to provide heat and power for biorefineries. However, heat and power are often the lowest-value use of lignin. Expensive processes for hydrocarbon fuels from biomass could benefit from the additional margin created by using lignin to create higher-value chemicals as side products.

There are many challenges to effective utilization of lignin, the following:

- Depolymerization of lignin polymers to usable monomers or to low-molecular weight products
- Stabilization of monomers to prevent re-polymerization
- Lack of catalysts and processes to upgrade lignin to fuels and chemicals.

Methods to convert the lignin into products are not well developed, if they exist at all. To address these barriers, R&D is needed to achieve the following:

- Develop catalysts
- Better understand the properties of lignin and its degradation products
- Develop enzymes to degrade lignin as an alternative to catalysts
- Perform techno-economic analyses to understand and determine which products can or should be made from lignin.

Session 3: Challenges and Barriers to Efficient Integration of Unit Operations

Integrating unit operations into end-to-end processes is a key challenge for scaling up conversion technologies and ensuring their eventual commercial implementation. Workshop participants identified key barriers to process steps that are necessary for integration, including a variety of separations technologies that could be improved upon. For all the discussed technologies, participants stressed the importance of working with equipment manufacturers to design and engineer equipment that is efficient and can be predictably scaled up or down.

Separations

Solid-liquid separations technologies are often used to remove biomass solids from pretreatment slurries before further conversion to fuels and chemicals. Some of the current R&D barriers include the particle size of the solid materials to be removed, the high-energy requirements for the technologies, the amount of water used during separations, the impact of residual solids on the downstream process, and the efficiency of sugar (or other intermediate) recovery.

These barriers could be addressed by R&D focused on the following:

- Integrating solid-liquid separations with pretreatment processes
- Tailoring technologies to the expected particle sizes
- Defining downstream process requirements to understand separations needs
- Use of real feedstocks and process streams.

Liquid-liquid separations are anticipated to be critical for separating products from aqueous solutions, such as fermentation broths. Currently, liquid-liquid separations are challenging because of the complexity of processes, lack of knowledge of appropriate solvents for separations, formation of emulsions, poor solvent recovery and recyclability, and overall cost for technologies. Participants identified many R&D needs, including the following:

- Use of analytical tools and predictive modeling to understand liquid-liquid properties
- Solvent identification and optimization
- Understanding how to handle impurities and azeotropes
- Utilization of real process streams, and techno-economic analyses and life-cycle assessments (LCAs) for understanding process conditions and drivers.

Membrane separations were discussed as another area with significant R&D barriers. The current challenges associated with membrane separations technologies are lack of materials and understanding of materials properties for separations, poor selectivity, fouling and impact of the various types of molecules present in the mixture, membrane stability, and molecular weight constraints. Membrane separations would be improved by addressing these barriers through the following:

- Development of catalytic membranes
- *In situ* recovery of products such as organic acids or alcohols
- Systems that can be scaled up or down in a predictable manner
- Reactors designed for membrane separations.

Currently, development of separations technologies is limited to model streams; increased use of real intermediate or product streams to design separations streams would add to collective knowledge and accelerate the development of technologies. Additionally, many of the R&D needs for separations technologies, including the predictability of scaling, must be addressed through technology development that includes and engages manufacturers.

Process Integration

Finally, the importance of process integration was discussed. There is limited information available in the public literature about the successes and failures of integration of deconstruction and conversion processes that could inform future work. Other challenges include the presence of inhibitors or fouling agents such as ash, solids handling during processing, the high capital expense of equipment, and a lack of scaled-down and flexible systems for testing. Also, different researchers define an optimized, integrated process differently, and there are no true standards or specifications for understanding the parameters for process integration. R&D that could address these barriers includes the following:

- Outlining and determining specifications for process integration, including the development of online monitoring capabilities and analytical tools
- Development of specifications and standards for various process streams, including hydrolysate, intermediate products, and final products
- Working with manufacturers to use off-the-shelf equipment designed for other processes and development of flexible facilities for process testing.

Session 4: Challenges and Barriers Not Addressed in Previous Sessions

During the fourth breakout session, participants were asked to discuss topics relevant to conversion that may not have been covered during the previous sessions. During this session, a variety of technologies and processes were discussed, including feedstocks development, logistics, and handling, anaerobic digestion, consolidated bioprocessing, fuel testing, and market drivers.

Feedstocks Development, Logistics, and Handling

Feedstocks are an important consideration for any conversion process, as overall conversion efficiency depends on the input materials. Critical barriers for efficient feedstocks utilization include the variability of sugar and lignin composition, ash content, water usage, temporal variability, the stability of the supply chain, impacts of blending feedstocks on downstream processes, storage of feedstocks, and transportation to biorefineries. These challenges may be overcome with R&D to develop the following:

- Better feedstocks through genetic modifications
- Field trials to understand compositional and temporal variability, as well as sustainability requirements
- Better analytical tools to understand impacts on processing
- Appropriate logistics (blending, storage, and transportation) and matching feedstocks to appropriate final products.

Anaerobic Digestion

Anaerobic digestion (AD) is a relatively established process that is emerging as a potential technology for biofuels and bio-based chemicals production. To adapt AD for this purpose, it is important to address R&D challenges such as use of biogas as a feedstock, lack of microbial tolerance to inhibitors, variability in ammonia and nitrogen present in the feedstock, and a lack of empirical data for TEAs and LCAs. R&D directed to addressing these problems would include the following:

- Engineering organisms that can produce molecules other than methane or that can use bio-methane to produce fuels and chemicals
- Understanding the microbial consortia present
- Pretreatment of the feedstock prior to AD
- Performing TEA and LCA of AD processes for fuels and chemicals.

Consolidated Bioprocessing

Consolidated bioprocessing (CBP) is the use of microbes to degrade biomass and convert the intermediates in a "one-pot" system. This is another area of research for which there is a significant lack of understanding of fundamental aspects of the technology. R&D needs include the following:

- Development of organisms and process relevant enzymes and cellulosomes
- Better understanding of process conditions, including temperature and pressure for reactors
- Comparative TEAs and LCAs to understand the benefits and drawbacks of CBP compared to more standard deconstruction and conversion processes.

Market Drivers and Fuel Testing

While conversion processes are crucial to the success of biofuels and bio-based chemicals production and partly determine reinvestment economics for production facilities, market drivers will be the key to commercial acceptability and success. Product acceptability is still relatively poorly understood; while it is assumed that bio-based products can directly replace their petroleum-derived counterparts, understanding of how to ensure direct replacement is still lacking. Currently, fuel testing is based upon specifications determined for petroleum fuels. Bio-derived fuels and chemicals may look chemically identical, but trace impurities from processing will likely be different and have different impacts. R&D is needed to understand specifications for biofuels and bio-based chemicals and the specific impacts of their properties.

The economic drivers of biofuels and bio-based chemicals must also be better understood. Athough there are some TEAs available in the literature, they are focused on specific technologies and are not generalizable to the industry as a whole. More effort to produce TEAs, even for novel and unoptimized processes, would allow for better evaluation of the economics and feasibility of market entry for fuels and chemicals. Also, one of the largest benefits of using biomass as a feedstock to replace petroleum is its inherent renewable nature and potential for a decreased environmental impact. To ensure that bioprocesses are sustainable and offer environmental advantages, LCAs must be performed and potential problems must be addressed as part of the eventual market adoption of biofuels and bio-based chemicals. It is important to marry the LCAs to processes that have the potential to be commercially viable and document the tradeoff between good LCA and commercial viability. Additionally, existing petroleum refineries and chemical production facilities may not be located near sources of biomass. The process supply chains and cost impacts of transporting biomass, intermediates, or products must be understood for commercial viability of improved conversion processes.

It was also noted that additional metrics besides cost of production should be utilitized to present a more complete picture and highlight the difference between commercial viability and technical feasibility. Metrics like energy return on investment and internal rate of return / free cash flow net present value may give a better indication for economic viability of a biorefinery concept that proposes to make both fuels and chemicals at one site. Use of these metrics would also help better answer the question as to how bio-based chemicals can help support and commercialize biofuels, as diversion of feedstock to produce chemicals will impact the cost of biofuels production.

Finally, participants suggested that the nature of biomass be considered in product selection. Biomass-derived intermediates contain far more oxygen than their petroleum counterparts. For biomass to be converted to hydrocarbon fuels, all of this oxygen must be lost during the process, which limits overall mass efficiency to roughly 20–25%. While the workshop focused on increasing carbon efficiency, i.e., the amount of carbon from biomass that is present in the final product, participants noted that overall mass efficiency may be a better target for R&D and ensure that biomass is utilized in the most beneficial manner. Biomass may be better suited for the creation of oxygenated products, such as oxygenated bio-based chemicals, instead of hydrocarbon fuels. Applications that take advantage of this may be more readily commercialized and have greater economic impact.

Appendix A: Agenda

Process Integration and Carbon Efficiency (PRINCE) Workshop Agenda

June 11–12, 2014 | Sheraton Denver West Hotel | Lakewood, Colorado

Day 1: June 11, 2014

Time	Topic
7:30 a.m.	Registration and Coffee
8:30 a.m.	Welcome—Leslie Pezzullo, Technology Manager, Conversion
8:35 a.m.	Introduction to the Bioenergy Technologies Office (BETO) Mission and Expanding the Bioeconomy, Jonathan Male, Director, BETO
9:00 a.m.	Conversion Program Strategic Goals, Kevin Craig, Conversion Program Manager
9:20 a.m.	Scaling Up R&D Breakthroughs and Lessons Learned from Demonstration and Deployment (D&D) Activities—Jim Spaeth, D&D Program Manager
9:35 a.m.	Overview of Workshop and Process
9:45 a.m.	Coffee Break
10:00 a.m.	Breakout Session 1 • Challenges and barriers to efficient biological conversion of lignocellulosic feedstocks, including enzymatic hydrolysis and biological upgrading of intermediates
12:30 p.m.	Lunch
2:00 p.m.	Breakout Session 2 • Challenges and barriers to efficient chemical conversion of lignocellulosic feedstocks, including chemical pretreatments and catalytic upgrading of intermediates
4:30 p.m.	Report-Out from Breakout Sessions
5:00 p.m.	Day 1 Conclusion and Dinner

Day 2: June 12, 2014

Time	Topic
8:00 a.m.	Registration and Coffee
8:30 a.m.	Breakout Session 3 • Challenges and barriers to efficient integration of unit operations, including novel separations technologies and feedstock preprocessing and handling
11:00 a.m.	Coffee Break
11:15 a.m.	Breakout Session 4 • Barriers and challenges not addressed in previous sessions
12:30 p.m.	Report-Out from Breakout Sessions and Wrap-Up
1:00 p.m.	Workshop Concludes

Appendix B: Workshop Questions

Breakout Session Topics

1. Biological methods for conversion of biomass to fuels and products, including enzymatic hydrolysis and upgrading intermediates using biological organisms.
2. Chemical and catalytic methods for conversion of biomass to fuels and products, including chemical pretreatments and catalytic upgrading of intermediates.
3. Separations and integration of unit operations, including novel membrane systems and mitigating inhibitors to downstream processing.
4. Technological challenges not covered by the above sessions and their relationship to the conversion pathways diagram (Fig. 1).

Questions

i. Technology-specific discussions, including successes, challenges and barriers to implementation (50 minutes for discussion)

   1. What can be leveraged from successful and relevant processes? (e.g., conversion of biomass to ethanol)
   2. What are early-stage technologies that may be ready to move into applied R&D projects relevant to the BETO portfolio?
   3. What R&D should be performed to overcome barriers for specific technologies? Suggest target metrics? What is the state of technology today?
   4. What is the level of impact if these barriers are overcome? Please compare impacts for various technologies.

ii. Discussion of critical issues that affect multiple technologies (50 minutes for discussion)

   1. What are common barriers that affect multiple technologies, a single technology that impacts multiple processes, or an entire process?
   2. What is the level of impact if these barriers are overcome? Please compare impacts for various technologies.
   3. What are some R&D needs to overcome these barriers?
   4. Are these technologies part of a critical path for successful implementation?
   5. Are there examples of common barriers that have been addressed to successfully impact an entire process?

Appendix C: Abbreviations and Acronyms

AD	Anaerobic Digestion
BETO	Bioenergy Technologies Office
CBP	Consolidated Bioprocessing
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
GGE	Gallon Gasoline Equivalent
LCA	Life-Cycle Assessment
R&D	Research and Development
TEA	Techno-Economic Analysis

Appendix D: Related Links

Process Integration and Carbon Efficiency Workshop

energy.gov/eere/bioenergy/process-integration-and-carbon-efficiency-workshop

Bioenergy Technologies Office

bioenergy.energy.gov

BETO Multi-Year Program Plan

energy.gov/eere/bioenergy/downloads/bioenergy-technologies-office-multi-year-program-plan-july-2014-update

Office of Energy Efficiency and Renewable Energy

energy.gov/eere/office-energy-efficiency-renewable-energy

U.S. Department of Energy

energy.gov

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