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

# Biorefinery Optimization Workshop Summary Report

Chicago, Illinois

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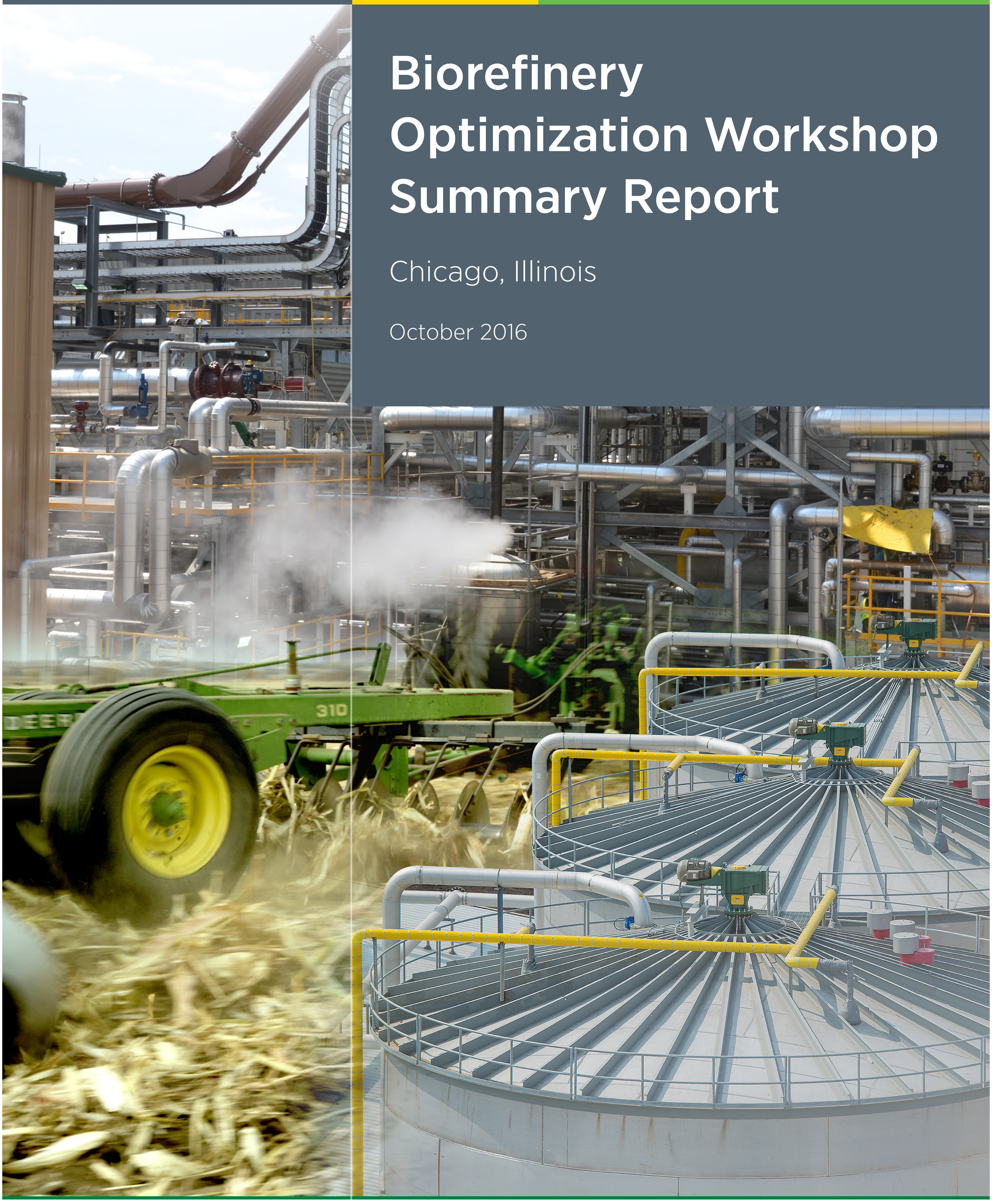

Summary report from the October 5–6, 2016,
Biorefinery Optimization Workshop in Chicago, Illinois

Workshop and summary report sponsored by the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Bioenergy Technologies Office

# Preface

The U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) invests in a diverse portfolio of energy technologies to create and sustain American leadership in the transition to a global clean energy economy. This report summarizes the results of a public workshop sponsored by EERE's Bioenergy Technologies Office in Chicago, Illinois, from October 5–6, 2016.

The views and opinions of the workshop attendees, as summarized in this document, do not necessarily reflect those of the U.S. 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. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. government or any agency thereof.

# Table of Contents

# Executive Summary

The U.S. Department of Energy's (DOE's) Bioenergy Technologies Office (BETO) hosted a workshop on October 5–6, 2016, to gather stakeholder inputs and opinions on integrated biorefinery (IBR) development and optimization issues. More than 100 bioenergy industry stakeholders, representing public and private sector organizations, national laboratories, and academic institutions, participated in the Biorefinery Optimization Workshop.

Workshop topics covered three areas of primary focus, including (1) feedstock and solid materials handling; (2) process scale-up, intensification, and cost reduction; and (3) co-product and waste stream monetization. Day one of the workshop featured a morning plenary session where key industry leaders presented on topics relevant to the IBR technology development community. In the afternoon, three concurrent breakout sessions focused on one of the three workshop topics. On the second day of the workshop, all three breakout sessions addressed the topics of stakeholder collaboration and BETO's role in addressing biorefinery optimization challenges.

The plenary presentation session highlighted common characteristics of successful integrated biorefinery operations. Some of the common characteristics include a clear vision, strong leadership and technology teams, adequate financing, broad professional networks, and an in-depth understanding of feedstock and solid material characterization, execution of proper scale-up approaches and techniques, and forward-looking methods for achieving higher profitability and maintaining competitiveness of the bioenergy industry. These industry perspectives emphasized the importance of stable government policies for the continued growth of the bioenergy industry.

The breakout sessions led groups of 25–35 stakeholders through a series of questions and exercises designed to provoke thoughts and gather information relevant to DOE's mission and needs of the advanced biofuels industry. The breakout sessions utilized ThinkTank web-based collaboration software, which is designed to improve group collaboration, enhance the generation and capture of ideas and solutions, and enable a more inclusive and better-integrated engagement process.

Key findings from the participant breakout sessions covered topics of best practices, lessons learned, challenges, potential solutions, and resources needed to overcome current challenges. Brief summary points during those discussions include the following:

## Feedstock and Solid Materials Handling

Workshop participants identified challenges related to transportation, storage, logistics, and engineering processes within the IBRs. The solutions involved proper feedstock characterization, increasing feedstock density, developing advanced feedstock supply system depots, and designing equipment based upon standardized feedstock material specifications.

## Process Scale-Up, Intensification, and Cost Reduction

Process intensification was noted as a critical area for increasing efficiency and decreasing both upfront investment, as well as operational expenses of IBRs. It is vital for projects to perform robust data collection and ensure proper pilot- and demonstration-scale testing activities before scaling up to the commercial level.

## Co-Product and Waste Stream Monetization

Discussions established that the monetization of the waste, co-product, and by-product streams is often an important aspect of achieving profitability in an IBR. In order to enhance the understanding of these streams and optimize facility operations, stakeholders recommended cross-sector collaboration while protecting intellectual property.

BETO would like to express our thanks to all the participants for their time, efforts, and contributions. The discussions and information provided through the plenary presentations, open forums, and breakout sessions are extremely valuable to BETO's Demonstration and Market Transformation Program, and BETO staff look forward to continued collaborative efforts as this utilize this feedback to inform program strategies moving forward.

# Introduction

The Bioenergy Technologies Office (BETO) is one of ten technology development offices within U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE). BETO supports EERE's efforts to expand the adoption of sustainable, domestically produced transportation and aviation alternatives, as well as to stimulate the growth of a thriving domestic clean energy manufacturing industry.

BETO's mission is to develop and demonstrate transformative and revolutionary sustainable bioenergy technologies for a prosperous nation. This mission is accomplished by transforming renewable, non-food biomass resources into commercially viable, high-performance biofuels, bioproducts, and biopower. Within BETO, the Demonstration and Market Transformation (DMT) Program supports the targeted research, development, and demonstration of technologies that will enable operational integrated biorefineries (IBRs) supported through public and private partnerships.

BETO's programmatic activities align with EERE's vision of a strong and prosperous America powered by clean, affordable, and secure energy. BETO works specifically on the following relevant strategic goals:

1. Accelerate the development and adoption of sustainable transportation technologies
2. Stimulate the growth of a thriving domestic clean energy manufacturing industry
3. Lead efforts to improve federal sustainability and implementation of clean energy solutions.

Since 2006, BETO's DMT Program has supported more than 35 first-of-a-kind IBR projects. These investments toward the development of pilot and demonstration facilities have allowed industry partners to utilize biomass resources as feedstocks for advanced biofuels and bioproducts. These initial projects have made important advances with regard to integrating unit operations, validating techno-economic assessments, and proving a variety of technologies at scales sufficient to enable a path to commercialization.

These projects are located around the country and cover a wide-range of technology pathways for the conversion of renewable feedstocks to biofuels at various technology development stages. BETO uses the following definitions to identify IBR facility scales:

**Pilot Plant:** Integrating unit operations and validating techno-economic assessments.

**Demonstration Plant:** Verifying performance at industrial scale and providing design specifications for a pioneer plant.

**Pioneer Plant:** Proving economic production of technology at commercial scales.

**Commercial Plant:** Full-scale production operations at commercial levels.

Federal support for first-of-a-kind IBRs could significantly reduce the technical and financial risks associated with new technology deployment, thus accelerating the growth of the U.S. bioeconomy. BETO refers to the "bioeconomy" as the industrial transition to sustainably using renewable aquatic and terrestrial biomass resources for the production of fuel, biochemicals, and bioproducts. This extension of the U.S. bioenergy industry has the potential to create employment, bring opportunities to rural regions and communities, reduce costs of consumer goods, reduce transportation sector emissions, and improve energy security. Despite years of continuous investments by BETO to de-risk the first-of-a-kind technologies, there are still technical challenges that need to be addressed in order to achieve reliable and continuous operation of IBRs that effectively complement the petroleum refining and petrochemical industries.

The robust and continuous operation of these IBRs has the potential to increase the volume of renewable, cellulosic fuels being produced. Bioenergy industry growth will serve to help the nation meet its renewable fuel targets. The use of renewable fuels nationally is tracked using a system of renewable identification numbers (RINS) as part of the Renewable Fuel Standard (RFS) Program, which is administered by the Environmental Protection Agency (EPA) pursuant to the Clean Air Act and the Energy Policy Act of 2005. The long-term objective of the RFS Program is to achieve "greater energy independence and security, to increase the production of clean renewable fuels," as per the Energy Independence and Security Act of 2007.[1]

In November 2016, EPA issued the final renewable fuel standards for 2017, setting increased renewable fuel volume requirements for the fourth consecutive year. These standards support the RFS Program by requiring that producers and importers of gasoline and diesel supply incrementally higher levels of cellulosic biofuel, advanced biofuel, and total renewable fuel. The 2017 renewable fuel volume requirements represent a 6% increase over the 2016 levels, requiring the production or import of 311 million gallons of cellulosic biofuel, 2 billion gallons of biomass-based diesel, and 4.28 billion gallons of advanced biofuel with the total volume of renewable fuel being 19.28 billion gallons.[2]

National production of cellulosic ethanol, biofuel, renewable diesel, and renewable natural gas, (referred to as D3 RINs) is currently 2.5 million gallons annually. This represents only a fraction of the full market potential of these fuel products. According to the 2016 Annual Energy Outlook, current U.S. Energy Information Administration fuel consumption projections anticipate that 176.9 billion gallons annually of motor gasoline and diesel will be used nationally in 2030. Renewable fuel substitutes to petroleum-derived jet fuel increase the market potential of biofuels further as the fuel consumption in the aviation sector alone is expected to reach 26.5 billion gallons per year by 2030.

At this time, there are only a few commercial-scale IBRs in the early stages of commissioning, start-up, and/or production. Ongoing obstacles in proving first-of-a-kind technologies have deterred the wider deployment of highly efficient IBR facilities. A variety of technical and non-technical barriers have resulted in schedule delays, increased capital expenditures (CapEx) and operating (OpEx) expenses, and complications with scale-up to subsequent technology development stages. These barriers include, but are not limited to, the following:

- Complexity and variability of non-food feedstocks
- Operational difficulty encountered with handling of solids in the production process
- Recalcitrance of feedstocks to efficiently convert into products
- Inhomogeneity of intermediates causing non-uniform heat and mass transfer during the manufacturing processes
- Complexity of multi-step separation and purification process steps
- Difficulty with monetization of by-products and residual streams
- Difficulty in translating bench-scale and pilot-scale learnings to the next technology development stage, such as demonstration scale, pioneer scale, or commercial plant
- Non-competitive cost of bioproducts due to higher CapEx and OpEx
- Shortage of capital for long-term industrial projects.

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1 Environmental Protection Agency, 40 CFR Part 90, "Renewable Fuel Standard Program: Standards for 2017 and Biomass-Based Diesel Volume for 2018," Fed. Reg. Vol. 81, No. 238 (Dec. 12, 2016), https://www.gpo.gov/fdsys/pkg/FR-2016-12-12/pdf/2016-28879.pdf.

2 "Final Renewable Fuel Standards for 2017, and the Biomass-Based Diesel Volume for 2018," Environmental Protection Agency, Dec. 13, 2016, https://www.epa.gov/renewable-fuel-standard-program/final-renewable-fuel-standards-2017-and-biomass-based-diesel-volume.

# Summary of Plenary Presentations

## Industry Perspectives

The stakeholders and bioenergy expert presentations summarized in this section provide insights to the workshop focus areas and also included valuable perspectives that are relevant to a wider adoption of bioenergy technologies. The perspectives are based on decades of industry experience, and they illustrate real-world considerations that bioenergy companies should account for to succeed in this environment. This section overviews and highlights perspectives of the industry and academic presenters.

Key industry suggestions for the implementation of successful feedstock and solid materials handling indicate the importance and need  for rigorous feedstock characterization, feedstock densification, improved feedstock quality diagnostics, utilization of non-pristine material throughout the pilot- and demonstration-scale testing, equipment design, and the plant scale-up. Proposals suggested utilizing the shared facilities for piloting and demonstration activities. Shared facilities for initial testing would offer a potential to decreased capital investments during the initial stages of the project development.

The success of an IBR is not dependent on any single factor. It is influenced by a number of technical and non-technical factors, some of which are outside of a project's control. It is important to focus on the factors that are within the company control and execute projects in a manner that allows flexibility to address external factors, such as policy uncertainty.

In order to achieve profitability and competitiveness with the traditional fossil fuels industry, the bioenergy industry processes must be accomplished through a series of efficient, compact, robust, and optimized process-intensified solutions. Monetization of the biorefinery co-products and by-products could significantly improve the project revenue, and hence, the profitability.  Addressing unique separation process requirements will enable improved operations.

Many successful projects exhibit similar defining characteristics: they have a clear vision, strong leadership and technology teams, adequate financing, broad professional networks, and an in-depth understanding of feedstock and solid material characterization; they execute proper scale-up approaches and techniques; and they have forward-looking methods for achieving higher profitability and maintaining competitiveness of the bioenergy industry. These factors are accretive to success when supported by steady government policies.

## Feedstock and Materials Handling

### Overview of Key Technical and Economic Challenges

The feedstock and materials handling session explored the movement of feedstocks from the plant gate through to the throat of the reactor. Panelists discussed the key challenges related to the commercialization of feed handling concepts, approaches to overcome these challenges, and DOE's role in supporting industry needs in order to overcome these challenges. Presentations were given by the following speakers:

- Carrie Hartford, Jenike and Johanson
- Kevin Comer, Antares Group
- Erin Webb, Oak Ridge National Laboratory (ORNL)
- Kevin Kenney, Idaho National Laboratory (INL).

## Biomass Material Handling Considerations

**Carrie Hartford**

*Senior Project Engineer, Jenike and Johanson*

Carrie Hartford is a senior project engineer at the Jenike and Johanson office in San Luis Obispo, California. Hartford shared her experience about how to avoid material flow problems in new biorefinery installations—especially design considerations for equipment such as transfer chutes, stockpiles, bins, and feeders.

The Jenike presentation provided an overview of considerations in bulk solids handling and its application to the movement of biomass feedstocks within the feedstock handling unit operation of an IBR. The presentation touched on basic material "flowability" that is a function of both the material, as well as the design of the equipment. Due to the significant variations in feedstock characteristics such as particle shape, particle size, and moisture content, equipment must be properly designed to ensure that the material flows through the system efficiently. Poorly designed equipment can experience difficulty in handling even "easy flowing" material.

The presentation referenced a 1988 study by the RAND Corporation that demonstrated the extent to which solids handling can affect a commercial process plant.[3] This particular study investigated the planned start-up time of 40 commercial process plants in the United States and Canada over six years and demonstrated how the type of feedstock handled by the plant affected each plant's actual start-up time.

As explained in this presentation, the Rand Corporation study results indicated that 80% of the solids processing plants experienced bulk solids handling issues. On average, plants handling raw solids experienced the greatest deviation from the planned start-up time. The average start-up time for these solids handling plants was 18 months, while the average start-up time for plants handling liquids and gasses was three months and the solids handling plants were typically operating at only 40%–50% of design. Rather than attributing the source of reduced operation of these plants to poor process chemistry, the study suggested that "physics and mechanics of processes" were responsible. This was a clear indication that there is a capability gap in bulk solids flow for biorefineries that requires a multi-disciplinary project management team.

The presentation emphasized that the deployment of new technologies utilizing unique materials (as is the case in biorefinery deployment) requires proper project management or companies risk failure. The presentation cited a study of the mining and metals sector that demonstrated how poor knowledge utilization over the past decade has resulted in more than U.S. $20 billion in non-productive capital investments for 43 projects. Ms. Hartford advocated for an approach that identifies gaps in core competencies prior to forming the project management team. By first identifying these gaps, companies can bring in experts with the right experience to tackle project-specific problems before the cost of modification to equipment or processes becomes prohibitive.

After highlighting the difficult nature of bulk solids handling in processes and outlining the effect that poor knowledge utilization can have on overall project success, the presentation focused on the importance of measuring feedstock flow characteristics specifically for the feedstock that will be used in the process.

Ms. Hartford reiterated that feedstock flowability is a function of both characteristics of the feedstock, as well as equipment design. As such, processes must be designed around the actual feedstock that will be used when running commercial operations; otherwise, the plant risks running into a variety of bulk flow issues. For example, issues can arise in gravity flow and funnel flow systems, such as arching, erratic flow, and rat-holing. According to Jenike and Johanson, rat-holing occurs "when discharge takes place only in a flow channel located above the outlet and if the material being handled is cohesive; the material outside of this channel will not flow into it and may cake or agglomerate." Imperfect flow in a system can result in stagnation of material leading to feedstock oxidation, fermentation, runaway bioactive reactions, smoldering, and ignition. A properly designed system experiences "mass

[3] Edward W. Merrow, Kenneth Phillips and Christopher W. Myers, "Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants," Santa Monica, CA: RAND Corporation, 1981, http://www.rand.org/pubs/reports/R2569.html.

flow," in which material moves at a uniform velocity, there is a constant bulk density at the output, and the flow of material is reliable.

It is critical for project developers to perform tests that measure all relevant feedstock properties, set the specifications window for acceptable material, determine the flow pattern, and use proven methodology when designing solids handling systems. This presentation concluded with the request that project developers not neglect feeder equipment design and also that a bulk materials expert be consulted early in the development process.

## Processing and Handling Herbaceous Biomass

**Kevin Comer**
*Associate Principal, Antares Group, Incorporated*

Kevin Comer is a mechanical engineer and associate principal of Antares Group Inc., with more than 20 years of professional engineering and project management experience. Antares is a consulting and professional services firm, founded in 1992 to help accelerate the development and deployment of clean energy technologies for the private and public sector. Since the firm's inception, biomass and bioenergy applications and technologies have been core focus areas of the business. Comer has been a lead member of several multi-year, multi-partner cooperative agreements co-funded by DOE and industry team members, primarily focused on biomass supply chain development, logistics, and pre-processing for herbaceous biomass crops and residues. These projects have included design, permitting, construction, operation, and monitoring of automated biomass processing systems; development and demonstration of new biomass harvest and logistics equipment; and development of supporting information systems and tools. More than a dozen patents have been issued to date related to the work in those projects, with other patent applications in process.

Comer's experience in large-scale biomass handling projects has led to many lessons learned that are applicable for companies who face overcoming issues in scaling up biorefineries. These lessons came through Antares' work on a project at the Ottumwa Generating Station, a coal-fired power plant located in Ottumwa, Iowa. At this location, the company's Chariton Valley Biomass Project sought to demonstrate the co-firing of switchgrass, a renewable locally grown crop. The project sought to provide 2.5%–5% of the plant's heat input from switchgrass, which is the equivalent of around 12.5–25 tons of biomass per hour. This would equate to approximately 200,000 tons of renewable biomass per year. The project included a more than 2,000-hour continuous demonstration of the process.

A project of this scale provides a number of lessons that are transferrable to IBR operations. The presentation stressed the importance of engineering team member roles to the feasibility and design phase of the Chariton Valley project. Mr. Comer emphasized that a focus on the entire supply chain is important for facilitating reliable and efficient at-plant operations. Problems in the supply chain could result in lower-quality biomass, and the plant will likely experience greater processing issues feeding the material into the system. With this point, Comer reinforced the need for a robust feed handling system due to biomass variability and a system that is unable to adapt to different feed characteristics will not operate reliably.

An additional lesson learned from the Chariton Valley project is that plants require a more efficient process for loading and unloading bales of feedstock. Plants need predictive maintenance controls and improved biomass quality diagnostics. A concluding point was that public/private partnerships are needed to establish one or more regularly operating demonstration-scale biomass processing and handling "depots." The presenter stressed the importance of having facilities that can consistently deliver on-spec material despite a variable input.

An automated front-end system is critical to large-scale feed handling systems because it allows for multiple processes, such as de-stringing and de-stacking, that occurs during conveying biomass to the grinders. Antares is currently working with Kelderman Manufacturing to develop automated square bale infeed to feedstock grinders. Comer concluded by remarking on the ability of a market with little "pull" to hinder innovation investments and stated that investments from DOE will continue to be very important in overcoming barriers along the supply chain.

## Addressing Fire Risk in Biomass Handling

**Dr. Erin Webb, Ph.D., P.E.**
*Agricultural Engineer, Oak Ridge National Laboratory*

Dr. Erin Webb is a senior research engineer who works in the Environmental Sciences Division at Oak Ridge National Laboratory (ORNL). She leads projects related to simulation and analysis of systems to deliver biomass as a feedstock for production of fuels, products, and power. She is also a joint associate professor in the University of Tennessee Department of Biosystems Engineering and Soil Science.

Webb presented information on a DOE-funded project titled "Fire Standards, Codes, and Prevention in IBRs." The presentation explained that the fire risk associated with the large volume of flammable material present in the storage and handling of biomass is becoming a barrier to the growth of the biofuels industry. As an example, it cited a recent fire at the commercial-scale DuPont biorefinery in Nevada, Iowa. Through this project's effort, ORNL hopes to understand fire behavior in biomass feedstocks, improve codes and standards to better reflect the current knowledge of biomass fire risk and industry practices, and develop training and reference materials for design professionals, codes and standards developers, and code officials.

ORNL and DOE aim to engage industry in proactively addressing fire risks without adversely affecting the design and construction of future plants. The science-based codes and standards developed during the course of ORNL's project will ultimately work to reduce fire risk to company personnel, communities surrounding the plant, and the facilities themselves.

To date, ORNL's work has resulted in seven successful International Codes Council (ICC) fire and building change proposals. The founded change proposals have clarified that biomass is not a hazardous material. They provided clarification that allows for large stacks and piles of biomass, added bioenergy feedstocks to the wood chapters, and added biomass categories for sprinkler design. ORNL recently performed testing on the impact of feedstock type and bale shape on fire growth. The testing was performed indoors and on feedstock bales provided by Abengoa, Genera Energy, and POET-DSM.

Rectangular bales of corn stover, rectangular bales of switchgrass, and round bales of corn stover all underwent controlled burns. Observations from the testing were that switchgrass burns much better than corn stover, and the lower density of round bales enabled the fire more access to atmospheric oxygen. Additionally, once the net wrap of the round bales was burned away, the outer layer of biomass fell away, exposing fresh material to the fire. The testing showed that the researchers initially underestimated the sprinkler discharge rate for switchgrass and stover. Based on the results of these tests, ORNL plans to submit a proposal to add corn stover and switchgrass bales to the sprinkler discharge standard.

Webb explained that an ICC technical publication for biomass is currently in development, with a targeted release date of December 2017. This new report will include updates to the 2018 ICC codes and an overview of biomass supply systems and conversion and will provide a review of International Fire Code, International Mechanical Code, and International Building Code application. It will assist others in selecting and applying applicable codes for a proposed facility, as well as highlight other applicable codes such as fire or mechanical codes. The publication will provide additional resources to aid engineers or code officials when dealing with biomass facilities.

The next steps for ORNL fire codes and standards work is to assess fire risk in outdoor biomass storage. ORNL is working with the industry to plan outdoor fire stack experiments for spring 2017. The tests will focus on stack separation distance, testing water additives and fire retardants, and observing smoke generation and dispersion.

## Industrial Feed Handling of Lignocellulosic Feedstocks

**Kevin Kenney**

*Director, Biomass Feedstock National User Facility, Idaho National Laboratory*

Kevin Kenney is the Director of the Biomass Feedstock National User Facility at Idaho National Laboratory (INL). In this role, he is focused on establishing partnerships between the national laboratories and industry through deployment of INL capabilities in biomass characterization, logistics, and preprocessing. These partnerships work to address technology and risk barriers of bioenergy industry partners.

Kenney also provided an overview of the INL Process Demonstration Unit and explained how this resource can help overcome the issues that feed handling has presented to IBR start-ups. The facility consists of a fully integrated pilot plant with commercial-scale processing equipment located in a 27,000-$ft^3$ high-bay at INL's Energy Systems Laboratory. The facility, which has a production capacity of up to five tons per hour, provides extensive material characterization and data collection, and its modular design allows for the insertion of third-party equipment.[4] To date, more than 1,000 tons of feedstock has been processed to a variety of conversion pathway specifications. The facility assists in toll processing, piloting, toll characterization, third party testing and validation, process development, and pre-processing research and development (R&D).

Notable issues to the slow start-up of IBRs, as attributed by the industry, include grinding, conveyance, feeding, and solids handling up to and through the conversion process. The characteristics associated with these feed-handling problems are moisture, particle size, and foreign material. Feedstock moisture content affects grinder throughput, particle size variability, and results in inconsistent mass and heat transfer when it fluctuates. Foreign materials such as soil, sand, dirt, and metal can result in equipment plugging and deterioration.

Particle size distribution also has a significant role in feed handling issues, as both large and small particles can cause problems. Large particles in a system, also known as "pin chips," can cause plugging in bins and augers and often do not cook fully in the reactor unit operation. This incomplete cooking can result in plugging of downstream equipment and microbial contamination. Small particles tend to have high ash content and can plug weep holes in digesters.

Kenney emphasized that the feed-handling issues that current facilities face are not new. Similar to Hartford, he cited the RAND Corporation study from the 1980s that shows that plants processing bulk solids typically operate at less than 50% of design capacity the first year of operation. A 2005 paper by Timothy Bell stated that problems generally relate to an inadequate understanding of the behavior of particle systems. Particle systems are inherently difficult to work with because they are more likely to be inconsistent. Kenney stated that particles can almost be described as a fourth state of matter due to the interactions within a particle system. Particles can develop cohesive strength and transfer stresses like a solid, they can retain air and take on fluid-like properties, and they are often compressible and elastic like a gas. And while gases and liquids do not grow, agglomerate, aggregate, or suffer attrition, particles do.

Pilot-plant testing is recommended due to the effect that feed handling issues can have on the overall start-up and operation of large-scale biorefineries. The RAND Corporation study makes a strong case for large-scale, fully integrated pilot plants using identical process components as the final plant, but in practice this is seldom done.[5] Kenney identified three reasons for not piloting: (1) ignorance of the issues and potential problems, (2) pride (plant engineers do not believe that they need to pilot), and (3) haste to get the final product to market. Ultimately, failure to build and operate integrated pilot plants will cost companies time and money.

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4 "What is the BFNUF?" *Impact Bioenergy!* Issue 1, 2015, Idaho National Laboratory, https://bioenergy.inl.gov/Fact%20Sheet/Impact%20Biomass%20Feedstock%20National%20User%20Facility.pdf.

5 Edward W. Merrow, Kenneth Phillips, and Christopher W. Myers. "Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants. Santa Monica, CA: RAND Corporation, 1981, http://www.rand.org/pubs/reports/R2569.html.

Kenney further stated that the desire to duplicate an existing plant is common but quite risky due to the high number of requirements for success. As stated previously, the highly variable nature of feedstock means that a process that works for one plant may not necessarily work for a duplicate plant running different feed. Additionally, knowledge must be shared freely among plant operators, and products must be consistent in quality and chemical nature in order for duplicate plants to succeed. Kenney noted that it is probable that the design of the first plant was not optimal to begin with and also that an appropriate scale for solids handling at pre-commercial scale was 5 tons per hour (or approximately 120 tons per day).

A current issue facing IBRs is that a significant reliance has been put on vendor testing of equipment. Facilities are likely to be operating at a larger scale and for a greater length of time than is typically tested by equipment vendors. It is also unlikely that the test material will behave similarly to the actual material used in production since pristine feedstock is typically utilized. These vendors lack the characterization facilities and technical skills to determine how variable materials relate. Additionally, the pressure to sell their product forces optimism about the capabilities of their equipment.

Kenney stated that while vendor tests are better than no testing at all, the scale-up of vendor data is often required and further piloting is necessary in order for the equipment to be incorporated with the conversion technology. Kenney concluded by suggesting that projects should focus more intently on preprocessing to produce a more consistent and reliable feedstock, which could, in turn, reduce feed handling issues and lower costs.

## Process Scale-Up, Intensification, and Cost Reduction

This session explored efforts to successfully achieve project scale-up from pilot-scale to commercialization for the production of biofuels and biochemicals. Panelists discussed the factors essential to reducing operational risks and the key technical milestones that projects must overcome along the way. The session also considered the innovative opportunities that exist for improving in-plant IBR operational methods, implementing processes intensification, and reducing CapEx and OpEx. Presentations were given by the following speakers:

- Steven Mirshak, DuPont
- Robert Graham, Ensyn Technologies
- Martin Linck, Gas Technology Institute
- Theodora Retsina, American Process, Inc.

### Cellulosic Ethanol Collaborative Improvement Opportunities

**Steve Mirshak**
*Director of Cellulosic Ethanol, DuPont*

Steve Mirshak is the director of cellulosic ethanol at DuPont's Industrial Biosciences unit. He is a Board member of the BioEnergy Science Center at ORNL. He is the commercialization lead for DuPont's cellulosic ethanol technology in Nevada, Iowa. He introduced the idea that cellulosic ethanol investments benefit from global trends, such as growing carbon emissions regulations and the growing price of carbon. Mr. Mirshak stated that cellulosic ethanol's ability to "de-carbonize" transportation is beneficial to the cellulosic ethanol industry. It was further stated that cellulosic ethanol enables growth in rural counties as farmers are incorporating crop residue collection in row-crop and sugarcane production farming, and cellulosic ethanol production provides the opportunity to grow energy crops on marginal and low-producing land.

DuPont's cellulosic ethanol facility is located in Nevada, Iowa, and has a nameplate capacity of 30 million gallons of cellulosic ethanol per year. DuPont's facility aims to produce cellulosic ethanol for use as transportation fuel and renewable solid fuel that can be utilized in an on site boiler or sold to off site power generators.

Mr. Mirshak discussed the topic of collaboration and the barriers to collaboration that are faced due to industry competition and the desire to protect intellectual property (IP). He stated that while IP and trade secrets limit collaboration in some areas, the greatest opportunities for collaboration exist in step-changes downstream that are related to co-products and the "existing boiler" consumption of fuel. In addition, the presentation also covered the opportunities for collaboration related to feedstocks. Feedstock sustainability, transport and storage, and fire prevention and management are all areas that could benefit from collaborative efforts. On this front, DuPont is already collaborating with the Natural Resources Conservation Service to sustainably harvest corn stover within the Nevada region.

The presentation concluded with an overview of process and engineering areas ripe for innovation. Mr. Mirshak mentioned the opportunity for improvements in feedstock preprocessing such as improvements in screening for metal and rock, soil removal technology, material conveying, and the pre-separation of lignin. He also suggested that companies better apply the key learnings of the ethanol industry in the design and construction of new plants. By scaling up and improving the technologies associated with cellulosic ethanol production, he said that cost and capital will be driven down.

## Scale-Up and Optimization

**Robert Graham, Ph.D.**
*Chairman, Ensyn Technologies*

Dr. Robert Graham, chairman and founder of Ensyn Corporation, has led the company's commercial and technical development since 1984. He is an authority in his field of applied engineering and, specifically, on the topic of producing value-added products via fast thermal conversion of carbon-based feedstocks.

Dr. Graham provided background on the conversion of forest biomass to high-value products, called rapid thermal processing. This process is a non-catalytic, thermal process that is mechanically similar to fluid catalytic cracking. Rapid thermal processing converts biomass feedstock into liquid biocrude oil, which can be used as a chemical feedstock, a renewable fuel oil, and refinery feedstock. Ensyn has a growth story that dates back to 1984 and continues today. The company is focused on scale-up and crossing the "valley of death" to commercialization.

From 1984 to through the early 1990's Ensyn scaled up from a proof of concept to a 2-ton-per-day operation that was centered on producing food ingredients and industrial heating oils. Then, in the 1990s, the company scaled to 30 tons per day and continued producing food ingredients and heating fuels. From 1998 to 2005, the company moved from pilot scale to 300 barrels per day of residual heavy oil upgrading, which is approximately equivalent to 70 dry tons of biomass per day. Operated since 2006, the Renfrew Merchant plant is the company's first dedicated fuels facility. The plant has a nameplate capacity of 70 tons per day and up to three million gallons of fuel per year.

Ensyn is working to expand projects for fuels and increase biocrude production capacity. The company has collaborated with Honeywell/UOP under performance guarantees and has two designs for facilities, one at 5 million gallons per year and the second at 20 million gallons per year. Ensyn is currently partnered with Arbec Forest Products Inc. and Groupe Rémabec on the Corte Nord project, which is a 10-million-gallon-per-year facility in Port Cartier, Quebec, that is targeting the heating oil market. The project is fully financed with a CapEx of approximately $103 million Canadian dollars and is under construction with commissioning scheduled for the end of 2017. This is the first of several projects under a joint development agreement, and the product will be sold to heating and refining customers in the northeastern United States.

Dr. Graham explained that the current regulatory framework supports expansion. Under the Renewable Fuel Standard, Ensyn has three possible product pathways: (1) fuel oil (D-7), (2) renewable gasoline (D-3), and (3) cellulosic diesel (D-7). The company's renewable gasoline and diesel have Part 79 approval from EPA, and the Renfrew facility has Part 80 registration. The company has Low Carbon Fuel Standard (LCFS) approval within California. Ensyn has been generating renewable energy certificate-eligible fuel oil since August 2015, and the company is in the final stages of agreeing on measurement protocols with the regulatory authorities.

## Effective Deployment of Bioenergy Technologies

*Process Demonstration and Process Intensification*

**Martin Linck, Ph.D.**
*Senior Engineer, Gas Technology Institute*

Dr. Linck is a leading researcher in the field of biomass catalysis and hydropyrolysis. His present focus is the production of renewable liquid fuels and chemicals. From co-inventing to commercial pilot plant demonstration, he helped pioneer a process that efficiently converts biomass to drop-in fuels. This approach to biomass conversion incorporates process intensification and has been licensed to CRI Catalyst Company (Shell Group) as the $IH^2$® process.

Dr. Linck opened his presentation by stating that in the last decade, the energy landscape, the economic landscape, and the policy landscape have all changed dramatically. With this, he posed the question, "How do we translate research investments into solutions to today's energy problems at a pace that keeps them relevant and ultimately profitable?" Dr. Linck suggested that technical innovation is not sufficient, as some very good technical concepts never get developed, and some developed technologies never make it to the market. He used the example of shale gas, the "Shale Gas Revolution," that was supported by sustained research investments.

Advanced biofuels pose a worthy challenge to produce drop-in transportation fuels less than $3.00 per gasoline gallon equivalent to be profitable. Oil refineries must be gigantic in order to produce affordable fuel, due to the complexity of the operations and equipment. To compete with oil refineries, biorefineries must be simple and incorporate more processing steps into each piece of hardware. By simplifying the biomass conversion, CapEx and OpEx are both reduced, which provides the opportunity for IBRs to pull on the market. Currently, the number of companies that can finance a $1–$10 billion dollar plant is small. Companies must reduce the overall CapEx and OpEx through compact, smaller-scale, process-intensified solutions.

Dr. Linck explained that the $IH^2$ process for drop-in advanced biofuels allows multiple process steps to occur simultaneously in the hydropyrolysis reactor and that it comprises of a smaller number of steps that build of competencies in key technical areas. He stated that the technology is easily deployed at a 500–2,000 dry tons per day scale and that it is flexible in being able to work with many feedstocks, including wood, agricultural residues, algae, and sorted waste. The result is a drop-in fuel at $1.50 to $3.50 per gallon dependent on feedstock and scale. Shell India Markets Pvt Ltd. plans to build and operate a 5-metric-ton-per-day $IH^2$ demonstration plant in Bangalore, India. Dr. Linck stressed the importance of long-term support for shared test facilities. He explained that these facilities accelerate and economize development programs while giving component providers a place to prove their equipment. Shared facilities also enable technology developers to focus on their part of an integrated process and allow standardized performance validation in an industrial setting. At these facilities, scientists, engineers, operators, and technicians all work together to overcome problems.

## Sugar is the New Crude

**Theodora Retsina, Ph.D.**
*CEO, American Process, Inc.*

Dr. Theodora Retsina is the chief executive officer of American Process (API), LLC. In 1995, she founded American Process—a company that focuses on value enhancement of the forest products industries through process integration and biorefinery technology applications. API also provides engineering, procurement, and construction management and process integration consulting services.

Since 2005, API has been developing technologies for the conversion of biomass into cellulosic sugars to be used in the production of biofuels and biobased chemicals. API owns two patented cellulosic technologies, Green Power+® and AVAP®. From 2006 to 2010, the company worked on the development of technologies at the lab and pilot scale before moving forward with additional piloting and demonstration work from 2011 to 2014. In 2015, API was operating on a commercial scale.

Dr. Retsina proposed that "Sugar is the New Crude," in that through fermentation, sugars can be used to produce the same chemicals and products as can be made from fossil crude. API's technologies include AVAP, BioPlus, and GreenPower+ Technologies. AVAP focuses on bulk sugar production and conversion and currently operates at technology readiness level (TRL) 7.[6]

AVAP produces clean sugars from cellulose and hemicellulose and can be used with feedstocks such as softwoods, hardwoods, and agricultural residues. The BioPlus technology focuses on nanocellulose production from biomass. The GreenPower+ technology currently is at TRL 8 and works to produce alcohols through a simple process. It is a low-cost alternative for both bolt-on or standalone production. Dr. Restina explained that API has a patent portfolio of 37 granted patents and approximately 250 patents pending.

The API biorefinery in Alpena, Michigan, is a demonstration-scale facility that produced the first commercial woody cellulosic ethanol in the United States in November 2013. API underwent commercial integrated demonstration of their three technologies from 2010 to 2016 at the biorefinery in Thomaston, Georgia. That facility has operated for more than 8,000 hours at 3.5 dry tons per day. The plant provided the company its first sale of commercial nanocellulose in April 2015. The company's next step is to scale to 50 dry-tons per day.

Dr. Retsina explained what she sees as the necessary ingredients for a successful project. These ingredients include the right vision, steady governmental policies, a strong technology team, proper financing, strong leadership, networking, and an in-depth understanding of biomass. She provided a detailed analysis of the different pitfalls that companies face while scaling up from prefeasibility to commercialization and continued operations. Dr. Retsina also suggested that retrofitting an existing industrial facility and obtaining a high process yield are good ways to reduce CapEx, while energy integration and co-products can reduce OpEx.

## Co-Product and Waste Stream Monetization

The session explored the co-product and waste streams that exist in IBR operations but that are considered to be of little economic significance at this point in time. Panelists discussed methods for fully utilizing the potential of waste streams to produce higher-value products and how to separate valuable components. The session also addressed the challenges and barriers that have been obstacles to moving these products to market. Presentations were given by the following speakers:

- Bob Rozmiarek, Virent, Inc.
- Mark Warner, Warner Advisors, LLC
- Laurel Harmon, LanzaTech
- Amit Naskar, ORNL.

### Policy Drivers for Low-Carbon Fuel Value

**Robert Rozmiarek**

*Director, Program Management and Business Analysis, Virent Fuels and Chemicals*

Mr. Rozmiarek joined Virent in 2005 and has maintained various roles, from managing process engineering activities to leading business analysis in areas such as techno-economics, life-cycle assessments, feedstock evaluations, and market analysis. The value proposition at Virent is the production of biobased products to direct replacement chemicals and fuels. Mr. Rozmiarek explained that currently there aren't incentives in place for renewable chemicals and products, so drivers like consumer demand and sustainability concerns are playing a role in creating a market. He gave a background on the ways that the Renewable Fuel Standard 2 and LCFS provide additional value for low-carbon fuels but do not directly provide value to chemicals and products.

[6] Refer to Appendix E for as summary of BETO technology readiness level definitions.

Virent was founded in 2002 and is headquartered in Madison, Wisconsin. The company is leading the catalytic route to replace crude oil with "drop-in" biobased chemicals and fuels. Drop-in chemical and fuel products refer to those that can be used in existing engines, equipment, and processes. Various U.S. government programs have invested approximately $150 million in Virent to develop its innovative technology. The company has an extensive IP portfolio, as well as strategic partnerships in place with many industry leaders. The company is looking at petroleum replacement, including replacement of petroleum naphtha reformate by its High Aromatic BioFormate. The BioForming process can be adjusted to focus on the production of aromatics for chemicals production or on total liquid fuel for gasoline fuel production. When operating in the mode to produce chemicals and fuels, the mixed xylenes (C8 cut) can be removed for production of bio-paraxylene.

These petroleum-replacing technologies provide broad product optionality and demonstrate areas in which Virent products have real-world applicability. The company's gasoline was blended by Shell and used by the Scuderia Ferrari race team. On the chemicals side, the company worked with The Coca-Cola Company to produce the world's first PET (polyethylene terephthalate) plastic bottle made entirely from plants. Virent also worked to produce the world's first polyester shirt made entirely from plants. Product testing of traditional jet fuel with bio-based Synthetic Aromatic Kerosene is currently under review.

Mr. Rozmiarek's presentation included an overview of the Bio-Aromatics Consortium. This consortium includes Tesoro, Coca-Cola, and Toray. In this group, there is a shared risk and shared benefit approach to the scale-up and commercialization of sugars to bio-reformate platform. Consortium members include technology partner with experience in scaling up new technologies and manufacturers/end-users in fuels and polyester value chain. Each consortium member provides unique contributions and will receive specific benefits. The members will work collectively to determine the appropriate scale-up strategy for the first sugars plant, which could include expansion or enhancement of the Eagle demonstration plant. The sugars plant will focus on a configuration to produce fuels and bio-mixed xylenes for chemicals.

Mr. Rozmiarek posed a list of considerations for companies working with co-products:

- What is the scale of the market?
- What drives the underlying economics of the co-product?
- What are the product specifications?
- What additional cost is incurred to meet product specifications?
- Does the supply chain exist for the co-product?
- How complex is the supply chain?
- Does the co-product require additional product development?
- Are there market drivers for the biobased material?
- Are there government incentives?

### Co-Product Opportunities: Lesson Learned

**Mark Warner, P.E.**

*Founder, Warner Advisors, LLC*

Mark Warner is the founder of Warner Advisors LLC; a consulting firm formed to assist advanced biotechnology clients to take their process from concept to commercial operation, including acting in interim engineering leadership roles. He provided an example from his personal experience that demonstrated the way in which an inability to consistently sell co-products can result in the failure of a facility or process. Mark began his career at Monsanto making vanillin from waste lignin. The plant was very profitable and ran from 1946 to 1991 and was producing about 30% of the world's vanillin in the late 1980's. Eventually, a process to synthesize vanillin from crude oil was developed and the plant was unable to sustain profitability, which led to close out.

Mr. Warner has also worked with a number of projects, such as the Imperium Renewables biodiesel facility in Grays Harbor. He also has worked with companies such as Sapphire Energy, INEOS, and Solazyme Industrials. All of these projects have generated co-product streams that need to be handled. Given that all biobased processes produce co-products, it is up to the company to determine what options to take when marketing them. Using the example of residual biomass or cells from a process, Mr. Warner stated that there is a hierarchy of options that a company has when dealing with this co-product. However, as the price that the company can sell the co-product for increases, so does the difficulty in taking that option. Using biomass for its nutritional value (either for human or animal consumption) can generate the greatest revenue, but it is also the most difficult way to deal with the co-product steam. On the other end of the hierarchy is landfill disposal, which is the easiest method for dealing with the co-product, but it also generates zero revenue.

With this hierarchy of options in mind, he provided a list of considerations when dealing with co-products. He asked

- *Is the co-product better than what is out there now? Even if the answer is yes, the fact that it is new may extend timelines for adoption, especially if target customer is making an iso-certified product.*
- *Is there a consistent specification that can be met? Whether you are selling as a high value product or sending to a break-even energy recovery option, you will need to be able to consistently meet a specification for the option to remain.*

Co-product revenue can often be in the range of 10% of the revenue from the primary product, which is significant. This additional revenue stream can often determine whether a project finances break-even or become profitable, which means that project development teams must develop a plan for co-products while the process is being developed.

Projects must take into account the fact that up-stream processes have a direct impact on the quality of the co-product. How the biomass or organism is deconstructed and the degree of deconstruction impacts the recovery and quality of the co-product. There are three levels of deconstruction, and each affects the biomass/organism and the co-product differently:

1. **Excretion:** Product is taken without disrupting biomass/organism.
2. **Light Deconstruction:** Biomass or organism is partially deconstructed and product extracted; large pieces of organism/biomass survive and product is reasonably accessible.
3. **Robust Deconstruction:** Biomass or organism is completely deconstructed to allow access to product; resulting matrix can be complex to recover the target product and de-value the co-product.

Mr. Warner concluded his presentation by reviewing the lessons he has learned from his experience in utilizing co-product streams. He reinforced that the higher the degree of deconstruction of biomass, the lower the co-product will likely be on the hierarchy of options. He stressed that the projects need to take co-products into account when developing processes and that they need to always consider the impact of processing changes on the co-product. Projects keep multiple outlets open for co-products, including landfill disposal, in the event that markets shift and the co-product cannot be sold. Due to market shifts, it would be beneficial to consider base-loading key options, rather than trying to shift between "all or nothing" options, as interest may be lost from some areas and gained in others.

## Monetizing Biorefinery Residue and Waste Streams

**Laurel Harmon, Ph.D.**

*Vice President, Government Relations, LanzaTech*

Dr. Harmon is Vice President, Government Relations, at LanzaTech, where she provides policy direction on international legislative and regulatory matters and develops collaborative research and demonstration projects. LanzaTech is the global leader in gas fermentation technology and is commercializing novel and economic routes to low-carbon fuels and high-value chemicals from waste carbon streams, including industrial waste gases.

The presentation opened with the concept that carbon can be new or it can be recycled. Recycling carbon means that no new carbon is being pulled out of the ground in the form of natural gas, coal, or crude oil to add to current greenhouse gas emission levels. The company's technology recycles carbon through gas fermentation technology that converts carbon-rich gases to fuels and chemicals. LanzaTech feeds carbon rich gases that are captured from steel production facilities and manufacturing plants to microbes, which then produce ethanol. Dr. Harmon stated that because these gases are the sole source of energy in the process, the technology operates outside of the food vs. fuel argument.

LanzaTech has achieved and exceeded performance milestones of more than 1,000 hours of operation at a 100,000-gallons-per-year scale at its a BaoSteel Steel Mill in Shanghai, China. LanzaTech technology is currently operated overseas in China at four demonstration facilities, operated by Baosteel, ChinaSteel, Shougang Group, and WBT. These four facilities have more than 50,000 combined hours on stream and have performed multiple runs that exceeded 2,000 hours of continuous operation.

Dr. Harmon explained that LanzaTech ethanol can be upgraded into jet fuel through a four-step process. Ethanol is first dehydrated to remove any water and to produce ethylene gas. The ethylene hydrocarbons are combined through oligomerization to produce hydrocarbon chains that are longer and suitable for jet fuel. From there, the stream undergoes hydrogenation and fractionation to produce synthetic paraffinic kerosene jet fuel. Current combined ethanol production capacity is 42.7 million gallons per year.

Dr. Harmon also provided the differentiation between co-products, by-products, residues, and wastes. Biorefinery co-products and by-products can be produced either intentionally or unintentionally, but they have a high relative value. Biorefinery residues and wastes, however, are an unavoidable outcome of the facilities primary processes and have a low relative value. These residue streams can be found as gases, liquids, or solids. Residues include fermentation carbon dioxide ($CO_2$), off gases, wastewater, waste sludge, lignin, algae cell matter, and bacterial biomass residues. To maximize the contribution of these residues, it is critical to recycle the carbon found within them into liquid fuels and chemicals. She argued that because there were methods for producing energy without carbon, such as wind, solar, and water, it is important to prioritize carbon re-use for fuels and chemicals.

There are different considerations for plants when working to monetize residues and waste streams. It is important to balance the potential returns from monetized residues and waste streams against the additional CapEx and OpEx requires processing these residues. Companies were advised to avoid disposal and compliance costs if these waste streams can be utilized as co-products. Additionally, companies were told align their production capacity for co-products with the potential market while keeping in mind infrastructure, logistics, and regulatory approvals for the end use of the product.

## Biomass Waste Stream to Carbon and Composite Product Case Studies

**Amit Naskar, Ph.D.**

*Senior Research Staff Member, ORNL*

Dr. Amit Naskar is a senior research staff member and leader of the Carbon and Composites Group in the ORNL Materials Science and Technology Division. His areas of research include carbon fiber, alternative carbon precursors, sustainable polymeric materials, and composites. He is the lead inventor of ORNL's technology for conversion of polyolefin fibers into carbon fibers, sustainable polymer formulations for composites, and tailored carbon morphology for energy storage applications. The vision at ORNL is to produce and commercialize biomass waste stream-derived industrial-grade fibers, polymers, and their composites, with properties rivaling current petroleum-derived alternatives.

ORNL has demonstrated hardwood lignin web production and reported semi-production-scale web forming with softwood lignin at a quantity of about 20 pounds. ORNL is currently undergoing process modification and subsequent stabilization/carbonization protocols are being developed. Work is being done on the oxidation of lignin fibers to produce infusible carbon precursor filaments. Dr. Naskar explained that when melt-spun lignin fibers undergo tension while being oxidized, the result is more uniform fibers that are less porous.

Dr. Naskar posed the question of whether biobased chemicals can compete with petroleum chemicals and whether they are better options than their petroleum-based counterparts. One immediate functional application of lignin-derived carbon fibers is as a drop-in replacement for commercial isotropic pitch carbon fiber used in the company's commercial Graphite Rigid Insulation product. Another application is in high-performance battery electrodes and super capacitors with potential for low cost. Currently, both biorefineries and the pulp and paper industries are interested in developing new revenue streams to help drive down their overall costs. Automotive part manufacturers are also interested in accessing thermally and hydrolytically stable, ultra-violet resistant, and renewable polymers. The lack of an integrated knowledgebase and interdisciplinary approach are barriers to the development of such an economically advantageous technology. This knowledgebase and interdisciplinary approach would involve

- Lignin feedstock consistency
- The ability to control lignin self-assembly in soft polymer matrix
- Understanding chemistry and physics of lignin-derived polymers
- Process engineering
- Melt-rheology of the polymeric products.

There are additional scenarios for which biobased chemicals can be substituted for petroleum-based products. Currently, high-performance lignin-extended thermoplastics are being developed as a substitute for acrylonitrile butadiene styrene, and the product has exhibited outstanding performance. The tensile stress-strain profile of lignin-polymer materials synthesized by state-of-the-art method compared to newly developed method shows dramatic improvement in modulus, a yield stress, and extraordinary toughness mainly due to ORNL's ability to tailor the phase morphology and interface of the multiphase material.[7]

Dr. Naskar concluded by stating that ORNL's results demonstrate feasibility of functional carbon manufacturing from lignin, and synthesizing a new class of elastomers, prepared by nanoscale dispersion of lignin (a renewable phenolic oligomer) in rubber.

[7] Tran, C. D., J. Chen, J. K. Keum, and A. K. Naskar, "Recyclable Polymers: A New Class of Renewable Thermoplastics with Extraordinary Performance from Nanostructured Lignin-Elastomers," Adv. Funct. Mater 26, no. 16 (2016): 2585–2769. doi: 10.1002/adfm.201670101.

# Summary of Breakout Sessions

The purpose of the Biorefinery Optimization Workshop breakout sessions was to advance the understanding of the current capabilities, barriers, and opportunities for IBRs working to produce biofuels, biochemicals, and bioproducts. Discussions were broken into three focus areas: (1) feedstock and materials handling; (2) process scale-up, intensification, and cost reduction; and (3) co-product and waste stream monetization. Participants selected one of the three topic areas. The three concurrent breakout groups occupied separate rooms and comprised of 15–35 participants each. Each group was composed of participants from a range of disciplines and affiliations.

On the first day of the workshop, each breakout session group answered a set of questions specific to their particular focus area. On the second day, each group answered the same set of questions related to opportunities for stakeholder collaboration and input for DOE as the agency works to support biorefinery optimization. The input provided on day one is summarized in this section of the report and the day two responses are summarized in the "Day Two Summary" section of this report.

## Breakout Session One: Feedstock and Materials Handling

Overview of Key Technical and Economic Challenges

The goal of the feedstock and materials handling breakout session was to identify challenges around the handling of solid feedstock materials, develop potential solutions to these challenges, and determine resources needed to resolve the biomass feedstock handling challenges.

Participants in the breakout session included individuals from the agricultural and forestry companies, engineering firms, biorefinery developers, and researchers from universities, as well as national laboratories. The facilitated discussion began with a poll to determine the feedstocks with which each individual had familiarity. The results illustrated a breadth of experience from the agricultural feedstocks (i.e., corn, wheat, and soybeans), forestry feedstocks (i.e., pine, willow, and poplar), energy crops (i.e., miscanthus, switchgrass, and energy cane), agricultural crop residues (i.e., straws from wheat and barley, and corn stover), wet harvest (i.e., forage sorghum), and waste feedstocks (i.e., municipal solid waste ([MSW]), construction and debris waste, and food processing waste). The participating organizations had also considered working with waste such as manure, biogas, right-of-way grasses, microalgae, and forestry slash.

The depth of the group's experience includes all areas of the feedstock supply chain, including growing crops, harvesting from farms and forests, pre-processing, processing, evaluating the equipment for each process, supply chain sustainability, and analyzing both logistics and the costs of feedstock delivered to the facility gate. The group demonstrated experience in these areas on both a domestic and international scale.

### Feedstock Characterization and Particle Size Management

The participants were asked to describe how feedstocks differ with respect to handling and processing. Primary areas of contrast included the type of material (grains versus fibrous feedstocks such as corn stover, grasses, and woody biomass) and the type of processing equipment (rotary shears compared to grinding equipment).

The primary factor determining ease of handling is feedstock density. The main indication for ease of processing is flowability—the ability of a material to move throughout funnels—is dependent upon the moisture content, particle size, and particle variability of the material. Participants expressed that specialized mass flow bins must be designed based on the specific material flowability.

The group provided comments regarding feedstock handling topics, including particle size management, methodologies for sampling and monitoring materials, and opportunities to repurpose equipment. Feedstock specifications were provided with respect to several biorefinery processes, including conveyors, screens, discharge systems, pre-treatment, biochemical and thermochemical conversion, solids and liquid separation, waste removal, and storage. Input regarding the particle size management included the benefits and challenges, which are outlined in table 1.

### Table 1: Benefits and Challenges of Particle Size Management

| Particle Size Management | |
|---|---|
| **Challenges** | **Benefits** |
| • Potentially increased processing costs with additional processing steps (e.g., screening)<br>• Increased mechanical energy demand in the front end<br>  ◦ Adds cost spent on energy, as well as loss of energy that could be used elsewhere<br>• Decreased overall yields due to discarding reject material (e.g., oversized and undersized material)<br>  ◦ A co-product outlet or customer must be found for any unused material<br>• Loss of feedstock through screening increases feedstock needs and impacts sustainability<br>• Need to change traditional harvesting and collection technique. | • Reduction in energy use due to increased uniformity and improved heat and mass transfer in drying and in conversion processes due to narrow particle size distribution<br>• Improved operability and conversion yield with consistent particle size<br>• Increased solids loading yielding increased ethanol titer yielding improved capital productivity<br>• Improved rheology<br>• Improved conveying system design<br>• Reduced self-segregation<br>• More consistent feedstock. |

Particle size distribution is an important attribute that will affect feedstock handling strategies, as well as the type and design of equipment used to move and process the biomass into feedstock. Factors affecting particle size variability include the following: type of biomass, moisture content, level of degradation, processing equipment, and the screening or sieving technology used. The preferred particle size distribution may not vary between feedstocks, but rather, may depend upon the conversion process. Particle size distribution is feedstock specific and can be indicated with easily determined metrics such as the minimum, maximum, mean, and mode. These particle size metrics must be accompanied with the aspect ratio and moisture content at the time of measurement. The particle size can change as the material deconstructs, and there can be a large difference between fresh and aged materials.

Determining the required particle size and distribution can be the most difficult task in the design of conversion equipment. Session attendees proposed developing strategies and equipment to produce a less-variable particle size distribution as a way to ease the difficulty of conversion equipment design in relationship to particle size distribution. A solution for herbaceous biomass is a proper balance of first- and second-stage grinding, referred to as fractional milling. This process includes grinding or chopping, screening, and then further grinding over-sized materials. Other steps that support the success of the particle size distribution process include minimizing fine particles during harvesting and minimizing feedstock degradation during storage. An additional challenge with herbaceous biomass is the variety of tissue types such as leaves, cobs, flowers, and pith, which mill differently and cause variability.

The group discussed the equipment that can be utilized to achieve the desired particle size distribution. Grinders require that the feedstock is absent of any rock contamination. It was suggested the hammer mill is a robust deconstruction tool, but it creates a wide particle size distribution depending on screens used in the mill. Other tools include the knife mill, rotary shear (which is comparable to a paper shredder), screens, sieves, and air separators.

### Challenges in Biorefinery Operation and Biomass Feedstock Handling

Despite numerous large investments in the feedstock handling area, challenges persist. In this session, workshop participants discussed those challenges in-depth, shared lessons learned, and offered solutions. Challenges regarding IBR operation and biomass feedstock handling were addressed separately. Participants applied their experience to provide insight on each phase of feedstock and materials handling, including operational aspects and engineering design processes.

The following is a summary of participant discussions about challenges, solutions, lessons learned, and recommendations, as well as the tools and resources that will be needed.

#### *Operational Challenges*

The operational challenges in the IBR can be described broadly in the following categories:

- Flowability
- Variability
    - *Moisture*
    - *Size*
    - *Density*
    - *Ash content*
    - *Composition*
- Bale handling
- Safety and fire risk
- Grinding high moisture feedstock
- Sustainable feedstock availability
- Equipment up-time
- Feedstock contamination
- Solids and liquids separation
- Lack of equipment performance data
- Defining feedstock specifications
- High maintenance cost.

Participants discussed the challenges based on the highest priority. Challenges were ranked by using equal weighting of two factors: (1) severity of negative impact and (2) likelihood of being overcome within the near term. The resulting top five IBR operational challenges were flowability, moisture variability, equipment uptime, lack of equipment performance data, and defining feedstock specifications. Figure 1 displays the top five operational challenges in IBRs, as voted by the participants. Flowability was the greatest operational challenge by a large margin, while the votes on other four challenges were more broadly dispersed.

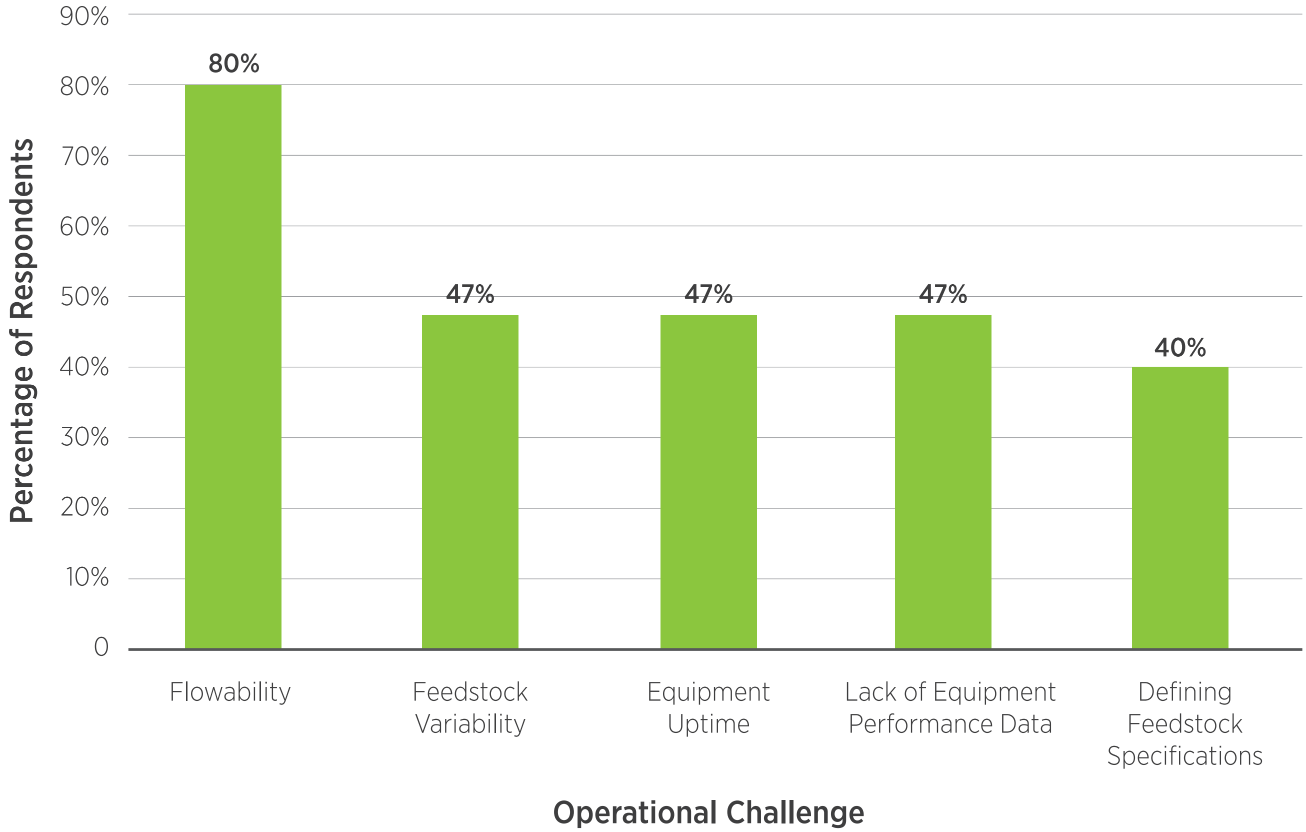


**Figure 1: Top Five Integrated Biorefinery Operational Challenges**

The flowability can be vastly improved, especially for woody biomass, with rotary shear comminution and screening. The equipment uptime can be significantly impacted by the removal of feedstock contaminants such as rocks and soil.

### *Potential Solutions to Operational Challenges*

The top operational challenge, flowability, is an often an overlooked concept that could benefit from establishing an improved definition. The identification of critical flowability measurements is a first step in achieving improved biomass particle flowability. The metrics that can be used include the following:

- Density (or permeability for fine wood powders)
- Particle size distribution
- Moisture content
- Angle of repose
- Shear stress
- Bridging tendency
- Cohesive strength (rat holing/arching potential)
- Friction of equipment surfaces.

Table 2 lists potential solutions to flowability issues, as well as the other top priority operational challenges.

**Table 2: Top Priority Operational Challenges in IBRs and Their Potential Solutions**

| Challenge | Potential Solutions |
|---|---|
| Flowability | **Feedstock Solutions**<br>• Increase feedstock densification.<br>• Ensure consistent feedstock particle size and low moisture.<br>• Study particle engineering approaches to reduce size of biomass material.<br>• Measure flowability for all potential feedstocks, including various moisture contents, particle size, and distribution.<br>• Establish feedstock specifications and enforce them with testing and rejection.<br>**Biorefinery Design and Equipment Solutions**<br>• Design for wider, more realistic range of feedstock specifications.<br>• Develop methodology and physical models to quantify and test flowability.<br>• Perform flow testing for materials from each feedstock supplier for input to design.<br>• Provide sufficient budget and set aside time early on to measure flowability.<br>• Use material flow properties to identify correct bin shape and bin geometry, including discharge opening, wall angles, and wall material.<br>• Add a feeder that withdraws evenly from the bin's full discharge outlet to get mass flow.<br>• Collect data on how material properties translate to equipment design and performance.<br>• Employ modern tools, such as computational fluid dynamics for multi-phase flows, especially discrete particle method (referred to as Fluent) to guide the designs of related equipment. |
| Feedstock Variability | • Utilize basic metrics, including density, moisture control, and particle size distribution.<br>• Incorporate advanced metrics, including angle of repose, compressibility, and shear stress.<br>• Require more data sharing.<br>• Perform additional characterization of incoming non-pristine feedstocks to understand ash, moisture, soil, and rock content.<br>• Assist IBRs with better understanding of their feedstock specifications.<br>• Develop a biomass payment contract that rewards good behavior and attention to the details put forth in the material specification.<br>• Help biomass suppliers understand the constraints of the conversion technology.<br>• Design handling equipment to handle a wider range of feedstock specifications.<br>• Design on non-pristine material (will ensure proper design).<br>• Design preprocessing equipment within the constraints of feasible feedstock quality.<br>• Pre-processing should be designed for as wide of a specification as possible. |

| Challenge | Potential Solutions |
|---|---|
| **Moisture Content** | • Develop integrated control systems.<br>• Utilize driers and re-wetting during processing.<br>• Harvest at optimal time.<br>• Develop storage practices to minimize moisture gain or re-normalize to a standard condition.<br>• Utilize in-line moisture measurement.<br>• Define physical property characteristics as a function of moisture control.<br>• Variability of particle moisture content compared to bulk moisture variability.<br>• Determine acceptable ranges for moisture control for different unit operations and equipment.<br>• Ensure adherence to harvest specifications, management practices, and quality assurance by suppliers.<br>• Utilize improved storage practices.<br>• Design equipment capacities and process lines to handle higher-moisture biomass. |
| **Equipment Uptime** | • Improve the incoming feedstock quality.<br>• Reduce the presence of foreign matter, such as rocks and metal, using in-line methods.<br>• Constant equipment operation.<br>• Introduce improved control systems.<br>• Develop preprocessing unit operation studies to determine optimal equipment performance settings. |
| **Lack of Equipment Performance Data** | • Collect continuous operational data at the pilot scale, rather than data from unit operations run on batch mode.<br>• Share collected data along with lessons learned.<br>• Develop at least one demonstration-scale facility where common equipment problems can be investigated and solved.<br>• Develop a commercial-scale test facility to allow for extended-duration equipment testing.<br>• Test equipment in commercial-scale facilities for extended periods of time, rather than introducing new designs at commercial scale.<br>• Collaborate with equipment manufacturers to improve the performance requirements to meet various feedstock properties. |
| **Defining Feedstock Specifications** | • Reconcile definitions of terminology used between feedstock suppliers and the biorefinery operators.<br>• Minimize the supply of biomass material that does not meet biorefinery specifications.<br>• Recognize the tradeoff between quality and affordability in biomass feedstock. |

### *Solids Handling Challenges*

The solids handling challenges were categorized into two categories: (1) those related to transportation, storage, and logistics to the plant infeed, and (2) those related to preprocessing between the infeed and the reactor throat, such as flowability, milling, screening, and drying.

Transportation, storage, and logistics challenges include (1) high cost of moving biomass material from the farm gate or forest landing to a biorefinery; (2) dry matter loss, material degradation resulting in composition changes, moisture management, fire during storage; and (3) inefficient logistics systems involving too much loading and unloading that results in material loss. Several solutions were proposed, as listed below.

Challenges related to pre-processing involve some overlap with the IBR operational challenges identified in the previous section. In the context of solids handling, challenges related to moving biomass materials through the refining processes were discussed at length. Flowability was again the common theme, with an emphasis that flowability depends on the equipment with which the material is handled, as well as the state of the material.

The various process methods related to milling, or grinding, could benefit from the improvements from an engineering design perspective. Screening, or removal of off-specification material, is important to equipment reliability and can be an engineering challenge. Screens that are too small have a risk of becoming blocked or plugged, while screens that are too large increase the likelihood of feedstock contamination and greater particle size variability. Variability in moisture content is also an issue that can be defined as an engineering challenge, specifically involving moisture management and drying equipment.

### *Solids Handling Potential Solutions: Transportation, Storage, Logistics*

The participants focused on identifying the potential solutions for solids handling in three primary stages of the supply chain, including transportation, storage, and logistics. These are summarized in Table 3.

**Table 3: Top Priority Solids Handling Challenges in IBRs and Their Potential Solutions**

| Challenge | Potential Solutions |
|---|---|
| **Transportation** | • Increase feedstock densification.<br>• Utilize intermodal shipping.<br>• Support innovation and demonstration through a platform for ongoing testing and development.<br>• Engineer trailers to handle bales to max weight of 25 tons per load.<br>• Build plants as close to the source as possible. |
| **Storage** | • Condition material periodically to avoid compression.<br>• Develop intermodal storage on site at biorefineries.<br>• Develop improved storage depots, which allow for moisture drainage and rain protection.<br>• Improve understanding and implementation of lightning protection systems.<br>• Utilize of ensiled storage of chopped and screened biomass.<br>• Utilize pelletizing and store pellets in silos.<br>• Utilize of a day bin between the process-metering bins and reclaim system.<br>• Include a day bin for 4–5 hours of storage with the goal of keeping operation moving when the reclaim is delayed. A day bin can smooth the flow of material into process by buffering fluctuations from the reclaim system.<br>• Introduce of preprocessing at harvest.<br>• Manage biomass feedstock piles with a first-in, first-out manner. This helps to avoid fires and material degradation.<br>• Consider a below ground reclaim system. |

| Challenge | Potential Solutions |
|---|---|
| **Logistics** | • Develop depots as intermediaries between feedstock suppliers and biorefineries.<br>• Minimize and/or streamline the number of transfers to avoid material losses.<br>• Minimize the movement of feedstock in the bale form.<br>• Develop an intermodal logistics system.<br>• Aggregate the biomass early in the supply chain into large loads and handle in large bulk loads until delivered to plant infeed line.<br>• Continue government and academic testing and development; the current market will not sustain innovation investments by private sector alone. |

*Solids Handling Potential Solutions: Engineering Processes*

This group described flowability as the greatest engineering process challenge that can be solved by achieving preferred particle size distribution. This goal requires the use of optimizing engineering processes related to equipment design, feedstock parameters, pre-processing, milling, screening, and drying. An extensive discussion identified many proposed solutions as listed in Table 4.

### Table 4: Top Priority Engineering Process Challenges and Their Potential Solutions

| Challenge | Potential Solutions |
|---|---|
| **Equipment Design** | • Design bins and feeders using material flow properties to avoid hang-ups and inconsistent discharge.<br>• Design equipment, including conveyors, bins, and handling systems, based on the flowability of the feedstock material and according to the likely range of material specifications encountered.<br>• Design transfer chutes to control the flow of material to minimize attrition and dusting.<br>• Conduct pilot testing over a range of feedstock properties so that a robust handling system can be developed. |
| **Feedstock Parameters** | • Establish realistic feedstock parameters and variability from suppliers and use data with generous safety factor in equipment design.<br>• Develop technology to increase feedstock densification.<br>• Manage feedstock moisture to reduce power requirements.<br>• Conduct pilot testing to assess feedstock flowability. |
| **Pre-processing** | • Develop feedstock specific flow additives.<br>  ◦ The effectiveness of flow additives can be tested on a bench scale before implementing the additive system.<br>• Develop preprocessing solutions that can be tuned to a flowability specification.<br>• Consider using a purge column to dry and store material in one step. |
| **Milling** | • Develop better understanding of different types of mills and impact on flowability (e.g., hammer vs. knife mill).<br>• Develop and/or select proper feeder for size reduction equipment. |

| Challenge | Potential Solutions |
|---|---|
| Screening | • Develop simple hand-held or in-line analysis devices for moisture, metals, etc.<br>• Implement air classification.<br>• Collect test data to compare different screening options.<br>• Improve understanding of separation technologies, such as magnets, required to clean feedstock and reduce size variability.<br>• Utilize float tanks or other wet separation methods for high-moisture downstream processes.<br>• Conduct more testing and demonstration to enable control of process parameters to produce a more desirable product specification with variable incoming material.<br>• Establish a regularly operating testing and demonstration facility at a commercially relevant scale. |
| Drying | • Improve dryer control systems.<br>• Design dryers specifically for new and emerging biomass materials.<br>• Design storage systems that promote moisture loss in storage.<br>• Improve understanding about moisture movement within biomass feedstock particles.<br>• Develop improved understanding about moisture movement through a pile of biomass feedstock (baled or loose).<br>• Develop pre-staging storage areas allowing bales to equilibrate to target moisture level prior to entering processing.<br>• Develop size reduction equipment that can process high-moisture biomass. |

### Resources Needed to Resolve Feedstock Handling Challenges

Addressing feedstock handling challenges will require advancements in research, development, and demonstration, as well as increased funding allocations and a prioritization of workforce development. Participants expressed that feedstock characterization should be more extensive and that there is a role for an institute to conduct research on characterizing the rheological properties of different biomass feedstocks, including the size, shape, moisture content, etc.

Regarding project development, participants suggested that a more interdisciplinary approach be utilized. Recommendations were made for federal agencies to provide more funding for project scaling from prototype to pilot scale and that a longer period of time be spent at pilot scale, including the continuous collection of equipment reliability data that captures the impact of feedstock variability.

Regarding workforce development, the group proposed that training and knowledge transfer be provided for operations of harvesting equipment, and biomass processing facilities, especially in rural areas.

### Future Directions

There are a number of milestones for the biorefining industry to reach in the near, mid, and long term. In order to stay on target for an increasingly stable and profitable supply chain, these goals encompass categories such as development of pilot and demonstration facilities, equipment improvements, modeling tools, storage programs, feedstock quality measurements and standards, logistics, education, financing, policy, and sharing lessons learned. Suggestions for future directions in each of these areas are listed in Table 5.

### Table 5: Future Directions in Feedstocks and Solids Handling

<table>
<tr><th colspan="2">Future Directions in Feedstocks and Solids Handling</th></tr>
<tr><td>Near-Term</td><td>
Pilot and demonstration facilities
<ul>
<li>Develop an operational pilot-scale (or larger-scale) facility that is open to biorefinery project planners to test processes and equipment that has been developed for the industry. This facility would be especially valuable with flexibility to various feedstocks (wet, dry, baled, loose, etc.). This facility could be a public/private collaboration, perhaps modeled after the National Corn-to-Ethanol Research Center or the Biomass Feedstock National User Facility at INL, with relevant partners including DOE and the national laboratories.</li>
<li>Provide funding for new technologies to complete the proof of concept developmental stage. The incubator program at DOE provides valuable assistance and could be expanded to accomplish this goal. On example of a concept that needs funding to be proven is intermodal feedstock logistics systems.</li>
</ul>
Equipment Improvements
<ul>
<li>Support increased development of the Biomass Feedstock National User Facility at INL.</li>
<li>Implement equipment and process improvements that are applicable to conventional feedstock supply systems and advanced feedstock supply systems. The proposed role for private sector was technical innovation and early technology stage development for the public sector.</li>
</ul>
Modeling Tools
<ul>
<li>Develop modeling or simulation tools to allow for some directional guidance on materials and unit operations. The national laboratories and universities were proposed as the appropriate entities to lead the development of these tools.</li>
<li>Expand database for physical and mechanical properties of various feedstock. INL is developing a Biomass Feedstock Library for DOE; this database is mostly computational to date. The tool would benefit from improved navigation and increased industry input and utilization.</li>
</ul>
Storage Programs
<ul>
<li>Create a program to develop harvesting and storage systems that can economically address some of the barriers to better-quality, more-reproducible feedstock (e.g., a first-pass harvest and baling system that is economic for growers). Partners in this effort could be DOE, USDA, and INL.</li>
<li>Develop an improved storage method to reduce dry matter loss and fire risk.</li>
</ul>
Feedstock Quality Measurements and Standards
<ul>
<li>Achieve commercially available advanced quality analysis sensors.</li>
<li>Expand the knowledge base on the subjects of solids handling within publications and journal articles.</li>
<li>Enhance bulk solids measurement techniques, such as shear strength, for elastic, granular materials (e.g., biomass, MSW).</li>
<li>Establish standards for biomass sampling for newly developed instrumentation.</li>
<li>Develop standards on sampling protocols and biomass feedstock quality specifications.</li>
</ul>
</td></tr>
</table>

| Future Directions in Feedstocks and Solids Handling | |
|---|---|
| **Near-Term (continued)** | **Policy**<br>• Enact policy that allows for the generation of RINs using timber on federal lands. This political barrier will require the engagement of congressional leadership.<br><br>**Lessons Learned**<br>• Publish lessons learned (to date) from key DOE commercial and demonstration projects. Including case study chapters for key projects that are related to biofuels production, biomass processing, etc. Some industry (not-government assisted) projects could also be included to fill in certain gaps. The National Renewable Energy Laboratory (NREL) published a similar report years ago about biomass heat and power plants. Denmark has also published a similar report for their straw plants and markets (combined-heat-to-power, pellets, biofuels, electrical power, etc.). |
| **Mid-Term** | **Collaboration and Knowledge Dissemination**<br>• Facilitate sharing of equipment best practices using resources such as the cooperative demonstration facility, online network, monthly e-newsletter, and annual conference.<br>• Facilitate more diverse collaborative efforts.<br><br>**Equipment Improvements**<br>• Develop advanced, low-cost materials to build equipment which will increase machine and plant uptime.<br>• Achieve advanced harvesting systems to improve feedstock cost and quality. This collaborative effort could be led by USDA and DOE, along with industrial partners.<br><br>**Modeling Tools**<br>• Develop predictive modeling software based on pilot, demonstration, and commercial testing and data for the various commonly used feedstocks after the specific case properties are determined and input. This tool could be seen as a material handling analog of the Advanced Systems for Power Engineering (or ASPEN) software used for process modeling and simulation. This effort could supplement existing models such as Discrete Element Modeling for biomass material handling (flowability) and IBSAL, which is a logistics model, not an engineering process model. Both funding and data would be needed to develop this resource.<br>• Support public and private sector on innovation of ideas and concepts. Public sector for modeling concepts and generating feasibility data and information.<br><br>**Storage Programs**<br>• Develop advanced supply systems that move biomass feedstocks toward a commodity supply system that meets certain specifications no matter the biomass source.<br>• Utilize existing technology in preprocess and harvest more fully. This involves the integration of existing technologies to improve the processes of feedstock pre-processing, intermodal logistics, and feedstock collection.<br><br>**Feedstock Quality Measurements and Standards**<br>• Feedstock suppliers need to pay more attention to what the biorefinery industry is asking for (in terms of feedstock specifications, especially).<br><br>**Financing**<br>• Create a platform for project financing, especially for smaller, cooperative ventures that struggle to acquire adequate financing under current lending regulations. |

<table>
<tr><th colspan="2">Future Directions in Feedstocks and Solids Handling</th></tr>
<tr><td>Mid-Term (continued)</td><td>Lessons Learned<br>• Publish an equipment engineering “handbook” for biomass materials. Identify correlations between biomass material properties and equipment design and performance parameters. Basic characterization has been done by Forest Product Labs (Madison, Wisconsin), but not to the level and properties of interest. Biomass properties change significantly based on particle size distribution, moisture content, hopper surface, etc., so a look-up book may be a significant challenge and not reliable. This work would benefit from collaboration between national laboratories and industry.</td></tr>
<tr><td>Long-Term</td><td>Logistics<br>• Intermodal (truck, rail, and river) transportation integration systems. These logistics systems should allow for the delivery of material up to 400 miles away. ORNL has looked at intermodal systems. The next step would be addressing cost of loading and unloading as well as identifying solutions to minimize stops along the route.<br>◦ The driving factor in logistics efficiency is carbon footprint. The EPA directive limited feedstock crops to those with a negative carbon footprint; using transportation modes other than trucks improves the efficiency of the overall system.<br>◦ Participants discussed the pros and cons of close proximity radius between feedstock source and refinery. Currently, most biorefineries are sited on railroads; for example, all cellulosic ethanol plants are on class 1 rail.<br>◦ In the mid-near term, the resource base is less dense, and thus, transportation becomes a greater challenge.<br>◦ Develop commodity-type feedstocks that can be a blend of many types of biomass.<br>Policy<br>• Reduce subsidies for the petroleum industry to reflect actual life-cycle costs. This political challenge would need to be addressed by both by federal and state government.<br>• Legislate a carbon tax for producers of traditional hydrocarbon products and use proceeds to support commercial development of low-carbon alternatives. California has enacted similar legislation. Better coordination among all entities, including federal agencies could serve to avoid duplication of efforts with this goal, and the agricultural industry has begun experiencing climate impacts and should be engaged on this political effort.<br>Education<br>• Expand public awareness and education. There are two primary approaches, either responding to a threat or embracing opportunity.</td></tr>
</table>

## Lessons Learned

At the end of the first day of the breakout session, participants were asked to share the lessons that they and/or their organizations have learned from feedstock handling efforts. The response ranged from very detailed to comical, including “Murphy’s Law is alive and well.”

Many of the lessons were related to prioritizing particular processes within the design and operational phases. Some of the lessons were directly related to IBR equipment and design, feedstocks, and pre-processing. Responses also addressed optimal decision-making in IBR business operations and methods for dealing with uncertainty. Table 6 provides lessons learned within each of these categories.

### Table 6: Lessons Learned For Feedstocks and Solids Handling

| Categories | Lessons Learned |
|---|---|
| **Prioritizing Processes in Design and Operational Phases** | • Feedstock grinding can prove to be more difficult than expected.<br>• Utilize gravity feeding from vertical silos to transport biomass within a biorefinery.<br>• Operability and maintainability are just as important as schedule and budget in project execution.<br>• Design scope needs to account for the fact that feedstock handling is going to be a high maintenance area within the IBR operations. |
| **IBR Equipment and Design** | • Robust control logic is necessary for integrated operation.<br>• Inter-machine communication to prevent overflows is critical.<br>• Correctly designed equipment, using material flow properties, will work well.<br>• Well-designed sensors and control systems are very important; a good control system can improve equipment and biorefinery up-time and system reliability.<br>• A screen is absolutely necessary piece of equipment. Few, if any, conversion feed systems can handle the wide particle size distribution resulting from grinding. |
| **Feedstocks and Pre-Processing** | • Herbaceous feedstocks are inherently variable.<br>• Milled herbaceous biomass will not flow by gravity.<br>• Corn stover is probably the worst handling feedstock.<br>• Understand gaps in knowledge and experience in feed handling; read, review, research, and seek guidance from experts.<br>• Failure to pilot front-end preprocessing and handling will ultimately cost time and money.<br>• There has been a lack of understanding of the feedstock characteristics within the preprocessing unit operations and how that affects downstream operability.<br>• Understand and study the effects that pre-processing steps can have on other downstream steps (either pre-processing or reactor area).<br>• Moisture content is an important factor for prevention of “plug flow” feeding feedstocks into pressurized reactors.<br>• What happens in the field during the collection, baling, transportation, and storage process has impacts all subsequent downstream processes to the finished product. |
| **IBR Business Operations** | • Last-minute decisions to save cost are generally very expensive.<br>• Segmented market needs are similar across biomass logistics.<br>• Trial and error is an expensive approach; a scientific approach is better.<br>• Saving money by not testing the flowability of the material and paying for experts to design the equipment can be costly in the end.<br>• Reduction in variability can be expensive if you have to cast out feedstock.<br>• You must revisit and communicate out your basis for feedstock material that the equipment design was based on.<br>• Bale reject rate is likely to be higher than you thought; it is preferable to have a plan for those bales.<br>• Engineering, procurement, and construction firms need to talk to people who understand biomass and not rely on vendors. |

| Categories | Lessons Learned |
|---|---|
| **Dealing with Uncertainty** | • Fire will happen during feedstock storage and processing.<br>• Systems need to be designed with a full realization of moisture variability.<br>• Biomass will vary in size, shape, and conveying characteristics; handling systems need to be designed to be flexible enough to handle the variance and to remove unacceptable material prior to further processing; design flexibility into the system.<br>• Plan for some in-line surge capacity; process machines of all types have some inherent flow variability. |

## Breakout Session Two: Process Scale-Up, Intensification, and Cost Reduction

This session aimed to explore efforts to successfully develop commercial scale IBRs, identify the factors essential to reducing operational risks, and determine the key technical milestones that projects must overcome along the way. Breakout session participants considered the innovative opportunities for improving in-plant IBR operational methods, implementing processes intensification, and reducing CapEx and OpEx. This session provides an overview of participant input regarding methods to achieving these opportunities.

The facilitated discussion began by gauging each participant's experience in working with biorefineries at different scales. The results displayed in Figure 2 indicate that 66% of the 35 respondents had experience working on pilot-scale biorefineries, while 40% and 34% had experience working on demonstration and commercial scale facilities, respectively. The group also listed the types of processes with which they had used to convert biomass to biofuels and bioproducts. The results, in Figure 3 below, indicate that the greatest number of respondents were familiar with thermochemical processes.

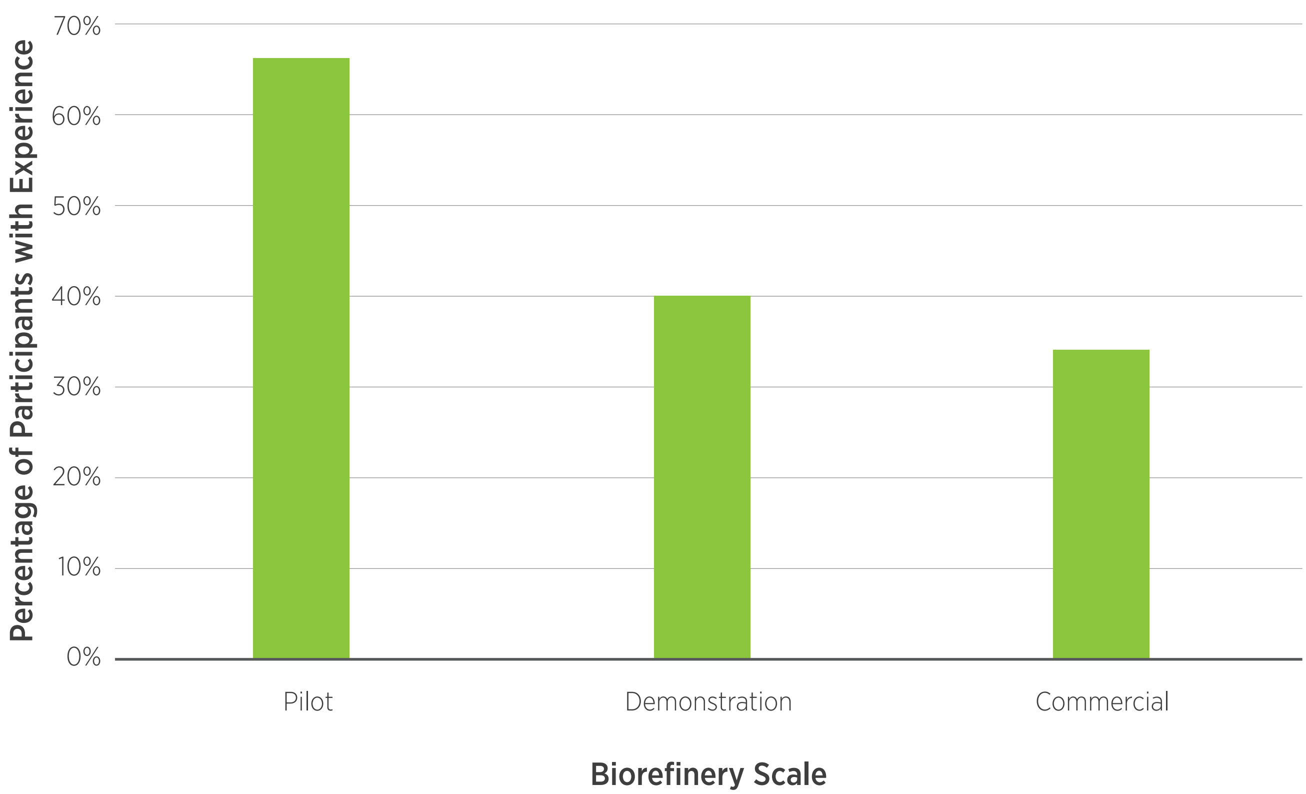


**Figure 2: Breakout session participant experience working on integrated biorefineries of various scale**

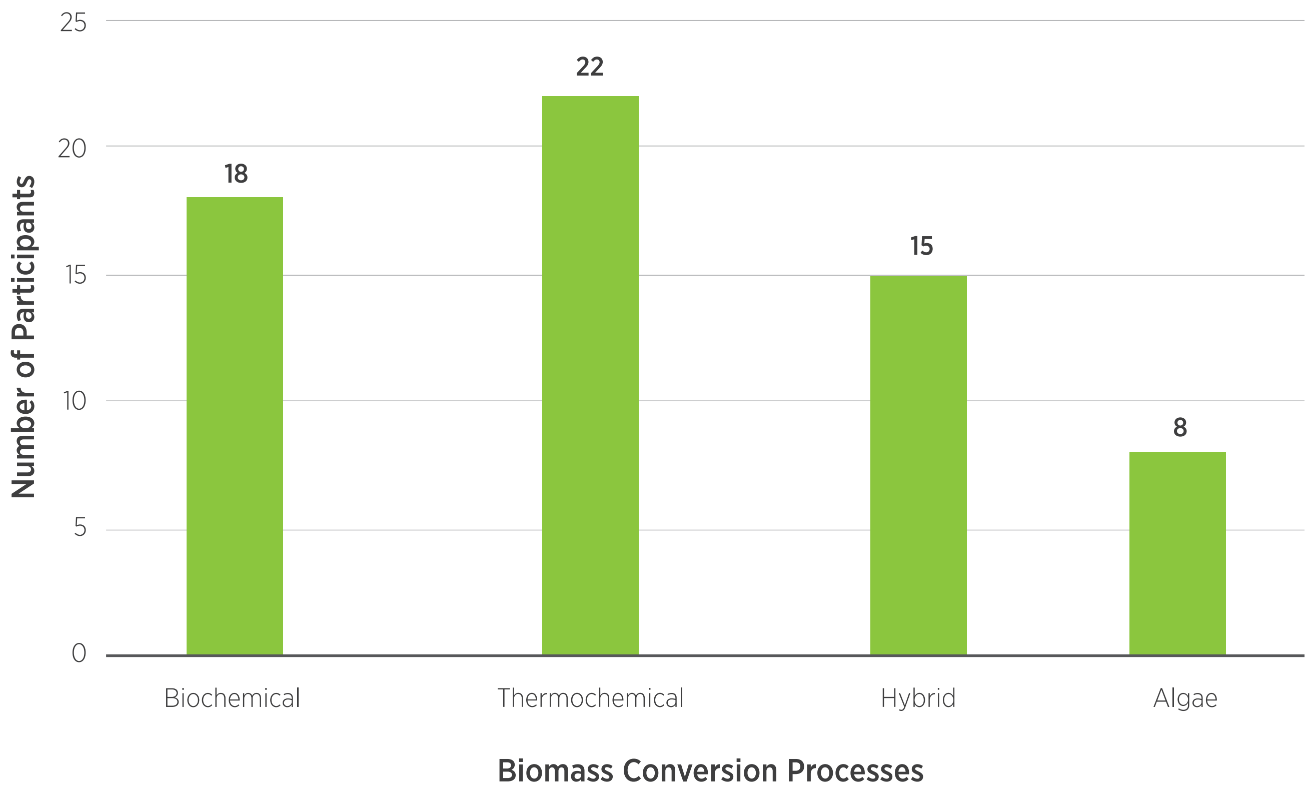


Figure 3: Breakout session participant experience with different biomass conversion processes

During this session, participants developed a working definition of process intensification with respect to IBRs and worked to identify major challenges facing IBRs at pilot, demonstration, and commercial scale. Challenges regarding process integration and conversion pathways were discussed along with methods for reducing both capital expenditures and operating expenses. Ultimately, the group established lists of best practices based on the lessons learned during their experiences with biorefinery operation.

### Major Challenges Facing Integrated Biorefineries

Biorefinery facilities can be defined by their objectives and operational scale. After developing processes at the bench scale, companies typically begin operation of a pilot facility. This developmental stage serves to verify the integrated technical performance of the given suite of technologies. Testing is completed at each step, from feedstock input through product output. Generally, the object is to attain production capacities equal to or greater than 1 dry ton of feedstock per day. A pilot-scale facility integrates key recycle streams to validate the process and techno-economic model, but it is not intended to produce cost-competitive fuels due to its small scale of operation. Any problems identified in the pilot stage must be corrected prior to further scale-up, or it is unlikely that the next plant will achieve its design capacity, operability factor, and profitability.[8] This is also true for demonstration- and commercial-scale facilities; if prior scale issues are not addressed, the performance at the next stage facility may suffer.

Breakout session participants discussed the critical challenges facing the successful scale-up and operation of IBRs at pilot, demonstration, and commercial scales. Then, the group identified potential ways that these scale-up issues could be addressed.

[8] A. Marton, 2011, "Research Spotlight: Getting off on the Right Foot – Innovative Projects," Independent Project Analysis Newsletter 3(1).

### *Pilot-Scale Challenges*

Pilot scale challenges were grouped into those associated with scale-up uncertainty, equipment design, feedstock variability, and project management. Specific challenges related to these areas are listed in Table 7 below.

**Table 7: Pilot-Scale Biorefinery Challenges and Potential Solutions**

| Pilot-Scale Biorefinery Challenges and Potential Solutions | | |
|---|---|---|
| | **Challenges** | **Potential Solutions** |
| **Scale-Up Uncertainty** | • Determining the correct scaling factors before moving to the next scale.<br>• Ensuring that the pilot facility will scale up and correlate with the demonstration and commercial scale facilities.<br>• Dealing with improperly designed equipment based off of lab data.<br>• Secure funding to build a pilot facility that is both flexible enough to change over time and locked in enough on the process of interest to provide data useful for larger-scale demonstration and pioneer plants. | • Collect the amount of integrated operational data required to sufficiently inform the commercial design basis and economics.<br>• Optimize the process and technology while gathering sufficient data to inform further scale-up. |
| **Equipment Design** | • Understanding kinetic and mass transfer limitations.<br>• Feeding solids under pressure.<br>• Dealing with clogged pipes, nozzles, and valves. | • Identify recycle and effect of recycles, right size of equipment to generate reliable mass/heat transfer data at commercial scale.<br>• Carry out heat integration and dealing with recycle streams. |
| **Feedstock Variability** | • Inability to address feedstock variability and non-pristine feedstock.<br>• Working with realistic particle sizes and geometry.<br>• Many others identified in the feedstock solids handling session. | • Solutions provided in the feedstock solids handling session |
| **Project Management** | • Accurately estimating and sticking to the project schedule.<br>• Handling the pressure from financing entities to meet unrealistic performance expectations.<br>• Managing expectations between promoting the business and the reality of the science and engineering of the project.<br>• Financially breaking even. | |

*Demonstration-Scale Challenges*

The list of difficulties faced at the demonstration scale can be described as related to either scale-up uncertainty or project management, which for this purpose includes management of government partnerships. Table 8 provides a list of these challenges within each area.

**Table 8: Demonstration-Scale Biorefinery Challenges and Potential Solutions**

| Demonstration-Scale Biorefinery Challenges and Potential Solutions | | |
|---|---|---|
| | **Challenges** | **Potential Solutions** |
| **Scale-Up Uncertainty** | • Ensuring that the demonstration scale will correlate with commercial scale.<br>• Operating using insufficient data from improper piloting.<br>• Dealing with changes in conversion efficiency after scaling to demonstration scale. | • Reproduce pilot data at demonstration scale.<br>• Do not scale-up before the technology is ready. |
| **Project Management** | • Operating at a loss despite the large expense to build a demonstration facility.<br>• Keeping the demonstration facility operating on schedule without cost overruns.<br>• Committing to the project's large investment due to the 50% cost share that is required by some federal agency's demonstration-scale funding opportunity awards.<br>• Underestimating the impact and cost of feedstock supply and logistics. | • Establish offtake agreements for co-products.<br>• Do not under estimate the impact and cost of feedstock supply and logistics.<br>• Train employees on how to operate the facility, as sometimes technology fails due to human error, lack of data, or misinterpretation of data.<br>• Find partners with capital or facilities that could be used at demonstration scale.<br>• Fully account for waste streams.<br>• Understand that at demonstration scale, time and capital investments may not have immediate returns.<br>• Secure the time and funding needed to scale up promising advanced technologies such as microwave- or ultrasound-assisted processes. |

### *Commercial-Scale Challenges*

Commercial-scale challenges were grouped into scale-up uncertainty, markets, and governmental policy. Table 9 below provides a list of the commercial scale challenges within each area.

**Table 9: Commercial-Scale Biorefinery Challenges and Potential Solutions**

| Commercial-Scale Biorefinery Challenges and Potential Solutions | | |
|---|---|---|
| | **Challenges** | **Potential Solutions** |
| **Scale-up Uncertainty** | • Obtaining enough funding to get through start-up and commissioning.<br>• Handling solids at full commercial scale while maintaining the robustness and tolerance for extended start-up.<br>• Lack of readily available debt for pioneer plants.<br>• Underestimating the risks associated with engineering, procurement, and construction contracts.<br>• Accurately estimating product yield.<br>• Dealing with high operational costs due to design deficiencies and interruption in operation. | • Do not build the commercial plant without proper pilot or demonstration data to support the design.<br>• Determine whether the issues at existing commercial plants can be fixed or if they require going back to R&D.<br>• Do not underestimate start-up issues, length, and cost associated with scaling a new complex process using solids. |
| **Markets** | • Dealing with the uncertainty in energy markets.<br>• Competing in existing commodity markets if very difficult for new technologies.<br>• Lack of an existing feedstock supply chain. | • Secure feedstock agreements and a reliable feedstock supply. |
| **Policy** | • Lack of policy certainty for investors.<br>• Permitting across states with different processes and requirements.<br>• Obtaining environmental permits. | |

## Resources Needed to Address Integrated Biorefineries Challenges

In listing the major challenges facing IBRs throughout scale-up, the group identified issues that were common throughout each scale of IBR, such as the inability to secure off-take agreements for co-products, the inability to adapt to feedstock supply variability, and ensuring that data collected at the prior scale will correlate to the next scale.

Participants proposed resources needed throughout several categories, including stakeholder collaboration, data modeling, financing, and policy. These responses are displayed in Table 10.

**Table 10: Proposed Paths Forward to Address Biorefinery Challenges**

| Proposed Paths Forward to Address Biorefinery Challenges | |
|---|---|
| **Stakeholder Collaboration** | • Encourage industry and academy to understand the scale-up mechanisms.<br>• Disseminate lessons learned from prior IBRs to industry and national laboratories. |
| **Data Modeling** | • Define the data that is required to generate a reliable data set for the commercial facility.<br>• Develop better models that are tailored to biomass systems to help predict heat and mass transfer changes at different scales.<br>• Provide access to pilot-scale data that was used to scale-up the process to better understand the reliability of extrapolating pilot data on comparable processes.<br>• Develop robust simulation models and life-cycle analyses that take uncertainty into consideration, especially those parameters that may be changed in a large scale. |
| **Financing** | • Develop public-private partnerships at funding levels sufficient to cover unforeseen overhead expenses and deal with regulatory and compliance issues.<br>• Fund the earliest phases of process development internally to avoid pressure from investors.<br>• Develop partnerships with agencies that are capable of giving offtakes with sufficiently long duration and floor value. |
| **Policy** | • Support an across-the-board tax on fossil carbon to level the playing field and dramatically increase the viability of truly renewable technologies. |

### *Challenges in Process Integration*

Current R&D efforts aim to identify issues at operation interfaces and opportunities for better integration by investigating the interaction of pretreatment and deconstruction technologies together with downstream upgrading technologies.

Participants noted that the overall goal in process integration is ensuring that all steps of the process have been sufficiently integrated, tested, and optimized at the pilot and demonstration scale before moving to commercial scale, all while using the best technology available. Table 11 shows the major challenges currently facing process integration efforts, which include difficulties related to engineering processes, quality assurance and control, and data collection.

### Table 11: Challenges in Process Integration

| Challenges in Process Integration | |
|---|---|
| **Engineering Processes** | • Understanding process sensitivities.<br>• Designing processes to prevent contamination.<br>• Managing separations in the product and recycle streams.<br>• Understanding the effect of feedstock soil content impact on process design and projected maintenance. |
| **Quality Assurance and Control** | • Piloting and demonstrating heat integration and close recycle streams.<br>• Ensuring reliable feedstock pre-processing at high volumes and low cost.<br>• Understanding design safety and standards, particularly for feedstock size reduction and dust removal.<br>• Integrating technologies from different providers and developers while assuring that each step meets specifications.<br>• Overcoming the inclination to cut corners to quickly demonstrate the feasibility or make do with insufficient equipment. |
| **Data Collection** | • Validating process models and simulations at demonstration and commercial scales.<br>• Demonstrating the integration technology along with thorough analytics for an extended period of time.<br>• Funding and perseverance required to generate reliable data. |

### *Challenges in Conversion Pathways*

Conversion pathways refer to the different methods and technologies that can be used to convert biomass to a variety of fuels and products. General categories of conversion pathways include biochemical, thermochemical, hybrid, algae, and others that may not have been represented by breakout session participants. For example, in the biological conversion of sugars to hydrocarbons pathway, biomass-derived sugars separated from feedstocks are further transformed, recovered, and purified to yield hydrocarbons for fuels and co-product commodities through a series of chemical and biological processes.[9] Challenges related to conversion pathways can be categorized as related to engineering processes, waste streams, equipment, business decisions, and policy. The challenges discussed during this breakout session are listed in Table 12.

[9] "Biological Conversion of Sugars to Hydrocarbons," U.S. Department of Energy Bioenergy Technologies Office, Nov. 2012, http://www.energy.gov/sites/prod/files/2014/04/f14/biological_conversion_of_sugars_to_hydrocarbons.pdf.

#### Table 12: Challenge Areas in Conversion Pathways

| Challenges in Conversion Pathways | |
|---|---|
| **Engineering Processes** | • Understanding and dealing with catalyst longevity in real-world conditions.<br>• Developing processes to valorize lignin.<br>• Removing biomass contaminants that can deactivate biological catalysts in conversion processes or produce a contaminated co-product.<br>• Dealing with efficiency of solids separations.<br>• Inability to maintain design process condition for conversion pathways. |
| **Waste Streams** | • Managing aqueous wastewater in hydrothermal liquefaction processes. |
| **Equipment** | • Dealing with the erosion and corrosion of reactor vessels, heat exchangers, and valves. |
| **Business Decisions** | • Understanding the balance between the economic feasibility and environmental impact of a pathway.<br>• Developing and implementing processes that are economically sound to compete in the market place with similar or identical fossil-based products.<br>• Achieving a positive cash flow and ensuring that there is a market for the intended product.<br>• Ensuring that sufficient funding structures are in place before moving on to next scale.<br>• Balancing the desire for process scaling and further development of core technology.<br>◦ Sometimes the rush to scale detracts resources from core technology improvements that are actually required for a successful deployment.<br>• Lack of encouragement for high-yield, low-profit margin pathways versus low-yield, high-profit margin pathways.<br>• Considering both the economic and societal costs when determining the true cost of technologies. |
| **Policy** | • Broadening set of approved pathways.<br>• Accepting that despite high levels of investment for pilot plants, technologies can still fail. |

### Methods for Reducing Capital and Operational Expenditures

Biorefineries aim to be competitive with fossil-based refineries but must reduce capital and operational expenditures in order to meet necessary cost goals. Participants recognized major technical and market barriers that significantly contribute to these capital and operational expenditures.

Technical barriers include process integration, reducing unit operations, minimizing waste, lack of operational data for scaling, and adapting to variations in feedstock supply. Market challenges include inadequate supply chain infrastructure, difficulty in securing offtake agreements, competition within existing commodity markets, and the reluctance of financers to invest in new technologies. Participants were asked to provide suggestions for methods to reduce CapEx and OpEx in IBRs. The most critical area noted for reducing cost in a biorefinery was process intensification.

Breakout session participants proposed that project developers should consider process intensification from the laboratory scale because it is easier to exhibit some process intensification steps at earlier stages by planning well in advance. Companies could also simulate and refine commercial plans while moving throughout each developmental scale. For example, two reactions can be combined into one by developing a new catalyst in the lab. The group explained that government support is needed for process intensification in areas such as feedstock logistics.

Co-location, which refers to the construction or placement of a new facility at or near an existing plant, provides many benefits, including CapEx and OpEx reduction that allows companies to operate and prove new technologies that might not be economically feasible otherwise. A primary benefit of co-locating with an existing facility is the ability to share resources. An existing plant already has utility distribution infrastructure that a co-located plant could share. Resources such as steam and electricity that are produced by the new facility could be shared with the existing plant. A negative aspect of co-location is that issues such as power outages can affect both plants simultaneously.

Additional input from the group regarding methods for CapEx and OpEx reduction included those related to business partnerships, waste management, and engineering processes are included in Table 13 below.

**Table 13: Methods for Reducing Capital and Operational Expenditures in Integrated Biorefineries**

| Methods for Reducing Capital and Operational Expenditures in Integrated Biorefineries | |
|---|---|
| **Business Partnerships** | • Secure long-term offtakes for feedstock and products with hedges in place when possible.<br>• Establish EPC contracts and insurances with the vendors to insure the equipment and the installation.<br>• Co-locate biorefineries with industries that have equipment on site. This is especially valuable when building demonstration scale plants due to the resulting reduction in CapEx.<br>• Provide services to mitigate waste $CO_2$ such as carbon capture via algae or fermentation.<br>• Focus on niche markets and areas where biofuel technologies can solve an existing problem to enable technology development and reduce scale-up risk and uncertainty. |
| **Engineering Processes** | • Develop biorefinery process sequences with selective reactions and fewer unit operations.<br>• Develop a robust design and know how all products, by-products, and co-products will be utilized.<br>• Use the same feedstock(s) as a planned feedstock at the commercial scale for a robust process during scale-up. |
| **Waste Management** | • Use waste streams as feedstocks (example waste materials include waste $CO_2$, municipal solid waste, wastewater from treatment plants, manure, and landfill gas).<br>• Minimize wastes, but maximize value, even if a niche market for smaller volumes. |

### *Bolt-On Technologies*

A bolt-on is a co-located facility that adds a new processing capability to an existing plant. For example, in a dry corn ethanol facility, cellulosic ethanol can be produced utilizing the carbohydrate fraction in the material composed of dried distillers grains and solubles (DDGS). In this example, bolt-on would refer to the new section used to produce cellulosic ethanol from DDGS, whereas the existing plant will provide the front-end and back-end interfaces including product purification and distribution.

Breakout session participants were asked to list the benefits and challenges of bolt-on technologies. Common benefits of bolt-on technologies listed by participants were the ability to share utilities with an existing plant, opportunity to utilize an existing feedstock supply chain, and the opportunity to repurpose facilities that may no longer be economically feasible. The group noted that the CapEx and OpEx reduction opportunities associated with bolt-on technologies could be substantial if done correctly. A critical challenge noted by the group is the difficulty in convincing existing facilities to take on new risk associated with bolt-on technologies, especially if they are already struggling financially.

Additional benefits and challenges for bolt-on technologies are provided below in Table 14.

### Table 14: Challenges and Potential Benefits of Utilizing Bolt-On Technologies

| Challenges and Potential Benefits of Utilizing Bolt-On Technologies | |
|---|---|
| **Challenges** | **Potential Benefits** |
| • Some bolt-ons are at first-generation ethanol plants, and they require a restrictive payback on capital investments of at least two years.<br>• There are significant issues related to metallurgy when renewable materials interact with existing systems such as with pyrolysis oil in refineries.<br>• It is difficult to convince an operating facility to make process changes or additions unless you can prove that the bolt-on will provide value.<br>• Existing upstream and downstream operations at the facility may not be the ideal operations for the bolt-on technology.<br>• Risk in harming the proven technology and facility if the new technology is flawed.<br>• Recommissioning older assets may be costly and finding spare parts can be difficult.<br>• Converting the wood yard and digester to biomass for hydrolysis pilot work is much more difficult than pilot work using the top quality wood chips normally used for paper making.<br>• A pulp mill's recovery and recaustization system may be oversized if the bolt-on technology involves biorefining processes with a decreased need for lignin removal. | • Equipment availability from the pulp and paper industry suppliers.<br>• Sharing utilities between the main facility and the bolt-on system.<br>• Utilizing existing supply chain infrastructure.<br>• Bolt-on systems can demonstrate a control case to drive analytics for differences to develop a better understanding of the process and pathway.<br>• Decreased CapEx from using shared facilities.<br>• Co-location may provide opportunities for easier permitting.<br>• Co-location can help form a strategic partnership.<br>• Ability to utilize waste streams from existing plants. |

#### *Opportunities for Refinery and Chemicals Integration and Co-Processing*

The ability to leverage the infrastructure of refineries could potentially provide CapEx and OpEx reductions for the production of biofuels and biochemicals. Participants were asked to list the different processes for which they saw an opportunity for refinery and chemicals integration or co-processing and then to list the benefits and challenges associated with integrating with these processes. Participants noted that besides reduced CapEx, companies could leverage refinery operations experience and reduce cost of production through large scale.

The processes and technologies for which participants saw opportunities for integration included hydrocracking, fluid catalytic crackers, refinery steam methane reformers, pressure swing adsorption, hydro treating, as well as separations and purification. Definitions for these terms are provided below.

- **Hydrocracking:** This is a process in which hydrogen is added to organic molecules at high pressures and moderate temperatures; usually used as an adjunct to catalytic cracking.
- **Fluid Catalytic Cracker (FCC):** In the FCC, fluidized catalysts like active zeolites are used to break the bonds of long-chain hydrocarbons at high heat.
- **Refinery Steam Methane Reformer:** The steam methane reforming process converts steam and methane, biogas, or refinery feedstock into hydrogen ($H_2$) and carbon monoxide (CO). The mix is referred to as synthesis gas or syngas.
- **Pressure Swing Adsorption:** This works to separate biogas by compressing it and contacting with adsorbent materials at near-ambient temperatures. $CO_2$ adsorbs to these materials at high pressure, and the purified methane is collected. When the material is saturated with $CO_2$, the system pressure is dropped in order to desorb it.

### *Co-Processing Benefits*

Participants were asked to list the benefits of refinery and chemicals integration for the processes listed above. A major benefit as listed by many participants is the ability for integration to ultimately lead to decreased cost and risk associated with producing biofuels, biochemical, and bioproducts. Their responses are included here.

Breakout session participants saw an opportunity for the refinery's hydrocracker to provide benefits to biomass conversion processes in that bio-derived hydrocarbons (paraffinic) could potentially be cracked to produce higher-value chemical products. The ability to produce these chemicals could provide additional revenue and increase the overall cost-competitiveness of biofuels. Hydrocracking could also serve as a tool to narrow product distribution.

Integration of the FCC with biofuel production processes minimizes capital for producing the final transportation fuel product from biomass. This is important because it would give the obligated party control over the generation of renewable identification numbers (RINs). Participants also noted that this extends the "blend wall" in the refinery by book-ending non-blended, drop-in production in the FCC with downstream blending.

By integrating with an steam methane reformer/pressure swing adsorption system, companies could provide $H_2$ to $H_2$short refineries or take $H_2$ from $H_2$ long facilities, to help in the $H_2$ balance. Producers could use the existing refinery $H_2$ infrastructure to supply $H_2$ to biomass conversion processes that require it such as oxygen removal, hydrotreating of pyrolysis oils, etc. This could ultimately reduce CapEx of biorefineries that consume hydrogen. Participants posed that this could be possible with DOE support for demonstration-scale efforts to integrate appropriate biomass conversion processes into a refinery.

Regarding separation and purification, the group noted that there are spare trains in large-scale petrochemical processes that could be potentially utilized in separations. The design would need to consider the proper scale-up for separation processes. Since separations can account for a large percentage of the product price, participants said that lowering this cost is critical. BETO support for separations R&D could drastically help to reduce costs in a biorefinery. Reponses noted that BETO support could identify promising strategies for purification/clean-up for bio-derived chemicals since advances in separations technologies that improve process economics for bioproducts can also apply in biofuels.

### *Co-Processing Challenges*

In order to fully realize the above co-processing benefits, companies need to identify key gaps associated with processing through engagement refiners. Companies must determine the data that a refiner needs to see (beyond cost numbers) to demonstrate that co-processing is a viable option. Technologies will also need further demonstration of on-stream time to drive down risk to refiners.

In regards to processes, participants discussed the volume of material and length of demonstration time a refiner needs in order to confirm risk levels. In the FCC, companies need to demonstrate the stability of the catalyst and prove that integration will have only a limited impact on downstream processing catalysts that minimize catalyst poisoning. Projects need to understand heat balance and control to demonstrate minimum impact on the catalyst. The group suggested that demonstration takes place at a pilot scale that is in line with an FCC rather than in fixed bed reactors or non-circulating systems. To further achieve the benefits, technologies should demonstrate process flexibility of bio-derived intermediates and show that the process can be tuned to improve desired yield of coproducts.

### *Refinery and Chemicals Integration*

After discussing the benefits and challenges associated with both bolt-on systems and co-processing, participants were asked to discuss the bio-intermediates that could be used in these processes. After listing the possible intermediates, participants were asked both why these bio-intermediates were a viable option and how they could be used within these scenarios.

Participants noted that biomass-derived sugar streams are viable bio-intermediates because sugars are the basic building block of the majority of starch and cellulose, and thus are a valuable commodity for many fermentation and catalytic processes. This bio-intermediate possibility makes these processes ripe for co-location with feedstock conversion facilities. At a co-located facility, sharing sugars would decrease the transportation costs on a mass basis and lower commodity costs for all users.

Sugar use in corn mills offers an advantage for co-siting chemicals production with ethanol if sugar can be shared. Fractionated pyrolysis oil, catalytic pyrolysis oil or hydrotreated pyrolysis oil all also provide a co-location opportunity since sugars are the base feedstock for much fermentation. This can provide an ethanol plant the opportunity to increase feedstock throughput when limited by ethanol nameplate capacity permits. The group also stated that corn pericarp fiber can be not only be used to produce cellulosic ethanol, but it also provides economic benefits from D3 RINs instead of low-value DDGS.

For boiler applications, biomass char and lignin are viable feedstocks. Lignin could also be converted via hydro-pyrolysis to produce deoxygenated hydrocarbon fuels with bio-derived hydrocarbons with various levels of oxygenation as useable bio-intermediates and could be generated via catalytic pyrolysis or hydro-pyrolysis. Bio-oil derived through Fischer-Tropsch synthesis could be used in hydrocracking to produce advanced biofuels.

### *Lessons Learned and Best Practices*

Throughout the session, participants provided information based on their own experiences working in the industry. The group was asked to discuss the major lessons learned that they have gathered from these experiences and to list the new best practices that have resulted from these lessons. Common lessons learned that came out of this conversation were that project teams should consist of both scientists that developed the technologies, as well as the engineers who will be operating it at scale. Process intensification steps should not be skipped, and projects should be able to adapt to variations in your feedstock supply.

The most common best practice noted by the group was the need to sufficiently execute the prior scale before moving to the next facility. With this, the participants were asked to provide input to a matrix listing the proper approach for pilot- and demonstration-scale facilities, along with the length of time that should be spent at this scale, the metrics by which the scale should be defined, and the feedstocks that are appropriate for this scale of facility. A full list of lessons learned and best practices are provided in Table 15.

**Table 15: Lessons Learned and Best Practices in Process Scale-Up, Intensification, and Cost Reduction in IBRs**

| Process Scale-Up, Intensification, and Cost Reduction in IBRs | |
|---|---|
| **Lessons Learned** | **Best Practices** |
| • If process intensification opportunities are missed, the resulting process may be sub-optimal and far less likely to succeed commercially.<br>◦ Heat integration and parallel processing (multiple process steps in one vessel or unit operation) are particularly of note.<br>• With scale-up, emissions increase and regulations may require you to install additional controls for permitting purposes.<br>• People tend to use a "standardized/ideal" feedstock quality early in the process development, which is not the commercial case.<br>• Fully integrated pilot demonstrations for extended duration with all recycle and waste streams captured and quantifies.<br>• Sufficient length of piloting with real feedstock in order to accurately predict yields, tars, impurities, catalyst life, etc.<br>• Robust data collection during operations that can be "mined" to develop process understanding and to solve problems. The data must be detailed and raw.<br>◦ Have a robust process monitoring software and have the operator, engineers, and research team access the process; use the software for diagnosis, trending, etc. | • Integrate people with different competencies. Scale-up is a multi-disciplinary project and the earlier different competencies are brought in, the smoother the scale-up will be.<br>• Avoid shut downs and operate 24 hours a day, 7 days a week. Only shut down for scheduled maintenance and not for reasons like lack of raw materials.<br>◦ Operate at capacity.<br>• Hire experienced employees from a similar process if none are available from your specific process.<br>◦ Use skilled operators in scale-up. Learn operational challenges early.<br>• Have enough flexibility in your commercial plant to deal with real world variability you just can't experience at demonstration and pilot scale. Similarly for the demonstration plant through pilot variability.<br>• Enforce true integration and a robust stage-gate process. |

## Scale-Up Approaches and Metrics

Scaling up an integrated biorefinery is not a standardized practice for which one approach will work for all facilities. Some projects may prefer greater lengths of continuous tests or achieving a certain throughput before moving to the next scale. Participants were asked to outline the various metrics that they believe define an adequate approach to IBR scale-up. A critical element that was raised was that pilot- and demonstration-scale facilities should prioritize meeting realistic performance targets regardless of how long it takes. Once these targets are met, scale-up should occur. A full breakdown of the scale-up approaches and metrics is displayed in Table 16.

**Table 16: Identification of Scale-up Approaches and Metrics**

| Identification of Scale-up Approaches and Metrics | |
|---|---|
| **Technology Development Stage** | **Pilot Scale**<br>**Demonstration Scale** |
| **Adequate Length of Time** | **Pilot Scale**<br>• Time periods given for adequate piloting included ranges from 6–18 months on the low end and 3–5 years for more intensive piloting.<br>• Some responses were based on hours of continuous operation and ranged from 1,000–2,000 hours.<br>• Responses also noted that defined performance targets need to be met in order to move on to the next phase. |
| | **Demonstration Scale**<br>• Adequate periods of operation given for demonstration-scale facilities ranged from of 2–24 months, depending on the technology.<br>• For some plants, proving fully integrated operations for a minimum 1,000 hour continuous run |
| **Scale** | **Pilot Scale**<br>• Commercial plant design is brought to the smallest meaningful scale possible to test the engineering principles and unit operation: Pilot plant should mimic commercial plant material-balance behavior, and all recycle streams are incorporated. Scale of a pilot could range from 0.05–1 ton biomass on the low end or up to 50 tons per day.<br>• Scale should allow generation of data on performance, recycle requirements, and by-products/waste products that allows simulation of commercial plant.<br>• 1% of commercial-scale feedstock/day |
| | **Demonstration Scale**<br>• Ranges given were from 1–5 dry tons per day (dtpd) on the low end and up to 50–250 dtpd.<br>• Facilities should be fully integrated at 10%–15% of planned commercial scale or larger. |
| **Feedstock** | **Pilot Scale**<br>• Same as envisioned feedstock for commercial plant.<br>• Purpose-grown crops.<br>• Waste streams: Agricultural waste or by-product, MSW, bio-solids, industrial waste streams, forest harvesting residues.<br>• Preference for waste woody biomass and forest residues discussed with reasons including relative abundance as well as established supply chains. |
| | **Demonstration Scale**<br>• Process dependent feedstocks require testing at this scale.<br>• Same feedstocks considered for commercial scale plant.<br>• Agricultural residuals, purpose grown crops, biomass wastes, MSW, forest harvesting residues. |

Pilot Scale    Demonstration Scale

## Breakout Session Three: Co-Product and Waste Stream Monetization

The breakout session addressed revenue diversification at biorefineries through exploration of the co-product and waste streams that exist in plant operations but that are considered to be of little economic significance at this point. The participants discussed methods for fully utilizing the potential of waste streams to produce higher-value products and how to separate the valuable components from these streams. DOE defines co-products as the "resulting substances and materials that accompany the production of a fuel product." In contrast, by-products are defined as "leftover material, generated as a result of an industrial process or as a breakdown product in a living system." Waste streams are any "unused solid or liquid by-products of a process."[10]

The session also addressed the challenges and barriers that have thus far served as obstacles to moving these products from waste streams to the market. Participants discussed the bounds of this topic space and worked through a series of questions and exercises designed to better understand the slate of potential co-products and waste streams, how these streams can be commoditized for trade and the roles of DOE and industry in this effort. The participants identified the next steps and potential policy considerations that could help to initiate the monetization of waste streams.

To open discussion the participants were asked to propose definitions for the various outputs of biorefinery processes, which would then serve as baselines for the session's questions. Participants recognized that a waste stream in one process could be a valuable feedstock in another process. The group provided examples that illustrated how facilities need to consider different key co-product and by-product streams based on the primary product.

The group then discussed the different factors considered in maximizing profit, such as adjusting yields and developing new secondary products. Participants noted that inefficiencies of the system can be the source of process wastes and that there are diminishing returns on the conversion of waste streams. Issues in separations processes for solid, liquid, and gaseous phases were listed as key barriers to monetizing waste streams.

Lastly, the group identified tools and resources needed in order to realize opportunities for monetizing materials that do not currently add value to biorefinery operations.

### Output Stream Utilization

This session began with a discussion to identify possible biorefinery waste streams, co-products, and by-products. The group identified five categories of primary processes that produce output streams:

- Thermochemical
- Biochemical
- Electrochemical
- Algal systems
- Hybrid systems.

These processes produce unique waste streams. For example, electrochemical processing produces ash from gasification, wastewater, counterions ($Cl^-$, $Na^+$), and organic acids. Hybrid processing produces ash, wastewater, and gas with carbon and nitrogen compounds. Both of these processes could potentially provide revenue to biorefinery operators.

Within each of these process categories, the streams were grouped by type (waste, co-product, or by-product). Participants noted that a given stream is only labeled as one of these categories until it is sold, at which point it

[10] Bioenergy Technologies Office Glossary, http://energy.gov/eere/bioenergy/glossary.

is simply a product. In order to make overall project economics work, these streams generally need to be sold (or monetized) at a reasonable price point.

Table 17 shows the various outputs from thermochemical, biochemical, and algal biomass conversion processes.

### Table 17: Biomass Conversion Process Outputs

| | Thermochemical Process Outputs | Biochemical Process Outputs | Algal Process Outputs |
|---|---|---|---|
| **Waste Streams** | • Ash (from gasification of feedstocks)<br>• Heat<br>• Carbon dioxide ($CO_2$)<br>• Wastewater<br>• Aqueous phase liquid (from pyrolysis)<br>• Metals<br>• Organic acids (such as acetic acid)<br>• Particulate matter<br>• Nitrogen (organic and inorganic)<br>• Plastic wrap (from the biomass feedstock supplier)<br>• Chemical wastes (from ion exchange regeneration). | • Lignin<br>• Water<br>• Cell mass (from fermentation of biomass)<br>• Sugar<br>• Gas<br>• Inorganic acids<br>• Proteins<br>• Enzymes<br>• Lipids<br>• Starches<br>• Meal (residue after extracting oil)<br>• Microbes (live or not)<br>• Solids waste. | • Algal biomass<br>• Waste cell biomass<br>• High biochemical oxygen demand wastewater. |
| **Co-Products** | • Short chain hydrocarbons<br>• Waxes<br>• Biochar<br>• Lignin<br>• $CO_2$ (possible uses as a feedstock)<br>• Nutrients<br>• Wastewater (can be important resource in arid zones)<br>• Bio-oil. | • Biogas<br>• Sulfur<br>• Animal feed<br>• Lignin<br>• High NaOH clean-in-place waste water. | • Nutrients<br>• Lipids and oils<br>• Edible proteins (to be sold as animal and fish feed)<br>• Nutraceuticals (such as omega 3)<br>• Starches and sugars<br>• Enzymes. |

| | Thermochemical Process Outputs | Biochemical Process Outputs | Algal Process Outputs |
|---|---|---|---|
| **By-Products** | • Carbon monoxide (CO)<br>• $CO_2$<br>• Hydrogen<br>• Chemical compounds: BTEX (benzene, toluene, ethylbenzene, and xylenes)<br>• Naphtha<br>• Naphthalenes<br>• Phenols<br>• Distillate<br>• Solvents (from gas fermentation)<br>• Kerosene<br>• Lignin<br>• Organic acids (such as acetic acid)<br>• Chemical building blocks. | • $CO_2$<br>• Lignin<br>• Protein<br>• Acetic acid<br>• Nutrient laden water<br>• Solid residues. | • $CO_2$<br>• Ash<br>• $O_2$<br>• Waste biomass suitable for digestion. |

## Stream Value

Breakout session participants recommended which waste, co-product, and by-product streams could potentially be sold by IBRs to add revenue streams. Some of the product suggestions include fertilizer inputs that offset petroleum, lignin, or biochar for water purification purposes, and specialty fuels such as lubricants.

Participants noted that the value of output streams is greatly affected by the required material upgrade process, the feasibility of cost-effective separation of material streams, the cost of transportation from supplier to customer, and, ultimately, the terms of a business arrangement between the supplier and customer.

### *Waste Stream Value*

Participants provided context around how each waste material streams can be utilized for producing additional revenue in a cellulosic IBR. According to one attendee, a general principle that applies to most waste streams is that they are devalued because they are low concentration and/or contaminated by the presence of other compounds. Separation and purification may be necessary steps to use some components of waste streams.

For example, $CO_2$ can be used as a feedstock for bioenergy processing via electrolytic and biologic processes that can upgrade the gas to fuels and chemicals. $CO_2$ can also be used as an input in the production of fine chemicals, plastics, refrigerants, polymers, dry ice, and cement. Further, it can be used as a carbon source in fermentation to make high-value co-products. Lastly, $CO_2$ is an important part of the enhanced oil recovery process.

CO and other gases can be burned or converted to liquid alcohols using the Fischer–Tropsch process. Biogas can also be burned to make either heat for the biorefinery processes or electricity. Biogas can also be used as a feedstock for production of fuels and chemicals, or for biological processes to make plastics and proteins. The methane in biogas can also be fermented into liquid fuels or solvents using microorganisms called methanogens. Fermented biomass cell waste can also be sterilized for use as a feed, fertilizer, or feedstock for biorefining.

Animal feed or feed supplements can be produced from material such as sugars, starches, proteins, lipids, enzymes, microbes, and meal (the name for residue remaining after extracting oil), after a level of processing that can range from simple purification to drying, fermentation, or hydrothermal processing. Some of these solid outputs also have potential value to be hydrolyzed to amino acids, which can either be sold for pharmaceutical purposes or fermented into mixed alcohols such as butanol or pentanol. Further, enzymes, microbes, and proteins can be used as feed for anaerobic digesters.

Fertilizer can be produced from materials such as lignin, the ash from biomass, and other mineral matter. Ash can also be used for making cement, for road aggregate and roofing supplies (depending upon the form and composition), for fuel additives in power generation, for aromatic chemicals, carbon composite materials (after a separation process), and even upgraded to high octane number gasoline (as demonstrated by the Southwest Research Institute).

Recycling or reuse is an alternative to disposal for output materials such as metals (which can be sold after separation and purification), organic acids (which must be recovered, a process which is currently cost-prohibitive), waste heat (high level heat is generally economical to reuse at the plant or can be recovered for use in secondary application), and waste water (which can be treated and reused outside of the conversion facility and, in some cases, can be used to earn remediation credits).

Lastly, chemical recovery is a monetization option for both aqueous phase liquid (an output of the various processes that can be converted either biologically or catalytically to fuel or high-value chemicals) and for inorganic acids (which currently lack cost-effective separations methods but have many traditional chemistry pathways available for upgrading).

The group voted on which waste streams have the highest likelihood for being valuable revenue streams and have the highest impact on the biorefinery's profitability. Results are illustrated in Figure 4 below. Participants ranked each stream's impact and likelihood on a scale of one through five. The results for each stream were multiplied with even weighting to provide the product displayed in Figure 4.

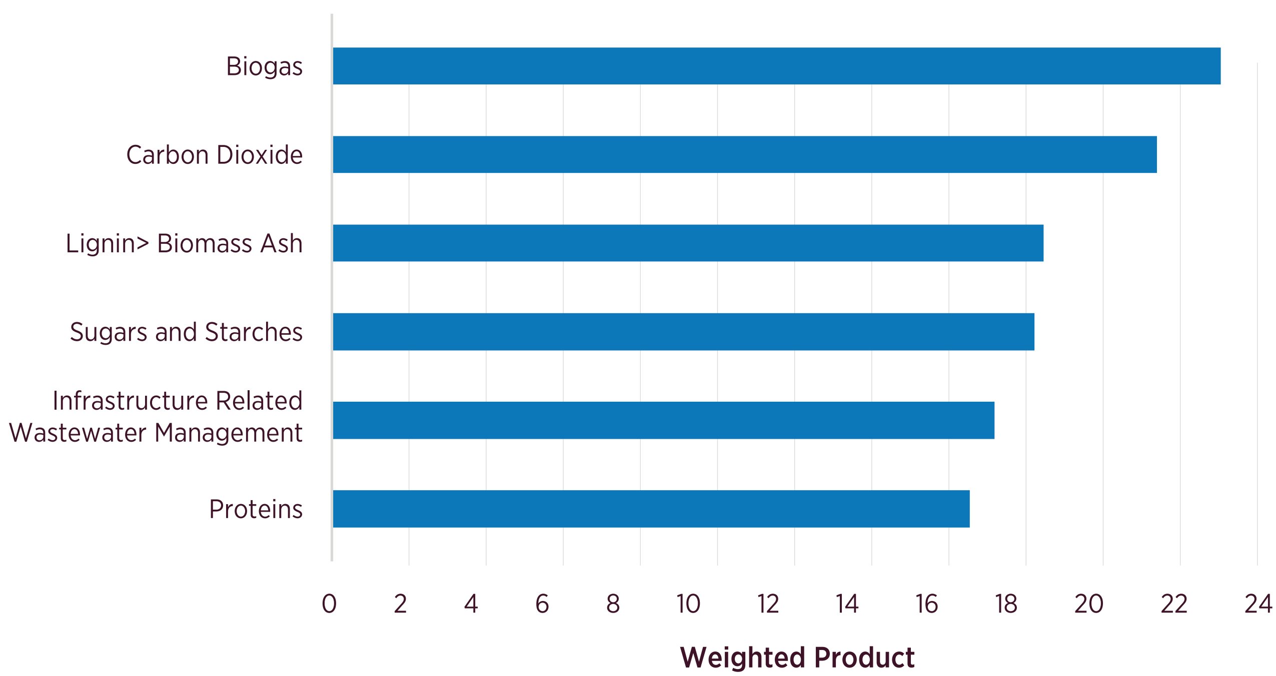


**Figure 4. Top priority waste streams as voted by session participants**

### *Co-Product Stream Value*

Several co-products that can be derived from biorefinery outputs are also described as waste streams in the previous section, including $CO_2$, lignin, biogas, lipids, starches, sugars, enzymes, organic acids, and wastewater. In addition to the potential value previously described, the breakout session participants mentioned additional end uses in the context of co-product value. These include using lignin to fuel the boilers, combusting biogas for electricity, using lipids as a feedstock for specialty chemicals, using $CO_2$ as a carbonation product for the soda industry, and separating organic acids to be sold as high-value di-acids.

Fertilizer, animal, and fish feed were also discussed as potential co-products, with a few additional comments provided by participants:

- Sulfur/sulfuric acids can be used as a fertilizer.
- Biochar can be used a soil amendment.
- Omega-3 can be separated and sold as a high-value nutritional supplement.
- Nutraceutical utilization requires additional separation, concentration, and purification steps before being sold; approvals may be costly and time-consuming.
- Animal feed utilization requires the removal of compounds that deter consumption or digestion and generally require drying.
- Waste water with high levels of sodium hydroxide (NaOH) can also be used for $CO_2$ capture purposes.

Biochar was also identified as containing value in anaerobic digestion, activated carbon, and as a substitute for carbon black.

Bio-oil was identified as a potential specialty chemical feedstock, although not particularly well suited as a commodity chemical feedstock. Bio-oil is derived through both pyrolysis and hydrothermal liquefaction processes and can be upgraded either in a standalone unit or in an existing petroleum refinery for use as a fuel or chemical feedstock.

Short chain hydrocarbon waxes hold potential value as fuel, through hydrocracking or hydrotreating processes. These waxes can also be reformed using the Fischer-Tropsch process to be reused in the biorefinery. Lastly, both furfural and furans can be separated and concentrated for use in the biorefinery or sold. A participant noted that hydroxymethyl furfural has a particularly high market value as a food-grade flavor ingredient.

The group voted on which co-product streams have the highest likelihood for being valuable revenue streams and have the highest impact on the biorefinery's profitability. Results are illustrated in Figure 5 below. Participants ranked each stream's impact and likelihood on a scale of one through five. The results for each stream were multiplied with even weighting to provide the product displayed in Figure 5.

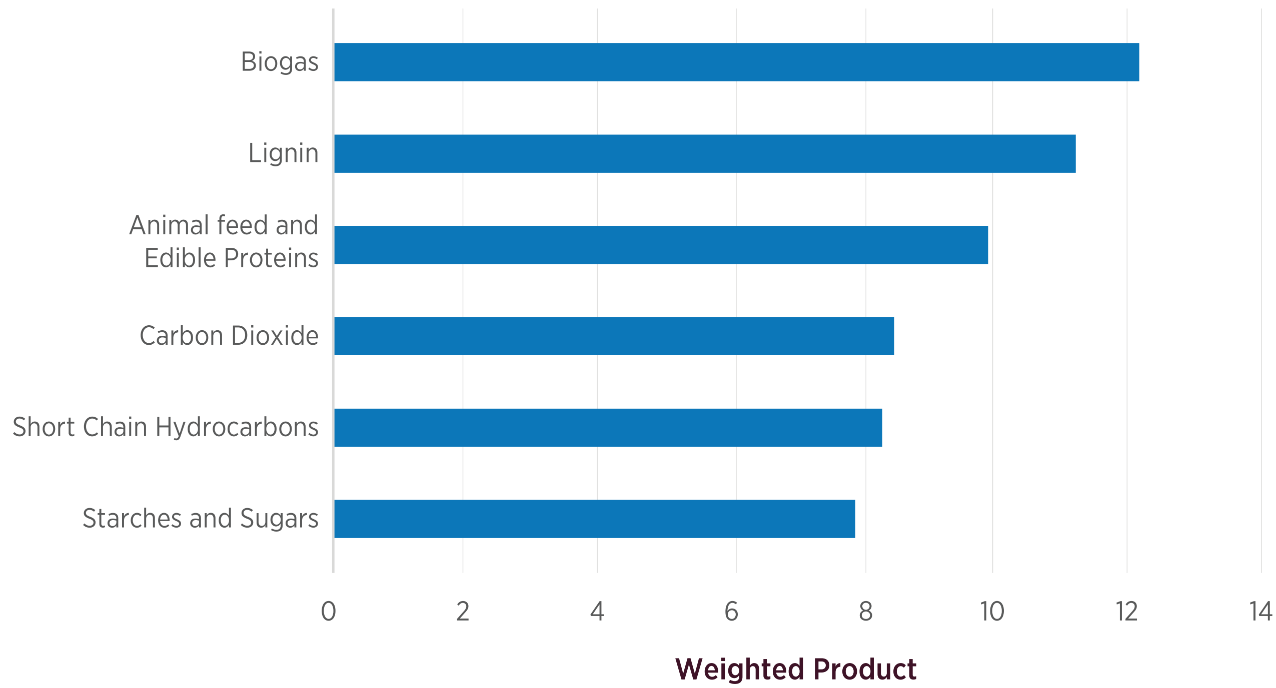


**Figure 5. Top priority co-product streams as voted by session participants**

### *By-Product Stream Value*

Several by-products that can be derived from biorefinery outputs are also described as waste streams, including $CO_2$, CO, lignin, ash, and organic acids. The breakout session participants provided additional comments about potential uses of these materials in context of by-product streams. For example, in addition to being a feedstock and a component of enhanced oil recovery processes, $CO_2$ can be used as a carbon source in fermentation to produce high-value co-products such as malic acid. In addition to being used to produce hydrogen, CO can be used to make oxo alcohols and ethanol or to burn for combustion. Organic acids such as acetic acid can be ketonized to intermediate building blocks for fuels or chemicals. Comments were made that generally ash does not need to be upgraded to use as an input for cement or bricks and thus can be defined as a by-product as much as a co-product.

Other by-products that can be sold to create additional revenue streams for biorefineries include hydrogen, which can be used in hydrotreating; oxygen, which can be used to make acids; naphtha and naphthalenes, which can be blended into fuels; distillate and kerosene, which can be sold as diesel and jet fuel, respectively; phenols, which are polymer precursors that can be sold as a commodity; and BTEX (benzene, toluene, ethylbenzene, and xylenes), which can be separated and sold as chemicals. Further, protein can be liquefied into polyols or amino acids and biomass residues can be used directly in hydrothermal processing or anaerobic digestion.

The group voted on which co-product streams have the highest likelihood for being valuable revenue streams and have the highest impact on the biorefinery's profitability. Results are illustrated in Figure 6 below. Participants ranked each stream's impact and likelihood on a scale of one through five. The results for each stream were multiplied with even weighting to provide the product displayed in Figure 6.

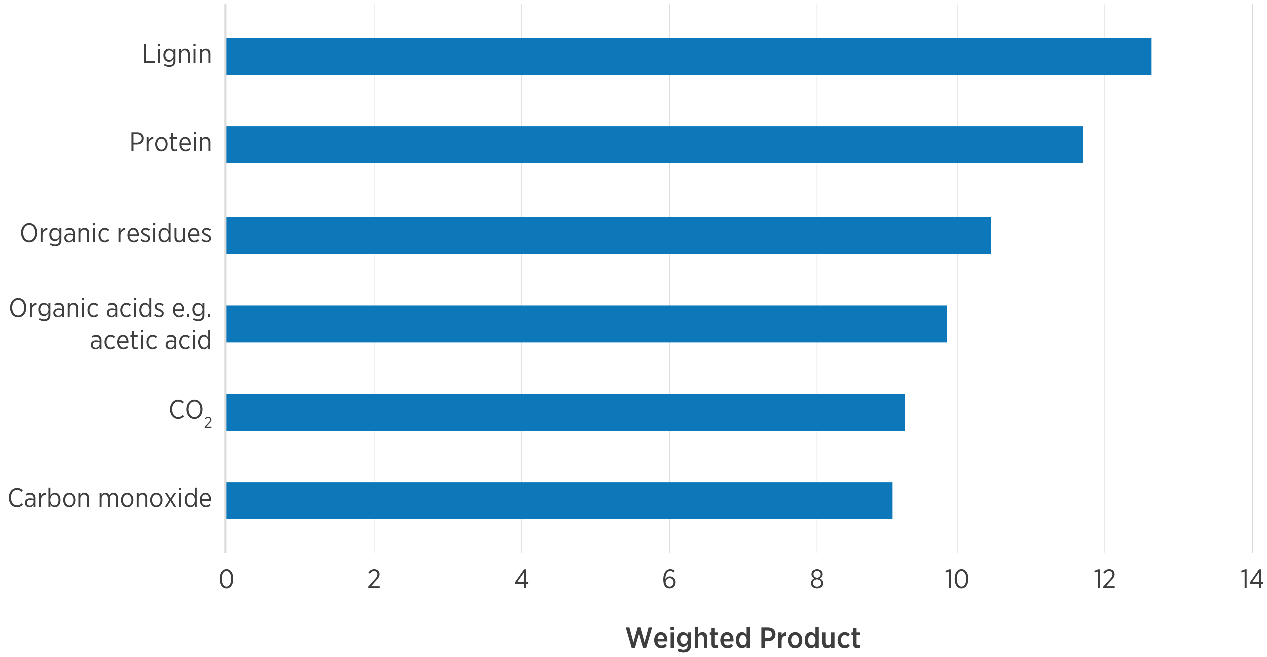


Figure 6. Top priority by-product streams as voted by session participants

### Monetization Challenges

Despite the potential of these waste streams to produce additional revenue, biorefineries have not yet sought to monetize them for various reasons. Biobased petroleum alternatives rely on crude prices to stay economically viable. The present low cost of a barrel of crude means that monetizing these streams may not fit into a company's business model, but if crude prices increase, the economics could change.

Participants pointed out that biorefineries are already quite complex and at smaller scales, it may not be cost effective for these facilities to incorporate the additional steps needed to capture and monetize a waste stream. Other barriers to waste stream monetization listed were on the market side of the equation.

The group noted that unless a product is a drop-in replacement, it would have to sit until the biorefinery finds a buyer, which is uneconomical for the biorefinery. Participants also found that there is lack of regulatory push for producers. Without the right market pull and regulatory incentives, these companies are not willing to invest their effort into finding the processes and markets needed to make it work.

### Waste Stream Value

The breakout group discussed the current value of waste streams to the biorefinery. In many biorefineries, lignin is fed to the boiler and is ultimately valued as equivalent to its heating value. This heating value is typically benchmarked against coal pricing, adjusted for British thermal unit (commonly referred to as BTU) value.

For some other streams, however, proper disposal may require that the waste be landfilled. Landfill costs may range from \$35–\$65 per ton of waste. These costs can add up for smaller facilities, and so utilizing these waste streams would not only produce additional revenue—it would also offset the cost of landfilling.

In addition, the value of $CO_2$ from a biorefinery is significant. Attendees noted that the ability to monetize $CO_2$ would drastically change the economics of the facility. Pure $CO_2$ can be sold to the soda industry and to enhanced oil recovery operations at prices up to \$160 per ton. Other biorefinery waste, such as ash, could potentially be sold to fertilizer producers at a lower cost of around \$10 per ton.

### Future Directions

In discussing these streams and their potential to produce additional revenue, participants expressed that they would be willing to work with national laboratories, universities, commercial partners, and vendors in order to better understand these streams and help optimize unit operations. Due to the sensitive nature of this type of work, participants stressed that strong confidentiality and material transfer agreements would need to be in place before agreeing to provide samples for research.

## Day One Summary

The first day of the workshop included a morning plenary session featuring presentations from pioneers in the biofuels industry and afternoon breakout sessions focusing on three topic areas: (1) feedstock and materials handling; (2) process scale-up, intensification; and cost reduction; and (3) opportunities and strategies for monetizing co-product and waste streams. The highlights from each of the plenary and breakout sessions are summarized below.

### Plenary Session

Industry leaders spoke to attendees about recent R&D achievements related to workshop topic areas. The objective of the plenary session was to set the stage for the breakout session discussions. Through short presentations, industry pioneers provided updates about the current state of the industry, shared perspective on the state of art, and suggested solutions for overcoming challenges.

Speakers highlighted current issues facing IBRs. One of the challenges is operator reliance on vendors for testing equipment. Feedstock challenges include the need to test non-pristine material and to improve both feedstock characterization and feedstock preprocessing methods. In addition, the industry needs proper scale-up and testing for significant periods of time to ensure reliable IBR operation with lower capital and operational costs during the commercialization steps.

Recommendations for successful IBR operations emphasized the importance of proper project management to de-risk new technologies utilizing unique materials. One aspect of proper project management is comprehensive engineering feasibility and design phases, with a focus on the entire supply chain. Pre-processing is an invaluable step to preparing a more consistent and reliable feedstock, which serves to reduce feed handling issues and lower operational costs.

Current efforts to improve safety include the development of training and reference materials for engineers, as well as the professionals who develop codes and standards, especially related to fire prevention. Suggestions for improving the economics of IBR projects included applying approaches from the first-generation ethanol industry to guide design and construction of new facilities, which could decrease capital expenditures and operational costs.

Workshop participants made suggestions of how to expand revenue streams by monetizing residue and waste streams. One way is to identify co-products during the initial process design and avoiding making process changes without assessing the co-product impact. Additionally, companies can work to align co-product production capacity with market potential, as well as infrastructure, logistics, and regulatory requirements. Another suggestion was to consider how biomass waste streams can be used to derive biobased chemicals that can be substituted for petroleum-based products.

The plenary session presentations from the Biorefinery Optimization Workshop can be found online at [energy.gov/eere/bioenergy/events/biorefinery-optimization-workshop](energy.gov/eere/bioenergy/events/biorefinery-optimization-workshop).

### Breakout Session One

*Feedstock and Materials Handling*

Participants in the feedstock and materials handling breakout session provided valuable input regarding the challenges and potential solutions associated with the biomass delivery and processing. The top operational challenge identified was flowability. Additional operational challenges included feedstock variability, equipment uptime, lack of equipment performance data, and feedstock specification standards.

Proposed solutions for these issues focused on improving feedstock consistency with the following actions:

- Perform additional characterization of incoming non-pristine feedstocks to understand ash, moisture, soil, and rock content.
- Define basic metrics for the processing system, including density, feedstock moisture content, and particle size distribution.
- Incorporate advanced metrics, including angle of repose, compressibility, and shear stress.

Solids handling related challenges were categorized into two groups: (1) those related to transportation, storage, and logistics; and (2) those related to engineering processes, such as flowability, milling, screening, and drying. The potential solutions for these solids handling challenges are listed below.

1. Transportation, storage, and logistics:

- Increase feedstock densification.
- Develop improved storage depots, which allow for moisture drainage and rain protection.
- Develop advanced feedstock supply system depots to serve as an intermediary between feedstock suppliers and biorefineries.

2. Engineering processes:

- Design equipment, including conveyors, bins, and handling systems, based on the flowability of the feedstock material and according to the likely range of material specifications encountered.
- Develop better understanding of different types of deconstruction equipment and impact on flowability (e.g., hammer vs. knife mill).
- Develop simple hand-held or in-line analysis devices for moisture, metals, etc.

### Breakout Session Two

*Process Scale-up, Intensification, and Cost Reduction*

Process intensification was noted as a critical area in which IBRs could increase efficiency and decrease both CapEx and OpEx. Additionally, the group identified that it is vital for projects to perform robust data collection and ensure proper pilot- and demonstration-scale activities before scaling up to the next facility. Participants proposed the following challenges and solutions:

- Scale-up
    - Ensure pilot facility will scale up and correlate with the demonstration and commercial scale facilities.
- Equipment design
    - Understand kinetic and mass transfer limitations.
- Feedstock variability
    - Characterize feedstock properties and use non-pristine feedstock during the design stages (pilot and demonstration).

- Project management
    - Maintaining project schedule.
    - Establishing performance expectations.

### Breakout Session Three

*Co-Product and Waste Stream Monetization*

Material that is not used directly towards the production of fuel may remain as a waste until it is sold as a by-product to a customer or until it can be processed into a co-product for sale. Participants explained their experience working to monetize material streams, including the challenges and proposed the ways on how to overcome the discussed challenges.

Monetization of the waste, co-product, and by-product streams is often an important aspect of achieving profitability at an IBR. To enhance understanding of these streams and optimize facility operations, stakeholders recommended cross-sector collaboration with a respect for IP.

## Day Two Summary

On the second day, all breakout session groups discussed the following primary questions: "What are opportunities for stakeholder collaboration?" and "How can DOE-BETO continue to support biorefinery optimization with future funding opportunity announcements?" This section includes responses to these questions, as well as a summary of overall workshop conclusions.

### Opportunities for Stakeholder Collaboration

As it relates to biorefinery optimization, stakeholders represent both the public and private sectors, governmental organizations, national laboratories, academic research institutions, industry associations, biomass crop suppliers, project developers, plant managers, fuel suppliers, and logistics operators.

To establish an optimized process across the entire supply chain, these stakeholders must coordinate effectively. During breakout session discussions, participants provided anonymous suggestions about which challenges could be addressed through collaboration, as well as which platforms could support collaborative initiatives. The input is categorized below in the following topics: consortia, IP, risk mitigation and project oversight, project development and scale-up, feedstock supply, and data availability and consistency.

*Consortia*

Consortia have the potential to provide a platform to aid collaboration. In the context of addressing value chain bottlenecks, participants noted that no one developer can solve the value chain bottlenecks on its own. Even large corporate facilities have peripheral issues related to "non-core" process steps. One suggestion was to use workshops to begin the process of coordination within the industry. These stakeholder workshops could serve to identify which specific process steps should be the focus of collaborative efforts. Workshop agendas could be developed around particular core technologies, such as either thermochemical or biochemical conversion. The Advanced Manufacturing Office within DOE funds large industry collaborations and could be a good model to follow for this effort. Other examples of industries that have collaborated in similar ways include SEMATECH (a 12-member global consortium of major computer chip manufacturers), the automobile industry, and the pulp industry.

Participants also recommended consortia be developed to facilitate collaboration around improving transportation storage and logistics, addressing political barriers, and optimizing engineering processes such as feedstock flowability and variability, equipment uptime, milling, screening, and drying.

### *Intellectual Property*

To address the speed with which biorefinery technology advances, participants noted that there is a need for a platform where companies can collaborate on their IP while retaining their rights. At this time, when companies work with national laboratories, IP rights are determined by DOE. Representatives from both companies and laboratories suggested that their organizations would like to work with strong industrial partners whose business models include robust IP and licensing capability. This is seen as a low-cost opportunity to quickly improve biorefinery optimization, compared to the current option of contracting with independent research organizations that offer broad technical know-how and industry connections while allowing the technologists to retain the IP rights.

### *Risk Mitigation and Project Oversight*

Current trends suggest that industry prefers to postpone risk mitigation because it is an additional cost to an already expensive project development process. Companies that discussed their experience with conducting a complete risk analysis at the beginning of a project explained that often it can be an uncomfortable and contentious effort but that the outcome and benefit is fundamentally positive. One company, in particular, changed its practices to involve a third party engineer to provide project oversight at every step of process execution. This approach has added value to the company by mitigating risk before money is spent.

### *Project Development and Scale-Up*

Breakout session participants suggested roles for each stakeholder category related to the process of project development and scale-up. Industry can work to form partnerships for large-scale demonstration projects, especially organizations with existing capabilities in pilot testing facilities. Academic institutions, as well as national laboratories, could contribute by licensing technologies to industry. Laboratories can also expand their existing user-facility, in-kind assistance, and technologist-in-residence programs. Lastly, the government could work to expand collaborative funding opportunities such as the Biomass Research and Development Initiative (BRDI).

### *Feedstock Supply*

Suggestions for potential areas of feedstock supply collaboration were related to expanding types of feedstocks, providing opportunities for small landowners to grow biomass crops, and establishing more feedstock aggregation operations. Several participants noted that wet biomass wastes, such as bio-solids from wastewater treatment, are a significant opportunity for feedstock supply growth that is currently under-represented in the biorefining industry. Developing a consortium around wet feedstocks was one suggestion made about how to encourage stakeholder collaboration to further develop this resource.

Another way of increasing the feedstock supply involves supporting the growth of new crops. Representatives of the agriculture industry explained that the current lending atmosphere requires that a farmer have three years of history growing a new crop before financing is available. In order to overcome this barrier, there must be support from more than one federal agency in demonstrating to bankers that the project is financially viable. Another way that the government can support financing for farmers is by introducing an insurance program that serves as a backstop to de-risk the initial investment.

In terms of improving feedstock quality and stability, participants suggested that there is a role for feedstock aggregators. These aggregator facilities would theoretically offer feedstock suppliers with long-term, take-or-pay, off-take agreements and then provide delivery services to biorefineries.

### *Data Availability and Consistency*

Data collection, reduction, and analysis are the keys to optimizing biorefinery operations. Currently, there is a lack of performance data from commercial equipment. This data could support scale-up efforts. Also, feedstock quality assurance and control could be improved by clearly defining feedstock specifications, cost, and availability. With respect to biomass properties, there tends to be inconsistency between metrics used by feedstock suppliers and those used by refiners. Both parties should collaborate to establish mutually agreed upon indicators, metrics, and measurement methods.

## Input for DOE

As the federal agency with a mission of ensuring America's security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions, DOE works to secure U.S. leadership in clean energy technologies, including biorefineries. As such, DOE supports BETO in establishing partnerships with key public and private stakeholders to develop and demonstrate technologies for producing cost-competitive advanced biofuels from non-food biomass resources, including cellulosic biomass, algae, and wet waste. BETO actively seeks input from its industrial, academic, agricultural, and nonprofit partners through sessions such as the Biorefinery Optimization Workshop.

During the breakout sessions, workshop participants made suggestions for BETO regarding collaboration with USDA, direction of R&D funding, scope of small business vouchers, availability of test facilities, support for market development, and facilitation of stakeholder collaboration.

### *Collaboration between DOE and USDA*

A strong partnership with USDA is very important for BETO, and the two federal agencies work closely together on projects such as the Biomass Crop Assistance Program (BCAP), BRDI, and the Federal Bioeconomy Initiative. Breakout session participants offered suggestions for expanding and improving upon these projects in order to provide further support to the biorefining industry. For example, one idea was to combine the facilities of a USDA Center of Excellence with BETO expertise to assist with project development, especially for projects using USDA loan guarantee money.

Another recommendation was to modify BCAP to allow for the establishment of bioenergy crops and for the harvest of those crops in order to provide feedstocks for biofuels and bioproducts. Participants described BCAP as a great tool for accelerating the adoption of proven biorefinery technologies that need greater eligibility flexibility. The discussion noted that earlier-stage funding mechanisms for farmers are still not sufficient within BCAP and that that a good model for expansion is the USDA Conservation Reserve Program.

Regarding BRDI, participants noted that the initiative is a valuable joint funding source with some room for improvement. One suggestion was to better align the funding awards with product development needs and provide more joint funding opportunities with a focus on supporting reliable feedstock supply and quality. The discussion also noted that BRDI could be used to fund large-scale demonstration projects among multiple companies, which could be used as models for future development efforts.

Regarding loan guarantee programs, participants suggested removing the three-year past history requirements currently in-effect for both DOE and USDA programs. Other recommendations applicable to the DOE-USDA partnership focus on how to expand collaborative funding for by-products. Participants noted that that DOE has the technical expertise on staff and a focus on grants but is limited by a focus on fuels, compared to USDA, which has funding and directive to push by-products, but only a model of loan guarantees for larger funding. The concluding point from that discussion was that a by-products grant program administered by DOE could push the bioenergy industry forward.

### *Support Stakeholder Collaboration*

Several comments focused on "Input for DOE-BETO" were related to the previous section, "Opportunities for Stakeholder Collaboration." Breakout session participants made recommendations specifically on how BETO can be actively involved with research, development, and demonstration efforts from their first inception.

To be a core part of the biorefinery industry network, attendees suggested that BETO continue to participate in industry organizations to develop deeper stakeholder relationships, exhibit at industry events, and hold workshops in coordination with industry meetings (following the model of oil and gas industry "user meetings"). BETO could also develop collaborative initiatives with bio-materials buyers groups, such as those that function within the American Chemistry Council. This effort could serve to build market pull, as well as establish coordination on biomass material specifications.

Further, stakeholders noted a need for funding to support groups of companies that are collaborating to solve common problems faced in commercial production. To help develop integrated biorefining models, participants suggested that BETO encourage university and government bioenergy experts to collaborate with the national laboratory efforts. DOE and/or other agencies could contribute funding to this work as appropriate.

### *R&D Funding*

Breakout session discussions noted that the bioenergy industry needs financing to develop bioproducts that are not necessarily tied to the production of fuels. Participants suggested DOE engage companies to develop specialized equipment for bioenergy crops. They also noted that national laboratories need access to industrial waste, co-product, and by-product streams (through proper Materials Transfer Agreement) for product development R&D. Lastly, for the Small Business Innovation Research program, participants recommended that the restriction on re-application be removed because it is detrimental for projects that did not receive an award on  their first application.

### *Small Business Vouchers Pilot*

Participants discussed that the vouchers that DOE awards through the EERE Small Business Vouchers Pilot provide a valuable contribution to the bioenergy industry by allowing small businesses to utilize the intellectual and technical assets available within the national laboratories.

A few suggestions for improving the program included the following: expanding the marketing reach, increase the funding levels, expanding the applications to meet commercial needs, and utilizing the program to further develop collaborations between industry and the national laboratories.

### *Demonstration-Scale Test Facility*

One of the more common suggestions made by workshop participants was that DOE sponsor a demonstration-scale test facility. It could involve a biorefinery test-bed hosted at either a neutral site (such as a university) or at a retrofitted stranded asset (such as a recently shutdown biorefinery). Participants noted that this type of facility could serve to further support collaboration between national laboratories and industry. Recommended sizes included 100,000 liters of daily production capacity or approximately 330 dtpd. Regular operation could be conducted through a public-private partnership.

### *Data Resources*

Breakout session participants suggested that DOE funding be provided for collaborative data collection and analysis from feedstock harvesting, mixing, cleaning, and delivery to the biorefinery. One recommendation is to make aggregate data available to all bioenergy industry stakeholders.

### *Support Market Development*

Stakeholders suggested that DOE has the potential to be a "market maker." Participants noted that there is often a gap between the level of funding competitively awarded by DOE and the financing provided through conventional banking. USDA was noted as having a good model of programs that serve as government-led product clearinghouses, as well as marketplaces for off-take purchases.

One suggestion was for DOE to create a "pre-loan guarantee." It is difficult for multiple producers to share off-take agreements from customers because of each company's interest in protecting its own IP. On the other hand, public off-take agreements can create a "market pull" for products that helps producers to develop a strong business case.

Participants also noted that biobased chemicals need less market pull. Both EPA and USDA already have market policies in place specific to chemicals. Grants are needed to have market parity for biofuels, biobased chemicals, and bioproducts. Furthermore, no two start-up companies are the same. Different companies have different strengths and requirements. With that understanding, DOE support should not require a firm mold; it needs to have the flexibility to accommodate the diverse needs of the start-ups.

## Conclusion

Based on the presentations made by IBR experts and the input received from stakeholders, there are several recommended areas of focus as industry moves towards the production of increasing volumes of biofuels. BETO would like to express thanks to all of the participants for their time, efforts, and contributions. The discussions and information provided through the plenary presentations, open forum, and breakout sessions are extremely valuable to the DMT Program, and we look forward to continued collaboration as we utilize this feedback to inform program strategies moving forward.

# Appendix A: Workshop Agenda

| Wednesday, October 5, 2016 | | |
|---|---|---|
| **Time** | **Agenda Item** | **Speaker Name** |
| 8:00 a.m.–8:30 a.m. | **Welcome & Opening Remarks, Bioenergy Technologies Office (BETO)** | • Jonathan Male, Director: BETO Overview<br>• Borka Kostova, Technology Manager: Workshop Overview |
| 8:30 a.m.–9:30 a.m. | **Feedstock & Materials Handling Efforts: Overview of Key Technical and Economic Challenges** | • Moderator: Mark Elless, DOE<br>• Carrie Hartford, Jenike & Johanson<br>• Kevin Comer, Antares Group<br>• Erin Webb, Oak Ridge National Laboratory<br>• Kevin Kenney, Idaho National Laboratory |
| 9:30 a.m.–9:45 a.m. | **Networking** | |
| 9:45 a.m.–10:45 a.m. | **Process Scale-Up, Intensification, and Cost Reduction** | • Moderator: Elliott Levine, DOE<br>• Steven Mirschak, DuPont<br>• Robert Graham, Ensyn Technologies<br>• Martin Linck, Gas Technology Institute<br>• Theodora Retsina, American Process, Inc |
| 10:45 a.m.–11:45 a.m. | **Co-Product and Waste Stream Monetization** | • Moderator: Prasad Gupte, DOE<br>• Bob Rozmiarek, Virent<br>• Mark Warner, Warner Advisors, LLC<br>• Laurel Harmon, LanzaTech<br>• Amit Naskar, Oak Ridge National Laboratory |
| 12:00 a.m.–12:45 p.m. | Lunch (provided) | |
| 12:45 p.m.–5:30 p.m. | **Breakout Session One:** Strategies for Improving Feedstock & Materials Handling | • Moderator: Mark Elless, DOE |
| 12:45 p.m.–5:30 p.m. | **Breakout Session Two:** Strategies for Scaling-Up IBR Processes and Improving IBR Operational Methods, Efficiency, and Project Financing | • Co-Moderator: Elliott Levine, DOE<br>• Co-Moderator: Siva Sivasubramanian, DOE |
| 12:45 p.m.–5:30 p.m. | **Breakout Session Three:** Opportunities and Strategies for Monetizing Co-Product and Waste Streams | • Moderator: Prasad Gupte, DOE |
| 5:30 p.m. | Adjourn Day 1 | |

| Thursday, October 6, 2016 | | |
|---|---|---|
| **Time** | **Agenda Item** | **Speaker Name** |
| 8:15 a.m.–8:30 a.m. | **Welcome Back Remarks** | • Jim Spaeth, DOE<br>• Borka Kostova, DOE |
| 8:30 a.m.–10:45 a.m. | **Breakout Sessions: Advancement Activity Action Plans** | |
| 11:00 a.m.–11:30 a.m. | **Breakout Sessions Day 2 Reports, Action Plans, and Q&A** | |
| 11:30 a.m.–11:45 a.m. | **Closing Comments and Next Steps** | |
| 12:00 p.m. | Adjourn Workshop | |

# Appendix B: Workshop Attendees*


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# Appendix C: Abbreviations and Acronyms

| | |
|---|---|
| **BETO** | Bioenergy Technologies Office |
| **BCAP** | Biomass Crop Assistance Program |
| **BRDI** | Biomass Research and Development Initiative |
| **CapEx** | capital expenditure |
| **$CO_2$** | carbon dioxide |
| **CO** | carbon monoxide |
| **DDGS** | dried distillers grains and solubles |
| **DMT** | Demonstration and Market Transformation |
| **DOE** | U.S. Department of Energy |
| **dtpd** | dry tons per day |
| **EERE** | Office of Energy Efficiency and Renewable Energy |
| **EPA** | Environmental Protection Agency |
| **FCC** | Fluid Catalytic Cracker |
| **$H_2$** | hydrogen |
| **IBR** | integrated biorefinery |
| **ICC** | International Codes Council |
| **INL** | Idaho National Laboratory |
| **IP** | intellectual property |
| **LCFS** | Low Carbon Fuel Standard |
| **MSW** | municipal solid waste |
| **NREL** | National Renewable Energy Laboratory |
| **OpEx** | operational expense |
| **ORNL** | Oak Ridge National Laboratory |
| **R&D** | research and development |
| **RIN** | Renewable Identification Number |
| **TRL** | technology readiness level |
| **USDA** | U.S. Department of Agriculture |

# Appendix D: Related Links

Biorefinery Optimization Workshop
energy.gov/eere/bioenergy/events/biorefinery-optimization-workshop

Bioenergy Feedstock Library
bioenergylibrary.inl.gov

Biological Conversion of Sugars to Hydrocarbons Pathway
energy.gov/sites/prod/files/2014/04/f14/biological_conversion_of_sugars_to_hydrocarbons.pdf

Biomass Research and Development Initiative
biomassboard.gov

Bioproducts to Enable Biofuels Workshop
energy.gov/eere/bioenergy/bioproducts-enable-biofuels-workshop-0

Bioproducts to Enable Biofuels Workshop Summary Report
energy.gov/sites/prod/files/2015/12/f27/bioproducts_to_enable_biofuels_workshop_report.pdf

Bioenergy Technologies Office
bioenergy.energy.gov

Bioenergy Technologies Office Glossary
energy.gov/eere/bioenergy/glossary

Bioenergy Technologies Office Multi-Year Program Plan: March 2016
energy.gov/eere/bioenergy/downloads/bioenergy-technologies-office-multi-year-program-plan-march-2016

Environmental Protection Agency: Renewable Fuel Standard Program
epa.gov/renewable-fuel-standard-program/final-renewable-fuel-standards-2017-and-biomass-based-diesel-volume

Environmental Protection Agency Renewable Volume Obligations
https://www.gpo.gov/fdsys/pkg/FR-2016-12-12/pdf/2016-28879.pdf

Office of Energy Efficiency and Renewable Energy
energy.gov/eere

U.S. Department of Energy
energy.gov

# Appendix E: Technology Readiness Levels

| | |
|---|---|
| **TRL 1** | **Basic principles observed and reported:** Scientific problem or phenomenon is identified. Essential characteristics and behaviors of systems and architectures are identified using mathematical formulations or algorithms. The observation of basic scientific principles or phenomena has been validated through peer-reviewed research. Technology is ready to transition from scientific research to applied research. |
| **TRL 2** | **Technology concept and/or application formulated—**applied research activity: Theory and scientific principles are focused on specific application areas to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application. |
| **TRL 3** | **Analytical and experimental critical function and/or characteristic proof of concept:** Proof of concept validation has been achieved at this level. Experimental research and development is initiated with analytical and laboratory studies. System/integrated process requirements for the overall system application are well known. Demonstration of technical feasibility using immature prototype implementations are exercised with representative interface inputs to include electrical, mechanical, or controlling elements to validate predictions. |
| **TRL 4** | **Component and/or process validation in laboratory environment—**alpha prototype (component): Standalone prototyping implementation and testing in laboratory environment demonstrates the concept. Integration and testing of component technology elements are sufficient to validate feasibility. |
| **TRL 5** | **Component and/or process validation in relevant environment—**beta prototype (component): Thorough prototype testing of the component/process in a relevant environment to the end user is performed. Basic technology elements are integrated with reasonably realistic supporting elements based on available technologies. Prototyping implementations conform to the target environment and interfaces. |
| **TRL 6** | **System/process model or prototype demonstration in a relevant environment—**beta prototype (system): Prototyping implementations are partially integrated with existing systems. Engineering feasibility is fully demonstrated in actual- or high-fidelity system applications in an environment relevant to the end user. |
| **TRL 7** | **System/process prototype demonstration in an operational environment—**integrated pilot (system): System prototype demonstrated in an operational environment. System is at or near full scale (pilot or engineering scale) of the operational system, with most functions available for demonstration and test. The system, component, or process is integrated with collateral and ancillary systems in a near production quality prototype. |
| **TRL 8** | **Actual system/process completed and qualified through test and demonstration—**pre-commercial demonstration: End-of-system development with full-scale system fully integrated into operational environment with fully operational hardware and software systems. All functionality is tested in simulated and operational scenarios with demonstrated achievement of end-user specifications. Technology is ready to move from development to commercialization. |

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**For more information, visit:** energy.gov/eere

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