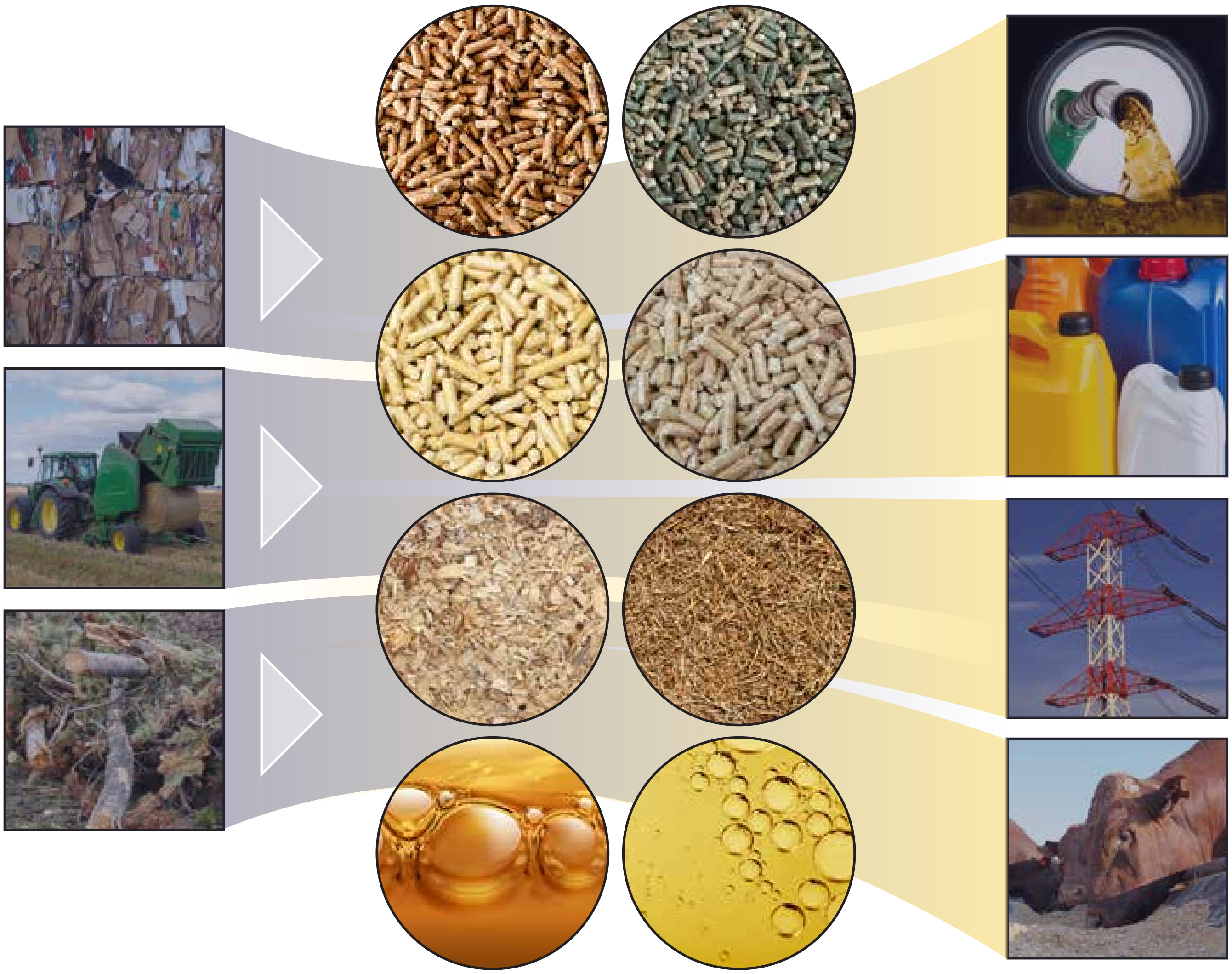
INL/EXT-10-18930

Advanced Feedstock Supply System Validation Workshop

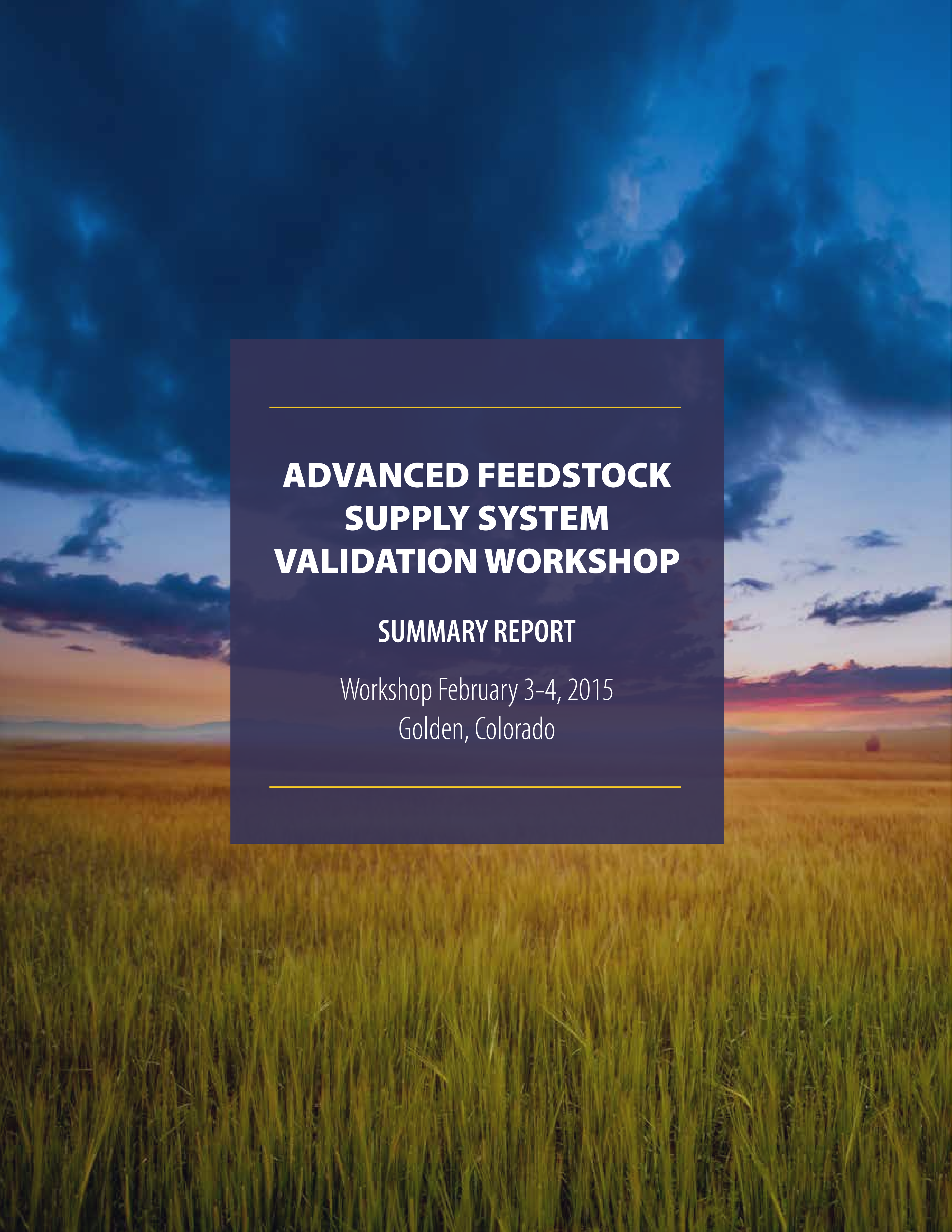
SUMMARY REPORT



Mobilizing the billion tons

U.S. DEPARTMENT OF ENERGY

Energy Efficiency & Renewable Energy



ADVANCED FEEDSTOCK SUPPLY SYSTEM VALIDATION WORKSHOP

SUMMARY REPORT

Workshop February 3-4, 2015
Golden, Colorado

ADVANCED FEEDSTOCK SUPPLY SYSTEM VALIDATION WORKSHOP

Sponsored by the U.S. Department of Energy (DOE) Bioenergy Technologies Office (BETO) in collaboration with Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL)

Authors

Erin Searcy, Patrick Lamers, Jason Hansen, Jacob Jacobson, Richard Hess, and Erin Webb

Workshop Organizers

Daniel Adams, Mary Biddy, Max Broad, Craig Brown, Alan Chute, Laurence Eaton, Mark Elless, Cindy Gerk, Alison Goss Eng, Kevin Kenney, Jody Henley, Jonathan Male, Leslie Ovard, Shahab Sokhansanj, Sam Tagore, and Steve Thomas

Availability

This report, as well as supporting documentation, data, and analysis tools, can be found on the Bioenergy Knowledge Discovery Framework at http://bioenergykdf.net and INL at www.inl.gov.

EXECUTIVE SUMMARY

The Evolution of Bioenergy Feedstock Supply System Concepts

Bioenergy feedstock supply systems have come a long way; rooted in improving supply systems designed for traditional agriculture and forestry industries, years of research, industry experience, and stakeholder input have conceptualized a path to a future of on-spec, merchandisable intermediates that can be delivered to a range of markets.

The initial expansion of the cellulosic bioenergy industry in the United States has been accompanied by an evolution in thinking on the part of many stakeholders with respect to bioenergy feedstock supply systems. Pioneer refineries have been built in the middle of or near high-yielding feedstock resources (such as corn stover in Iowa). They have been built with the intention of limiting transportation distance and its associated cost, while also reducing, to a minimum, the risk associated with obtaining an annual feedstock supply sufficient for achieving the desired production capacity of the conversion facility. Initially, feedstock supply systems research funded by DOE was focused on improving this "conventional" model by increasing equipment efficiency and reducing losses during harvest, transport, and storage operations (Figure 1). Research efforts specifically targeted high yielding areas, which are regarded as niche opportunities, and were successful. BETO demonstrated significant cost reductions relative to conventional systems for both woody and herbaceous biomass, supporting 2012 DOE targets. Contributions to this effort and the resulting improvements were made by a variety of parties, including national laboratories, solicitations funded by DOE (in particular, the five high tonnage projects), academia, and others.

After meeting its 2012 goals, DOE established more aggressive cost and quantity targets that will require new strategies and systems to bring in the

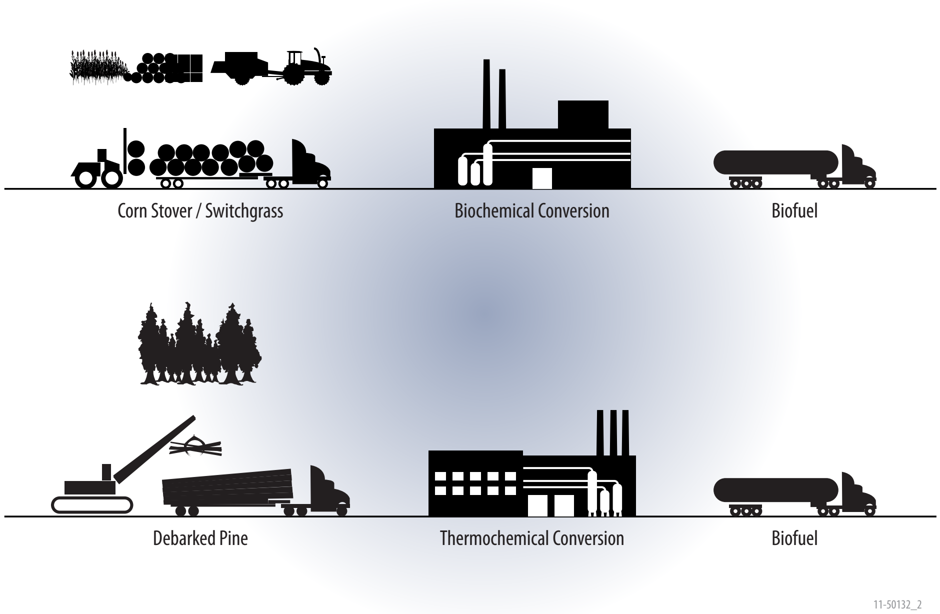


Figure 1. The bulky, highly variable nature of biomass introduces challenges to feedstock supply and logistics, as highlighted in the schematic. Improvements to conventional feedstock supply systems addressing these (among other) challenges resulted in cost reductions and contributed to meeting DOE's 2012 target for delivered feedstock costs.

anticipated larger national volumes of resources from areas outside of these limited high-yielding regions, while simultaneously meeting cost and quality targets required by conversion processes to produce fuels competitive with petroleum-derived gasoline, diesel, and jet fuels. To address higher logistics costs associated with bringing in more remote and less highly concentrated resources in a range of formats and physical and chemical qualities, DOE explored the potential for increasing biomass stability and transport/storage/handling efficiency by increasing biomass density. DOE solicited feedback from stakeholders on this densification challenge, hosting the "Transforming Biomass into Feedstocks" workshop in August 2011, in Idaho Falls, Idaho. Some key themes emerged from the feedback provided by the workshop participants and include the following:

- Increasing logistics equipment and conversion performance and reducing variability by transforming "as-harvested" biomass into feedstocks will be important for developing industrial-scale bioenergy.
- Research and development (R&D) are needed to help address tomorrow's barriers that have a positive impact on today's biorefineries and feedstock supply systems.

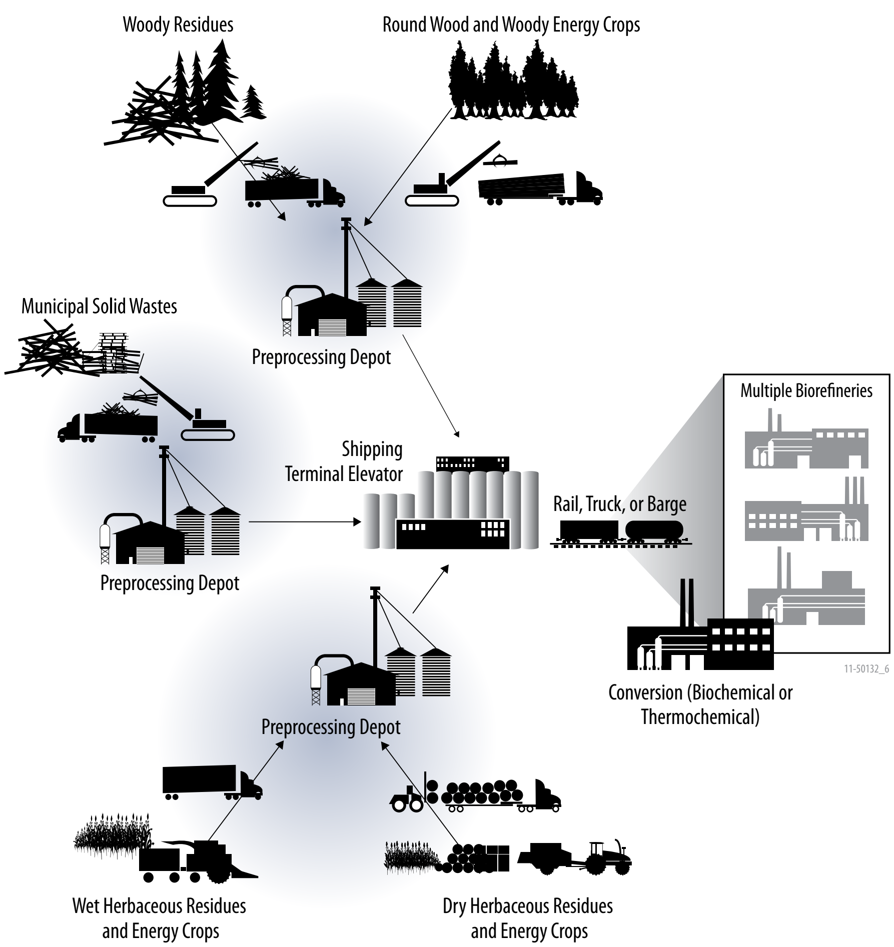


Figure 2. Advanced Feedstock Supply Systems incorporate biomass preprocessing depots to format biomass into a stable, tradable commodity. Initial system designs were vertically integrated with the energy industry and lacked a transition strategy from conventional to advanced systems.

In response to comments and feedback from the workshop, DOE developed the concept of Advanced Feedstock Supply Systems, which are designed to support expansion of the bioenergy industry in the United States by providing strategies and mechanisms for reliably and sustainably supplying biorefineries with on-spec, affordable feedstock at the volumes required for sustainable operation (Figure 2). Advanced feedstock supply systems transform an array of raw biomass resources from a highly variable, aerobically unstable, low density form into a fairly uniform, aerobically stable, high density, tradable, aggregatable commodity. This is accomplished by preprocessing biomass (including milling, densifying, and often drying) at local preprocessing depots and leveraging existing high-capacity handling and transport infrastructure (e.g., trucks, rail, and barge) to move the formatted, uniform biomass commodity longer distances to distributed biorefineries. The uniform format material could be blended with other formatted biomass at a transport terminal and then distributed to biorefineries as an on-spec feedstock for various types of conversion processes that may have different in-feed specifications.

Development of the first set of advanced designs warranted further stakeholder engagement; this time through a workshop focused specifically on vetting Advanced Feedstock Supply System assumptions. The "*Advanced Feedstock Supply System Validation Workshop"* was held Feb. 3 and 4, 2015, in Golden, Colorado. The take-home message from the workshop was resounding—Advanced Feedstock Supply Systems have a place in future supply chains, and the depot concept presented to workshop participants would be effective in supporting a biorefinery industry. It was acknowledged that depots are not required by the industry today and that a transition plan from the present situation is lacking. The industry needs a strong transitional strategy to move us from where we are today with conventional systems to the implementation of Advanced Feedstock Supply System designs and concepts. In response to this feedback, DOE will expand their Advanced Feedstock Supply Systems concept to a model that evolves from producing a tradable, aggregatable biomass commodity to one that has a strong transition component. The strategy moving forward is one that incorporates merchandisable intermediates that can be incorporated into a variety of uses (including and beyond biofuels), providing a value added to generate viable business opportunities in the near term and as the industry grows (Figure 3).

Taking participant feedback into account and building from the initial depot concept of distributed preprocessing centers, these modularized depots would be capable of incorporating advanced preprocessing systems, preconversion processes (such as ammonia fiber expansion [AFEX]), or even modular conversion processes (such as pyrolysis). Rather than merely creating a stable, densified, uniform product, depots would have the option of producing a salable intermediate, eliminating any complete dependency on a single biorefinery or a single industry. The ability to sell products into multiple markets would greatly increase the customer base for depots, removing reliance on an expanding, nascent bioenergy industry. However, this strategy is only now evolving and will require significant effort to materialize.

This report sets forth the key considerations, assumptions, and reasoning behind the Advanced Feedstock Supply System concept and summarizes stakeholder feedback that was received during the *Advanced Feedstock Supply System Validation Workshop* on those elements.

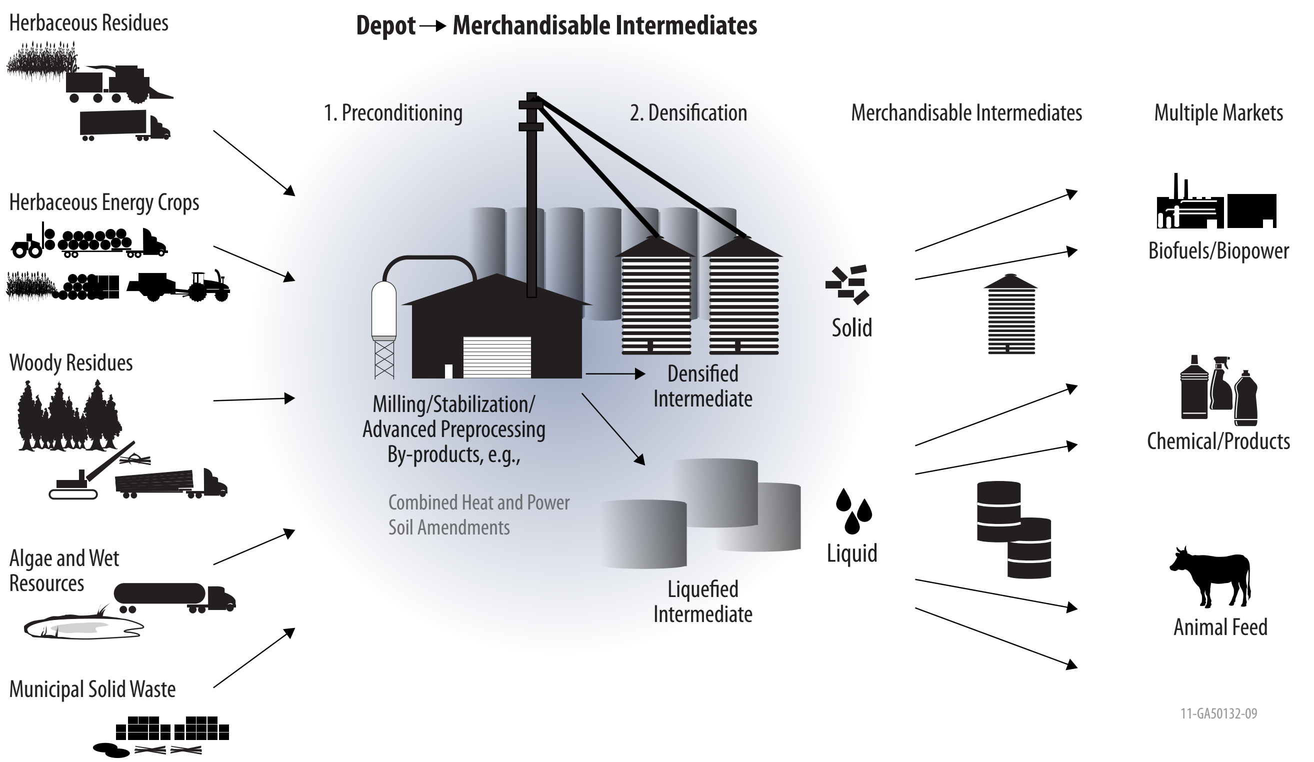


Figure 3. Incorporation of stakeholder feedback has resulted in improvements to the Advanced Feedstock Supply System model by evolving depots from being vertically integrated to producing merchandisable intermediates, serving a plethora of customers and markets.

Delivered Feedstock Cost

Many factors impact delivered feedstock cost, which is comprised of feedstock procurement (i.e., grower payment or stumpage fee) and logistics cost. Factors that impact procurement cost include but are not limited to type of biomass, biomass yield in that region, and competing uses of biomass. Logistics costs are impacted by variability, type of feedstock and format, moisture content, transport distance, quality requirements at the conversion facility, and other factors.

Biomass Energy Resources

As defined in the Multi-Year Program Plan (DOE 2015), biomass is an energy resource derived from plant and algae-based material that includes agricultural residues, forest resources, perennial grasses, woody energy crops, algae, wet waste (e.g., biosolids), municipal solid waste, urban wood waste, and food waste. It is unique among renewable energy resources in that it can be converted to carbon-based fuels, chemicals, or power.

FOREWORD

The United States benefits from a diverse portfolio of energy sources, including renewable energy. Renewable energy includes, but is not limited to, wind, solar, and bioenergy and has numerous benefits in the United States such as job creation and economic growth, contributing to energy independence, and reduction in greenhouse gas emissions. Biomass is a key resource for renewable energy, particularly cellulosic biomass and algae. In fact, as part of a greater resource assessment effort, DOE and the U.S. Department of Agriculture jointly verified that a billion ton per year biomass production industry was possible within the "Billion Ton Study" released in 2005 and updated by DOE in 2011. This biomass could be used as a feedstock for various conversion processes that are used to produce biopower, biofuels, and/or bioproducts. However, the use of biomass as a feedstock on a national scale presents many challenges.

Biomass is inherently widely dispersed and highly variable in terms of material properties among species (e.g., wood vs. herbaceous material). Genetic differences between varieties within each species are the cause of some of this variability. Biomass variability is also impacted by environmental conditions, including soil type, weather patterns, and management practices (e.g., plow vs. no-till, fertilizer and chemical applications, and harvest and storage practices). This variability has many implications, not the least of which is supply chain economics, including effects on conversion process efficiency. Different conversion processes have different material in-feed requirements, with most of them often not being met by field-run biomass. The viability of a growing bioenergy industry is tightly coupled to successfully addressing these biomass diversity and distribution challenges.

Conventional feedstock supply systems exist and have been developed for traditional agriculture and forestry systems. These conventional feedstock supply systems can be effective in high biomass-yielding areas (such as for corn stover in Iowa and plantation-grown pine trees in the southern United States), but they have their limits, particularly with respect to addressing feedstock quality and reducing feedstock supply risk to biorefineries. They also are limited in their ability to efficiently deliver energy crops. New logistics technologies and systems are needed to address these challenges and support a growing bioenergy industry.

The proposed solution put forth by BETO to address these challenges is Advanced Feedstock Supply Systems. The Advanced Feedstock Supply Systems incorporate densification, drying, and other preprocessing technologies to create a biomass commodity. A feature of these advanced systems is biomass preprocessing depots that format biomass in fairly close proximity to the location of production. However, validating assumptions used to develop these advanced systems is critical.

The *Advanced Feedstock Supply System Validation Workshop* gathered experts from industry, DOE offices, DOE-funded laboratories, and academia to discuss approaches to addressing challenges associated with an expanding bioenergy industry and assumptions used in the Advanced Feedstock Supply System. The workshop was sponsored by DOE-BETO.

The Workshop

DOE-BETO hosted the *Advanced Feedstock Supply System Validation Workshop* on Feb. 3 and 4, 2015, in Golden, Colorado. The purpose of the workshop was to bring together a diverse group of stakeholders to examine, discuss, and validate analysis assumptions used to move beyond the existing conventional feedstock supply systems designed to support the agriculture and forestry industries. At the highest level, the assumptions discussed included the following:

- Feedstock supply systems limit biorefinery economies of scale
- Quality is limiting to the biorefinery industry and must be managed in the feedstock supply system
- Risk is important to the biorefinery industry and must be managed in the feedstock supply system.

The workshop was essentially a focus group that was brought together to validate Advanced Feedstock Supply System assumptions related to quantity and transportation logistics, biomass quality, and operational risks. This report is a summation of the expert opinions shared during the workshop.

Session Topics

The topics covered in each session included the following:

1. Barriers to delivering 1 billion tons of biomass to biorefineries annually
2. Advanced feedstock supply system concepts, including depots
3. Business models for advanced feedstock supply systems
4. Siting and sizing considerations for depots
5. Open discussion of unresolved issues.

The goals of the workshop were to (1) validate, modify, or refute Advanced Feedstock Supply System fundamental assumptions, (2) discuss and explore potential industry-scale solutions, and (3) collect and document expert opinion regarding the purposed solutions. To that end, leaders from industry and academia were invited to actively engage in the review and provide recommendations on the Advanced Feedstock Supply System vision.

This report summarizes each of the workshop sessions and provides an overall summary section that captures the high-level conclusions that were garnered from the sessions. The workshop included 23 experts from academia, industry, and other national laboratories. Attendance was by invitation only and all participants paid for their own time and travel expenses.

Workshop Conclusions

The *Advanced Feedstock Supply System Validation Workshop* brought together a variety of experts from academia and industry; the range of participant feedback reflected the diverse set of backgrounds. Nonetheless, several topics/themes repeatedly emerged from the dialogue and are summarized as follows[1]:

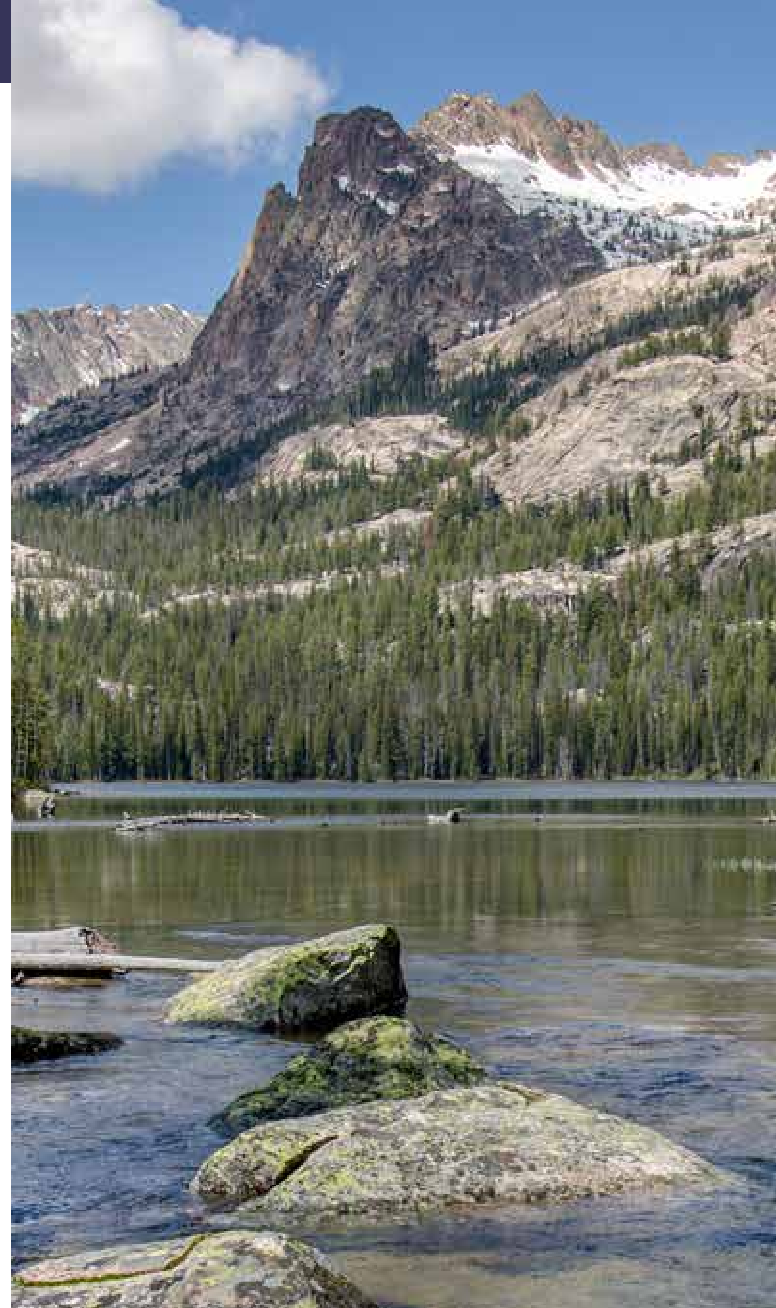
There are fundamental barriers to the expansion of the bioenergy industry in the United States. Despite support from several federal agencies and other stakeholders, the numerous challenges associated with converting biomass into energy and bioproducts have led to a slow rate of industry growth. Feedstock variability and associated costs, financing challenges (i.e., access to capital and financing conditions), sustainability considerations, conversion technology scale-up challenges, the lack of a long-term national energy policy to support long-term investments in conversion facilities, and others, all constrain the rate of industry expansion. A related barrier that was commonly mentioned is business risk and its distribution across the value chain. There appears to be a clear need to identify and reduce risk to biomass producers, biorefineries, and equipment manufactures.

[1] Participant comments are presented in their entirety in Appendix A

Conventional biomass supply systems have a limited ability to support expansion of the biofuel industry in the United States. Conventional systems have a limited ability to address and manage feedstock variability and reduce related supply risks. However, these systems can be effective under certain circumstances and they continue to have a place in supporting expansion of the bioenergy industry in the United States.

Advanced Feedstock Supply Systems and depots could play a role in addressing many of the barriers that currently hinder industry growth. Distributed biomass preprocessing centers (i.e., depots) that convert raw biomass into a stable, flowable, densified feedstock intermediate could address issues associated with variability and would reduce biorefinery supply risks. Standardized, interchangeable feedstock intermediates traded in a commodity-type market would be very desirable to biomass producers and biorefineries alike. However, a key to success is the depot provides added value and the small and mid-sized farmers can secure contracts and benefit from a commodity system, rather than get forced out by larger producers.

A transition strategy from conventional to Advanced Feedstock Supply Systems is needed. The Billion-Ton reports (Perlack et al. 2005, 2011) describe "existing" and "potential" biomass resources that could be available for biorefining, totaling approximately 1 billion tons of annual supply by the year 2030. General consensus among the participants was that a significant barrier to achieving this billion-ton bioeconomy vision would be transition from the current conventional design to the Advanced Feedstock Supply System design.



Sustainability

BETO's approach to sustainability is consistent with Executive Order 13514, which provides the following definition: "To create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations."

CONTENTS

Biomass Formats

Biomass can take on various formats throughout the feedstock supply chain, many of which require different equipment for handling. Examples of different formats include round bales, square bales, woodchips, whole trees, bulk forest residues, and pellets.

WORKSHOP OVERVIEW

The Cost, Quality, and Quantity Challenge

The *Advanced Feedstock Supply System Validation Workshop* was hosted by BETO, which is one of the 10 technology development offices within the Office of Energy Efficiency and Renewable Energy at DOE. BETO funds research is aimed at reducing the cost of producing liquid transportation fuels derived from renewable resources in the United States; BETO has several goals that reflect this effort. This workshop focused on the feedstock portion of the value chain and mobilizing more than a billion tons of biomass for energy production by transforming raw biomass into tradable, aggregatable, merchandisable, and stable feedstock.

The Bioenergy Technologies Office: Relevant Goals and Targets[2]

The mission of BETO is as follows:

> *Develop and transform our renewable biomass resources into commercially viable, high-performance biofuels, bioproducts, and biopower through targeted research, development, and demonstration supported through public and private partnerships.*

BETO's goal is to develop commercially viable bioenergy and bioproduct production technologies to do the following:

- Enable sustainable, nationwide production of biofuels that are compatible with today's transportation infrastructure, can reduce greenhouse gas emissions relative to petroleum-derived fuels, and can displace a share of petroleum-derived fuels to reduce U.S. dependence on foreign oil
- Encourage creation of a new domestic bioenergy and bioproduct industry.

The overall 2017 cost target for BETO is to validate, at pilot scale, at least one technology pathway for hydrocarbon biofuel production at a mature modeled price of $3/gallon gasoline equivalent ($2011) with greenhouse gas emissions reductions of 50% or more compared with petroleum-derived fuel. BETO is organized into six program areas (Figure 4); each area has its own strategic goal that contributes to the overall BETO goal.

The workshop involved personnel from various programs and was planned by the Terrestrial Feedstock Supply and Logistics Program. The strategic goal for the Feedstock Supply and Logistics Program is to *develop technologies to provide a sustainable, secure, reliable, and affordable biomass feedstock supply for the U.S. bioenergy industry,* in partnership with the U.S. Department of Agriculture and other key stakeholders. This workshop supports this goal by soliciting feedback from BETO stakeholders (including other federal agencies, national laboratories, academia, industry, producers, and universities) on technologies that could affect the different aspects of this strategic goal.

In addition to strategic goals, the Feedstock Supply and Logistics Program has performance targets that are directed at mobilizing large amounts of biomass. One 2017 target is to establish criteria under which the industry could operate at 245 million dry tons/year of biomass and validate feedstock supply and logistics systems that can deliver feedstock at or below $80/dry ton ($2011), including both grower payment and logistics cost to in-feed of the conversion reactor.

Feedstocks

Feedstocks are biomass materials that have undergone preprocessing, such as drying, milling, chopping, size fractionation, de-ashing, blending and formulation, densification, or extraction to make them acceptable for feeding into a biorefinery process that converts then into biofuels, biopower, and/or bioproducts.

[2] Portions of this section have been excerpted from: DOE BETO, 2015, Bioenergy Technologies Office Multi-Year Program Plan, March 2015, DOE/EE-1193, http://www.energy.gov/eere/bioenergy/downloads/bioenergy-technologies-office-multi-year-program-plan-march-2015-update.

Bioenergy Technologies Office Strategic Goal

Develop commercially viable bioenergy and bioproduct technologies to enable the sustainable, nationwide production of biofuels that are compatible with today's transportation infrastructure, can reduce greenhouse gas emissions realitive to petroleum-derived fuels, and can displace a share of pertroleum-derived fuels to reduce U.S. dependence on oil and encourage the creation of a new domestic bioenergy industry

Research, Development, Demonstration, & Market Transformation

Feedstock Supply & Logistics R&D

Develop technologies to provide a sustainable, secure, reliable, and affordable biomass feedstock supply for the U.S. bioenergy industry

Converion R&D

Develop commercially viable technologies for converting biomass feedstocks via biological and chemical routes into energy dense, fungible, finished liquid transportation fuels such as gasoline, diesel, and jet fuel, as well as bioproducts or chemical intermediates and biopower

Demonstration, & Market Transformation

Develop commercially viable biomass utilization technologies through public/private partnerships that build and validate pilot-, demonstration-, and pioneer-scale integrated biorefineries; and develop the supporting infrastructure to enable a fully operational and sustainable biomass-to-bioenergy value chain in the United States

Crosscutting

Sustainability

Understand and promote the positive environmental, economic, and social effects and reduce the potential negative impacts of bioenergy production activites

Strategic Analysis

Provide context and justification for decisions at all levels by establishing the basis of quantitative metrics, tracking progress towards goals, and informing portfolio planning and management

Strategic Communications

Conduct strategic outreach to target audiences that promotes the benefits of sustainable production of biofuels, bioproducts, and biopower, highlighting the role that a thriving bioeconomy plays in creating green jobs, spurring innovation, benefitting the environment, and achieving national energy security

Figure 4. Strategic goals for BETO (source: DOE 2015).

Feedstocks are essential to achieving BETO goals because the cost, quality, and quantity of feedstock available and accessible at any given time limits the maximum amount of biofuels that can be produced. The U.S. Billion-Ton Update (Perlack et al. 2011) report provides several biomass supply scenarios that show potential biomass resources that could be developed under different sets of assumptions regarding yield improvements over time, some of which lead to a sustainable national supply of more than 1 billion tons of biomass per year by the year 2030.

The terrestrial Feedstock Supply and Logistics Program focuses on (1) reducing the delivered *cost* of sustainably produced biomass, (2) preserving and improving the physical and chemical *quality* parameters of harvested biomass to meet the individual needs of biorefineries and other biomass users, and (3) expanding the *quantity* of feedstock materials accessible to the bioenergy industry. This is done by identifying, developing, demonstrating, and validating efficient and economical integrated systems for harvest and collection, storage, handling, and transport and preprocessing raw biomass from a variety of crops to reliably deliver the required supplies of high-quality, affordable feedstocks to biorefineries as the industry expands. The elements of cost, quality, and quantity are key considerations when developing advanced feedstock supply concepts and systems.

Key Elements of the Challenge

Physical and chemical characteristics of raw biomass render one or more of the Feedstock Supply and Logistics Program goals for cost, quality, and quantity challenging. Whether in a field or forest, biomass is inherently dispersed across a landscape and is not typically concentrated in a single contiguous area of land. Once biomass is collected from the ground, it may be baled or chipped, depending on the biomass type, or packaged some other way. Although these biomass formats facilitate transportation, biomass is still often of relatively low bulk and energy density. These features make biomass expensive to collect, transport, and store. Also, raw biomass is highly variable in quality and format. This variability increases handling costs, but also impacts downstream conversion efficiency at the biorefinery. Finally, the high moisture content often encountered in freshly harvested biomass makes it unstable, leading to dry matter and quality degradation during storage, as well as safety hazards (such as spontaneous combustion). All of these factors impact cost, which could, in turn, impact the quantity of material that can be affordably supplied for biofuels production. Another overarching consideration when evaluating feedstock supply systems is sustainability, which must remain a top priority.

Workshop Purpose

The *Advanced Feedstock Systems Validation Workshop* began with an opening session where DOE-BETO Program Officials and INL management welcomed attendees. A welcome by Jonathan Male, BETO Director, was followed by the R&D focus areas and objectives for the workshop.

Focus Areas

In order to achieve the terrestrial Feedstock Supply and Logistics Program R&D goal of developing sustainable technologies that provide a secure, reliable, and affordable feedstock supply for the U.S. bioenergy industry, challenges and barriers identified in the Multiyear Program Plan (DOE 2015) need to be prioritized and addressed as funding permits. However, the following issues are considered to be most critical and will be emphasized within the program's efforts (DOE 2015):

- Increase the quantity of sustainable, acceptable-quality, cost-effective feedstock available to biorefineries by developing an Advanced Feedstock Supply System and strategies
- Incorporate sustainability and feedstock supply risk into the resource assessments
- Work with conversion technology areas to understand the range of acceptable physical and chemical infeed specifications for the various conversion technologies
- Develop high-capacity, high-efficiency, low-cost, commercial-scale feedstock supply and logistics systems that deliver stable, dense, flowable, consistent quality, and infrastructure-compatible feedstock.

These barriers were categorized for the workshop as shown in Table 1.

Table 1. Advanced Feedstock Supply System Validation Workshop Session, Assumptions, and Associated Barriers List as Presented to Workshop Participants.

Advanced Feedstock Supply System Validation Workshop Session, Assumptions, and Associated Barriers	
Assumption: Feedstock supply systems limit biorefinery economies of scale	
Cost & Quantity	Barriers: 1. Biorefinery scaling up will be limited under the current supply system design 2. Infrastructure will limit scale (transportation, storage...) 3. Variable and uncertain feedstock availability will limit biorefinery size 4. Scale will require biorefineries to use a diversity of feedstocks
Assumption: Quality is limiting to the biorefinery industry and must be managed in the feedstock supply system	
Quality Constraints	Barriers: 1. Variability exists and will be important at the scale of a single biorefinery (due to weather events, flood, drought, and rain) 2. Variability increases biorefinery cost and risk 3. Quality attributes must be managed to achieve expected performance 4. Specification targets are ever moving and evolving 5. Cost to value added
Assumption: Risk is important to the biorefinery and must be managed in the feedstock supply system	
Operational & Financial Risks	Barriers: 1. Cost 2. Transitioning from Conventional to Advanced 3. Feedstock competition

Objectives

The purpose of the workshop was to examine, discuss, and validate assumptions for analyses of Advanced Feedstock Supply Systems that are capable of sustainably and economically supplying hundreds of millions of tons of on-spec feedstock to future biorefineries. Participants were asked to validate, modify, or refute the Advanced Feedstock Supply Systems' fundamental assumptions (Table 2), including biorefinery scale (Session 1); the need for active quality control, including preprocessing, blending, and densification (Session 2); and feedstock supply risk and uncertainty (Session 3).

Participants were also asked to discuss/explore industry-scale Advanced Feedstock Supply System solutions, mobilization of a billion tons of biomass, and expert opinion regarding transitioning from present day to tomorrow's Advanced Feedstock Supply Systems. Finally, the participants were asked to collect and document expert opinions to inform the DOE feedstock R&D plan moving forward and to shape the analysis supporting the Billion Ton 2016 update.

Table 2. Summary of Assumptions Underpinning Progressive Design of Advanced Feedstock Supply Systems Targeted for a Biochemical Conversion Process (Jacobson et al. 2014). Note that 2017 Design Case Specifications are Based on Davis et al. (2013).

	2012 Conventional Design	Baseline	2017 Design Case
Feedstock(s)	Corn stover	Corn stover	Blended feedstock: corn stover, switchgrass, and select municipal solid waste (MSW)
Grower Payment	Minimal	Increases based on marginal cost differential	Calculated and modeled according to specific location and resource blend/ formulation
Moisture	Field dried to 12%	Arrives at 30% Dried to 20%	Arrives: corn stover 30%, switchgrass 20%, and MSW 20%; All dried to 9%
Ash	No ash management assumed	11%, dockage accessed for ash content Greater than 5% spec	Blended ash content of 4.9% Corn stover: multi pass 7%; single pass 3.5% Switchgrass: 4% MSW: 10%
Logistics	Uses existing systems	Uses existing systems	Fractional milling High moisture densification Rail transportation for MSW
Quality Controls (passive)	Field drying to meet moisture spec Ample available resource; quality spec manually selected	Dockage fee assessed to supplier for below quality material	Multi versus single pass harvest/collection Harvest/collection and storage best management practices
Quality Controls (active)	None assumed	Rotary drying	Multiple resource blending/formulation High moisture densification High efficiency pellet drying
Meet Quality Target	No	Yes	Yes
Meets Cost Target	Yes	No	Yes
Accesses Dispersed Resources	No	No	Yes

The Advanced Feedstock Supply System includes active quality control systems for both physical and chemical characteristics, helping stabilize and mobilize the feedstocks to reduce cost to storage, transportation, feeding, and dry matter losses. DOE was soliciting feedback on the Advanced Feedstock Supply System concepts via this workshop.

Workshop Participants

The workshop consisted of 23 participants from industry and academia (a full list of participants and affiliations is included in Appendix B), as well as observers from INL, ORNL, National Renewable Energy Laboratory, and DOE.

Workshop Structure

Summary of Workshop Sessions

All workshop sessions had a moderator and presenter who framed the discussion and presented sufficient information to spark conversation from participants about the assumptions. Key questions that were prepared prior to the workshop by INL and ORNL were presented to the group and discussed orally. Simultaneous with the oral discussion, comments written by the participants were captured using ThinkTank software (see Appendix C). Experts responded directly to each question and to comments made by other experts about the questions. The workshop was broken out into the following sessions:

Session 1: Cost and quantity focused on issues of cost, quantity, and scaling that prevent the bioenergy industry from reaching the desired billion ton bioeconomy by 2030. The assumption presented to participants was that feedstock supply systems will limit biorefinery economies of scale. Research informs this assumption; however, because analysis of these issues is beyond the data (the billion ton bioeconomy is a future that is not yet realized), engaging experts is an important part of ensuring research is properly focused.

Session 2: Quality began with a brief presentation on the underlying assumption "*feedstock quality is a barrier that will limit the expansion of the biorefining industry and must be managed in the feedstock supply system*." The moderators' brief presentation of identified barriers similar to Session 1 generated rich discussion from the experts.

Session 3: Risk covered the topic of risk and risk management where the overarching assumption was, "*risk is important to the biorefinery industry and must be managed in the feedstock supply system*." The session focused on the diversity of risks (including operational and financial) and the financial benefits of reducing risks across the entire supply chain. A key discussion point was that risk impacts cost and risk needs to be managed across the feedstock supply system. Key barriers presented included cost (particularly with respect to variability) and securing feedstock supply, transitioning from a conventional to an Advanced Feedstock Supply System, and feedstock competition.

The workshop was concluded with a group discussion that focused on the question "How do we transition from the current conventional biomass supply system to the Advanced Feedstock Supply System?" Based on earlier discussions in Sessions 1, 2, and 3, most agreed on the vision that an Advanced Feedstock Supply System was necessary to expand the biofuels industry in the United States. However, participants had many questions regarding how to enable the transition from today's conventional supply system to the Advanced Feedstock Supply System. Based on these enquiries and the desire to address these questions, the final group discussion was dedicated to discussing transition barriers.

Summary of Workshop Presentations: Mobilizing a Billion Tons of Biomass

BETO director Jonathan Male opened the workshop by directing participants to look toward the long–term state of the bioenergy industry (i.e., the year 2030 and beyond) by focusing on mobilizing a billion tons of biomass for bioenergy (Perlack et al. 2011). Pioneer biorefineries have relied on the conventional approach to biomass feedstock supply systems, which was developed for traditional agriculture and forestry systems and was designed to move biomass short distances for limited-time storage (i.e., less than 1 year). DOE has made significant investments in improving conventional systems; these systems can be effective in certain circumstances. Dr. Male highlighted the limits of conventional feedstock supply systems, which includes, but is not restricted to, a limited ability to address the physical and chemical variability of biomass (they can only address quality indirectly through passive controls such as resource selection and best management practices) and limited access to available biomass. Conventional feedstock supply systems constrain biorefinery locations to areas with sufficient supplies of biomass within a limited distance; this limits the scale-up capacity of the biorefinery and exposes the biorefinery and its investors to increased risk from potential local feedstock disruptions (Hess et al. 2009, Argo et al. 2013, Jacobson et al. 2014, Muth et al. 2014).

Capturing Stakeholder Feedback

Each session began with an overview of the session topic. Using ThinkTank software, participants had the option of entering comments during the presentation, and could continue to enter comments throughout the subsequent discussions. Note takers captured additional comments that were not entered into the workshop tool. Comments captured during the workshop were reviewed and consolidated into the "Industry Perspective" sections of this report. Numbers in square parentheses (i.e., [1.2.3.4], correspond to comments or a group of comments located in Appendix A). Workshop participants were given the opportunity to review and comment on a draft of the report, including the participant feedback summaries in the industry perspective sections; that feedback was incorporated into the final report. Feedback received on the written report is referenced similarly to ThinkTank feedback, but preceded with the letter D (i.e., [D1]).

In the past, BETO-funded Feedstock Supply and Logistics Program research focused on modifying conventional terrestrial feedstock supply systems. Dr. Male mentioned that the research objectives with respect to conventional systems were to increase machinery capacity/efficiency, reduce material losses (particularly during collection/baling), increase the operational window, and simplify/reduce logistics unit operations. To achieve these objectives, conversion and logistic technologies were developed for each feedstock type. These research efforts resulted in feedstock supply system cost reductions; however, the conventional systems are only applicable in high-yielding biomass regions. A large fraction of potentially harvestable biomass lies outside of these highly productive regions; therefore, relying on conventional systems restricts the resources available for bioenergy production. Dr. Male referred the audience t biomass resource assessment work published by ORNL and sponsored by BETO, including the U.S. Billion Ton Update (Perlack et al. 2011). This report identifies more than 1 billion tons of cellulosic biomass that could be available for energy production by 2030; however, this biomass is distributed unevenly throughout the United States

Research funded by DOE suggests that sustainably supplying the required quantity of quality and affordable feedstock to the emerging biorefining industry will be achieved by transition from conventional feedstock supply systems to more advanced, purpose-designed, economically advantaged systems (this has been termed Advanced Feedstock Supply Systems in this and other DOE reports) (Hess et al. 2009).

Richard Hess, Director of the Energy Systems and Technologies Division at INL, elaborated on the inability of conventional systems to support the long-term goal of enabling hundreds of millions of tons of cellulosic biomass to be sustainably and economically supplied to U.S. biorefineries at an acceptable quality. Dr. Hess introduced the concept of Advanced Feedstock Supply Systems, including the biomass preprocessing depots and the role these advanced systems could have in mobilizing the billion tons of biomass potential. Advanced Feedstock Supply Systems could enable a larger quantity of affordable, sustainable biomass to be available for energy production, while also meeting the broad range of conversion in-feed quality requirements.

Dr. Hess elaborated on the potential role of the biomass preprocessing facilities, or depots. This role included reducing feedstock variability, stabilizing feedstock cost, reducing mass losses and quality deterioration due to microbial action, and reducing supply risk through active feedstock supply systems. Taking into account the need to address feedstock format, feedstock quality, and logistics cost, Dr. Hess explained that INL is exploring the incorporation of depots to produce infrastructurecompatible commodity formats, which decouples feedstock supply from conversion. The depots would transform raw biomass into tradable, aggregatable, and merchandisable intermediates by managing feedstock characteristics to be within acceptable ranges for a variety of potential biomass consumers. Dr. Hess emphasized that density and stability are critical for economic transport, improved handling characteristics, and improved stability during storage. He also pointed out that researchers are only beginning to grapple with quality (i.e., physical, chemical, and rheological properties) and that one approach being explored by researchers to address quality is increasing the number of logistics unit operations within cost constraints.

Advanced Feedstock Supply Systems are designed to deliver infrastructure-compatible feedstocks with predictable physical and chemical characteristics, longer-term stability during storage, and have highcapacity bulk material-handling characteristics that facilitate economic transport over longer distances. These properties are needed for development of a commodity-based, specification-driven supply system analogous to U.S. grain and coal commodity systems. Feedstock supply systems designed for the purpose of bioenergy production can eliminate inefficiencies in conventional harvest and delivery systems. In addition, Dr. Hess emphasized the value of mitigating feedstock risk to biorefineries.

Figure 5 shows a high-level depiction of how an Advanced Feedstock Supply System could draw in resources that are currently too expensive to collect and

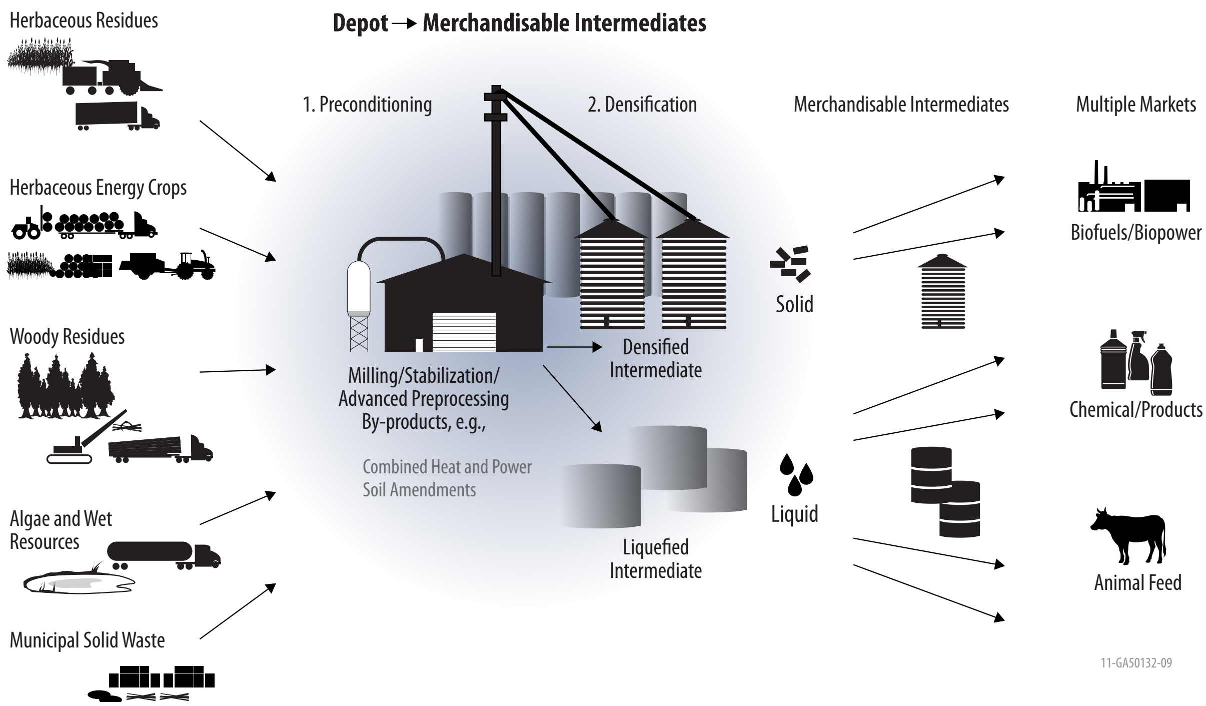
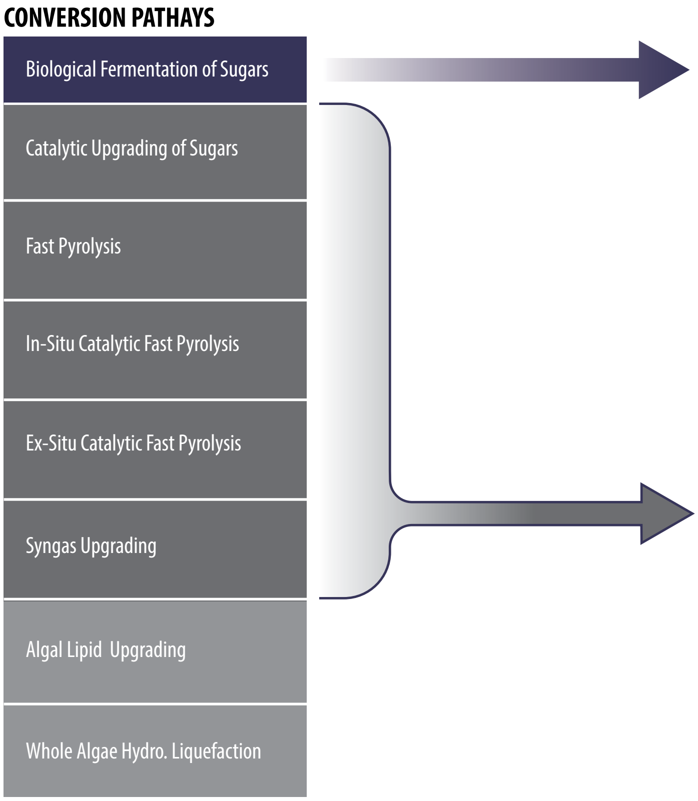


Figure 5. Schematic of the Advanced Feedstock Supply System depot concept. Depots produced aggregatable, merchandisable, and tradable intermediates that could be sold into a variety of potential markets, depending on market demand considerations.

transport (termed "inaccessible") via local preprocessing depots that transform biomass into a stable, bulk, densified, and flowable feedstock. The formatted feedstock could be transported into a network of supply terminals, where material aggregated from a number of depots could be blended or further preprocessed to meet biorefinery or other user needs. Another option is for the depot to produce merchandisable intermediates, which could be sold directly into any number of markets, including biofuels, biopower, chemicals, or animal feed.

Dr. Hess explained that Advanced Feedstock Supply Systems transform raw biomass materials into commodity feedstocks, which have a standardized format and quality specification ranges that are assured through use of adopted national and international standards and national market systems and are tradable on commodity exchanges.

Supplying feedstock to a growing bioenergy industry requires increasing the accessible and affordable quantity of lignocellulosic feedstock (moving toward a billion tons of annual supply), while increasing the emphasis on quality to meet the in-feed specifications of a variety of biorefinery processes (and other end users), as well as reducing variability and risk. Kevin Kenney, Platform Lead at INL, gave an overview of biomass quality and feedstock specification considerations and how Advanced Feedstock Supply Systems can play a role. He provided examples of feedstock specifications, including physical properties/handling behavior (e.g., bulk and particle densities, tissue structure, grindability index, shear strength, particle-size distribution, and shape factors), chemical properties/reactions behavior (e.g., proximate and ultimate analysis, organic composition, functional groups, and bond energy), and storage behavior (including equilibrium moisture, biodegradability,



Model Feedstock: Corn Stover

Component	Composition (dry wt%)
Glucan	35.05
Xylan	19.53
Lignin	15.76
Ash	**4.93**
Acetate	1.81
Protein	3.10
Extractives	14.65
Arabinan	2.38
Galactan	1.43
Mannan	0.60
Sucrose	0.77
Total structural carbohydrate	**58.99**
Total structural carbohydrate + sucrose	59.76
Moisture (bulk wt%)	**20.0**

Model Feedstock: Pulpwood

Component	Composition (dry wt%)
Carbon	50.94
Hydrogen	6.04.
Nitrogen	0.17
Sulfur	0.03
Oxygen	41.90
Ash	**0.9 -1.0**
HHV (BTU/lb)	8.601
LHV (BTU/lb)	7.996
Moisture (%, w.b.)	**10.0**

15-GA50315-Fig. 6

Figure 6. Example of differences in feedstock spec "assumptions" for different conversion pathways, as presented by Kenney.

Active Quality Management

Aqueous and non-aqueous leaching and extraction of feedstocks allows for a targeted removal of ash species. For example, alkaline extractions may selectively remove large amounts of silica, nitrogen, and sulfur, because these elements require structural modifications to be liberated from cellular material. Conversely, dilute-acid leaching or non-aqueous extractions using polar solvents (such as methanol and ethanol) will selectively remove the majority of alkaline earth metals and alkali metals, including potassium, sodium, magnesium, and calcium. Adding leaching as a subsequent step following a mechanical fractionation may reduce costs by focusing leaching efforts only on feedstock fractions with very high ash fractions. In addition, applying non-aqueous leaching technologies may reduce costs by lowering the required drying costs necessary to recover the leaching/extraction solvent.

phytosanitation, and ignitability and explosivity). Mr. Kenney delved further into the impact of feedstock quality on the bioenergy production system, particularly bioenergy product yield and cost. The primary assumption Mr. Kenney presented for workshops discussion was that feedstock quality is a barrier that will limit expansion of the biorefining industry and must be managed in the feedstock supply system.

Mr. Kenney outlined some active quality management strategies, including best management practices and preprocessing. Preprocessing is a general term that includes many activities such as densification, drying, and combining various feedstocks (i.e., "blending" or formulation) (Kenney et al. 2013, Jacobson et al. 2014). By combining analyses using biomass price projections with quality information obtained from the Bioenergy Feedstock Library (see Appendix D), gains in the projected quantity available at cost and within biorefinery specifications can be realized by transitioning to a blended feedstock approach (Kenney et al. 2013, Jacobson et al. 2014). Formulating a designed feedstock through blending and other preprocessing methods allows low-cost and, typically, low-quality biomass to be blended with biomass of higher cost and, typically, higher quality to achieve the specifications required at the in-feed of a conversion facility. Note that different conversion processes may require different specifications (Figure 6)[3] and the cost required to meet those specifications will vary. Blending low-cost and/or low-quality biomass allows the supply chain to implement additional preprocessing technologies that actively control feedstock quality, while also bringing more biomass into the system. This analysis and design approach is referred to as the "least-cost formulation" strategy. Analysis suggests that blending multiple feedstocks enables the acquisition of higher biomass quantity and reduces feedstock variability to meet biorefinery in-feed specifications, while delivering feedstock to the biorefinery at $80/dry ton (Jacobson et al. 2014).

Mr. Kenney also introduced the concept of dockage, which is a penalty imposed by the end user for delivery of off-spec feedstock. He provided examples of dockage fees such as moisture dockage, ash dockage, and convertibility dockage. Moisture dockage assesses a penalty due to increased grinding and drying cost for excess moisture. Ash dockage includes replacement cost, disposal cost, and cost of other effects not accounted for such as increased wear on processing and handling equipment and increased buffering capacity in pretreatment. Convertibility dockage assesses a penalty cost due to reduced convertibility associated with storage degradation/losses.

Biomass Preprocessing

Preprocessing involves operations that transform raw, field-run biomass into stable, standardized format feedstocks with physical and chemical characteristics that meet the required quality specifications of conversion facilities and enable the use of existing, high-volume transportation and handling systems. Preprocessing upgrades biomass for stability during longer-term storage and improves durability and performance in handling, transport, and conversion. Preprocessing also can reduce the physical and chemical variability of raw biomass to enable more reliable, predictable, and efficient conversion performance (DOE 2015).

Transitioning from feedstock quality, Alison Goss Eng, Program Manager for the Feedstock Supply and Logistics Program, highlighted the need to consider sustainable supply systems and bioenergy resource development for sustainable landscape-scale production. Dr. Goss Eng gave an overview of the economic and social drivers associated with the global need for renewable biofuels in tandem with other important issues, including carbon sequestration, water and air quality, wildlife food and habitat, erosion, sedimentation, hypoxia, community development, and transportation infrastructure.

Participant comments from a previous DOE BETO-sponsored "densification" workshop titled, *Transforming Biomass into Feedstocks*, were incorporated into the Advanced Feedstock Supply System vision. The *Transforming Biomass into Feedstocks* workshop was held August 2011 in Idaho Falls, Idaho; its purpose was to gather stakeholders to discuss potential solutions for the densification challenge and to accelerate bioenergy industry expansion.

Building from and moving beyond the success of that densification workshop, DOE saw the need to again solicit stakeholder input on biomass feedstock supply systems, with discussions on major assumptions associated with Advanced Feedstock Supply Systems (Table 1).

[3] For example, Davis et al. 2013, Dutta et al. 2011, and Jones et al. 2013.

References

Argo, A. M., E. C. D. Tan, D. Inman, M. H. Langholtz, L. M. Eaton, J. J. Jacobson, C. T. Wright, D. J. Muth, M. M. Wu, Y.-W. Chiu, and R. L. Graham, 2013, "Investigation of biochemical biorefinery sizing and environmental sustainability impacts for conventional bale system and advanced uniform biomass logistics designs," *Biofuels, Bioproducts, and Biorefining* 7(3): 282–302.

Davis, R., L. Tao, E. C. D. Tan, M. J. Biddy, G. T. Beckham, C. Scarlata, J. Jacobson, K. Cafferty, J. Ross, J. Lukas, D. Knorr, and P. Schoen, 2013, *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons,* NREL/TP-5100-60223, October 2013, http://www.nrel.gov/docs/fy14osti/60223.pdf.

DOE, 2015, *Bioenergy Technologies Office Multi-Year Program Plan*, DOE/EE-1193, March 2015, http://www.energy.gov/eere/bioenergy/downloads/bioenergy-technologies-office-multi-year-program-plan-march-2015-update.

Dutta, A., M. Talmadge, J. Hensley, M. Worley, D. Dudgeon, D. Barton, P. Groenendijk, D. Ferrari, B. Stears, E. Searcy, C. Wright, and J. Hess, 2011, *Process Design and Economics for Conversion of Lignocellulosic Biomass to Ethanol - Thermochemical Pathway by Indirect Gasification and Mixed Alcohol Synthesis*, NREL/TP-5100-51400, May 2011.

Hess, J. R., K. L. Kenney, L. P. Ovard, E. M. Searcy, and C. T. Wright, 2009, *Commodity-Scale Production of an infrastructure-compatible bulk solid from herbaceous lignocellulosic biomass. Uniform-format Bioenergy feedstock supply system design report series*, INL/EXT-09-17527, April 2009.

Jacobson, J., P. Lamers, M. Roni, K. Cafferty, K. Kenney, B. Heath, J. Hansen, and J. Tumuluru, 2014, *Techno-economic analysis of a biomass depot*, INL/EXT-14-33225, September 2014.

Jones, S, E. Tan, J. Jacobson, A. Meyer, A. Dutta, and L. Snowden-Swan, 2013, *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-oil Pathway*, PNNL-23053, NREL/TP-5100-61178, September 2013.

Kenney, K. L., W. A. Smith, G. L. Gresham, and T. L. Westover, 2013, "Understanding biomass feedstock variability," *Biofuels* 4: 111–127.

Muth, D. J., M. H. Langholtz, E. C. D. Tan, J. J. Jacobson, A. Schwab, M. M. Wu, A. Argo, C. C. Brandt, K. G. Cafferty, Y.-W. Chiu, A. Dutta, L. M. Eaton, and E. M. Searcy, 2014, "Investigation of thermochemical biorefinery sizing and environmental sustainability impacts for conventional supply system and distributed pre-processing supply system designs," *Biofuels, Bioproducts, and Biorefining* 8: 545–567.

Perlack, R. D. and B. J. Stokes (Leads), 2011, *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*, ORNL/TM-2011/224, p. 227, August 2011.

Feedstock Quality

Feedstock production, especially in the case of agricultural residues, is prone to large uncertainties in biomass quality. In its simplest form, feedstock can be described as a mixture of biomass, moisture, and ash. When any of these components fail to meet a user's specifications, additional costs may be incurred in feedstock procurement, handling, or disposal. In order to mitigate these costs, they must be subtracted from the purchase payment of feedstock or "docked" – at the point of sale.

SESSION 1: COST AND QUANTITY

Mobilizing the Billion Tons

BETO funds various activities in biomass resource assessment to establish the potential quantity and price of biomass resources at a given time. One such assessment is presented in the U.S. Billion Ton Update (Perlack et al. 2011) and its predecessor, the U.S. Billion Ton Study (Perlack et al. 2005). This work includes an estimate of "potential" biomass within the contiguous United States based on numerous assumptions about current and future inventory and production capacity, availability, and technology through 2030. This strategic analysis was undertaken to determine if U.S. agriculture and forest resources have the capacity to potentially produce at least one billion dry tons of biomass annually, in a sustainable manner, which is enough to displace approximately 30% of the country's present petroleum consumption. While the 2011 update focuses on resources available at forest roadside or farmgate prices of $40 or $60 per dry ton, additional resources are available at higher prices, meaning some potential feedstocks would likely be too expensive to actually be economically available. The U.S. Billion Ton Update includes various scenarios outlining various potentials; Figure 7 shows an example.

Although significant amounts of biomass could be harvested sustainably, the biomass is highly variable both spatially and temporally (Kenney et al. 2013), which can have big implications when considering a national-scale feedstock supply system for biofuels. A comparison of U.S. resource assessments for 2012, 2017, and 2022 (Perlack et al. 2011) shows large variability in quantity, location, and type of feedstock (Figure 8). This variability adds complexity to the required feedstock storage, delivery, and supply systems. [4]

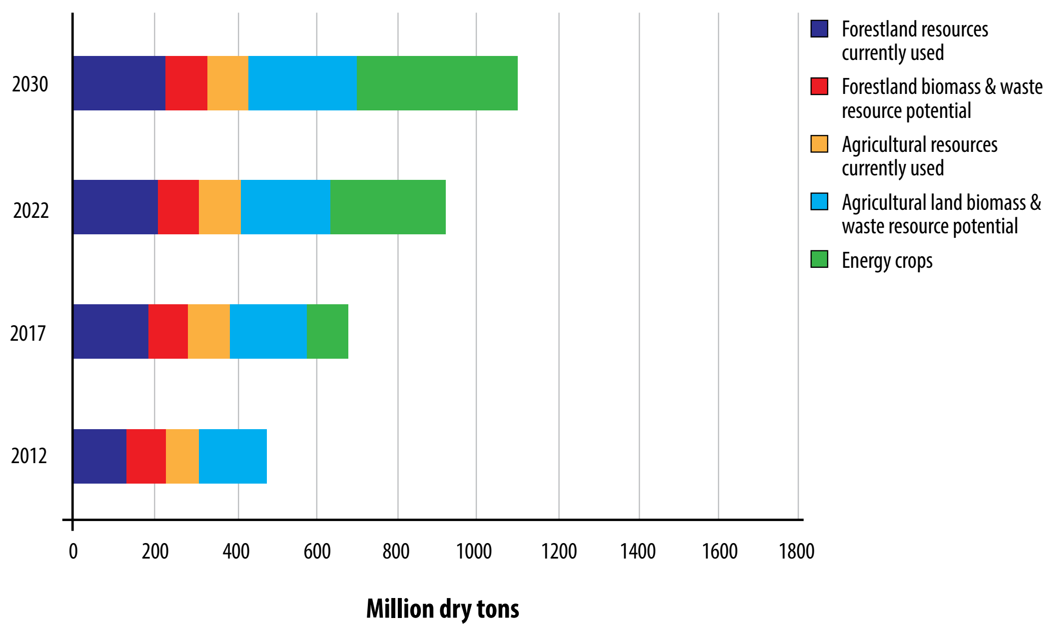
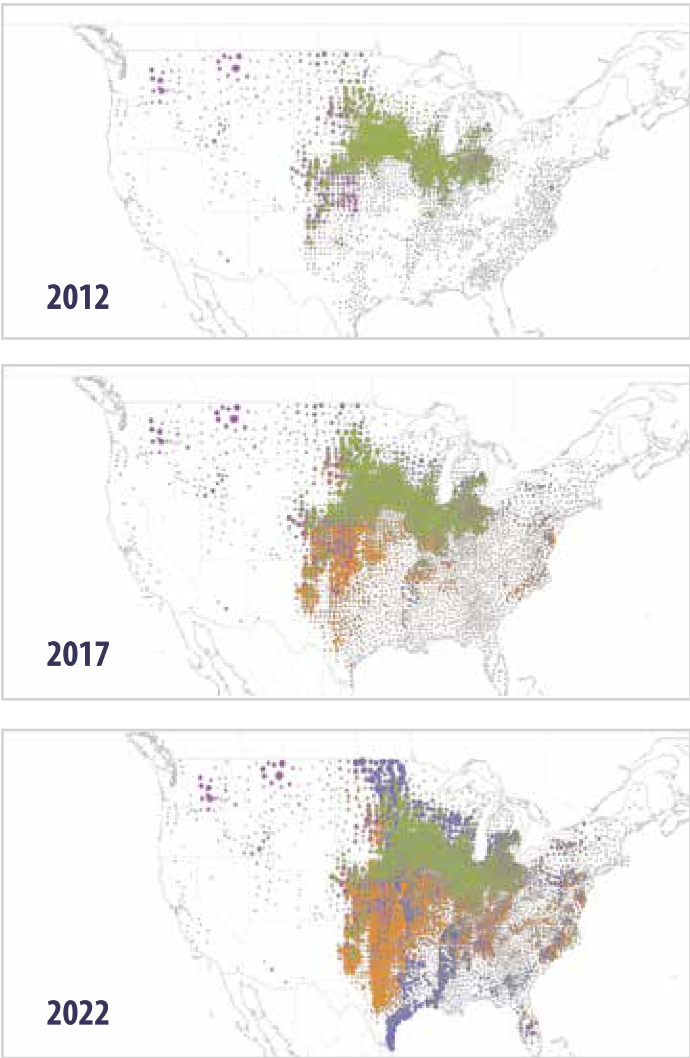


Figure 7. Summary of currently used and potential resources in 2012, 2017, 2022, and 2030 at $60/dry ton or less that are identified under baseline assumptions (DOE 2011).

[4] Portions of this section were taken from Jacobson, J., P. Lamers, M. Roni, K. Cafferty, K. Kenney, B. Heath, J. Hansen, and J. Tumuluru, 2014, Techno-Economic Analysis of a Biomass Depot, INL/EXT-14-33225, September 2014.



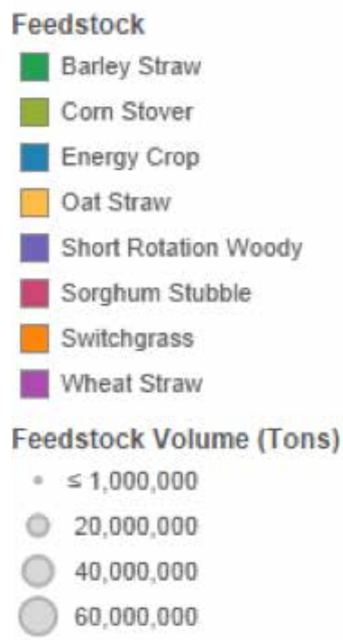


Figure 8. Biomass resource assessments for 3 years, which illustrate both the spatial and temporal variability of biomass resources in the continental United States (Jacobson et al. 2014).

The "lowest hanging fruits" of biomass resources are those that are in high-biomass-yielding regions, such as corn stover in Iowa and pine trees in southeastern United States. Locating a biorefinery in the center of the biomass resource would limit transport cost. However, a growing demand for resources will eventually necessitate expansion outside of these high-yielding regions. In addition, larger biorefineries that take advantage of economies of scale will need more resources than can be drawn from a single resource area. Mobilizing these resources to support an expanding bioeconomy, drawing up to and even beyond a billion tons of annual biomass supply, will require Advanced Feedstock Supply Systems. The Advanced Feedstock Supply Systems will incorporate technologies and system designs that reduce feedstock variability in format and quality, while also reducing supply risk to the biorefinery. Biomass preprocessing depots, located near the point of biomass production, produce a stable biomass intermediate (either liquid or solid) that is tradable and aggregatable, much like other commodities.

Transitioning from existing logistics technologies, primarily those developed for agricultural and forestry industries, to Advanced Feedstock Supply Systems that can sustainably and economically supply large quantities of quality, on-spec feedstock to future biorefineries will require significant investment in feedstock supply infrastructure, including innovative harvest and collection equipment, advanced preprocessing technologies, and depots.

Bioenergy production cost comprises several components in a value chain, including biomass procurement (e.g., grower payment for herbaceous crops or stumpage fee for forest biomass), biomass logistics cost, the cost associated with converting the feedstock into bioenergy, and product distribution; each operation flows into the next. For example, lower ash content results in reduced acid usage in pretreatment and increased product yield per ton of biomass input to the process. Higher investments made early in the supply chain (such as for higher quality biomass) or quality improvements through feedstock supply operations can result in lower cost at the biorefinery (Kenney et al. 2014). The challenge lies in balancing the quantity of desired product (i.e., amount of biomass required), the appropriate investment in feedstock improvements through logistics, conversion facility size, and conversion performance.

Regional Feedstock Partnership

DOE and the Sun Grant Initiative formed the Regional Feedstock Partnership in 2008 to support BETO's goal of sustainably producing 1 billion tons of biomass by the year 2030. The project resulted in the collection of yield and sustainability data on many cellulosic biomass crops that are candidate for energy production, such as corn stover, poplar, and woody and herbaceous energy crops. Each of the five Sun Grant Regions (Northeast, North Central, Southeast, South Central, and Western) actively engaged with stakeholders through workshops, conferences, and other meetings.

Biorefinery Sizing: Balancing Feedstock Cost and Economies of Scale[5]

The appropriate size of a biorefinery has been an area of debate and will have a significant influence on supply system costs (Argo et al. 2013, Muth et al. 2014). Aden et al. (2002) showed that a biorefinery size of at least 2,000 dry tons/day capacity is required to reach a competitive minimum fuel selling price. More recent studies indicate that in order to achieve conversion process economics, facilities of 5,500 to 11,000 dry tons/day are required (Carolan et al. 2007, Argo et al. 2013, Muth et al. 2014). However, the truck frequency for biorefinery capacities at 5,500 dry tons/day in the conventional system is one truck every 3 minutes, which represents a key system limitation in terms of overall truck traffic and constriction due to loading and unloading times. Larger facilities are predicted to more than offset the minimum fuel selling price increase associated with more expensive preprocessed feedstock (Argo et al. 2013; Figure 9). Moreover, biorefineries with capacities in excess of 11,000 dry tons/day are only possible with Advanced Feedstock Supply Systems due to transportation limitations (Argo et al. 2013). With conventional systems, logistic costs increase as biorefinery capacity and/or feedstock collection radius increase.

One approach for reducing transport cost and reducing truck congestion is to leverage high-capacity transport modes such as rail and barge. Although these modes may be impractical when moving raw biomass, these options can be cost effective when moving densified, stable biomass (and, of course, when access to modes such as via rail lines and waterways exists). Part of the functionality of the Advanced Feedstock Supply Systems is to achieve these characteristics, enabling the efficient, long-distance transport of stabilized materials that can be aggregated to meet the conversion in-feed specification of the biorefinery.

[5] Portions of this section were taken from Jacobson, J., P. Lamers, M. Roni, K. Cafferty, K. Kenney, B. Heath, J. Hansen, and J. Tumuluru, 2014, Techno-Economic Analysis of a Biomass Depot, INL/EXT-14-33225, September 2014.

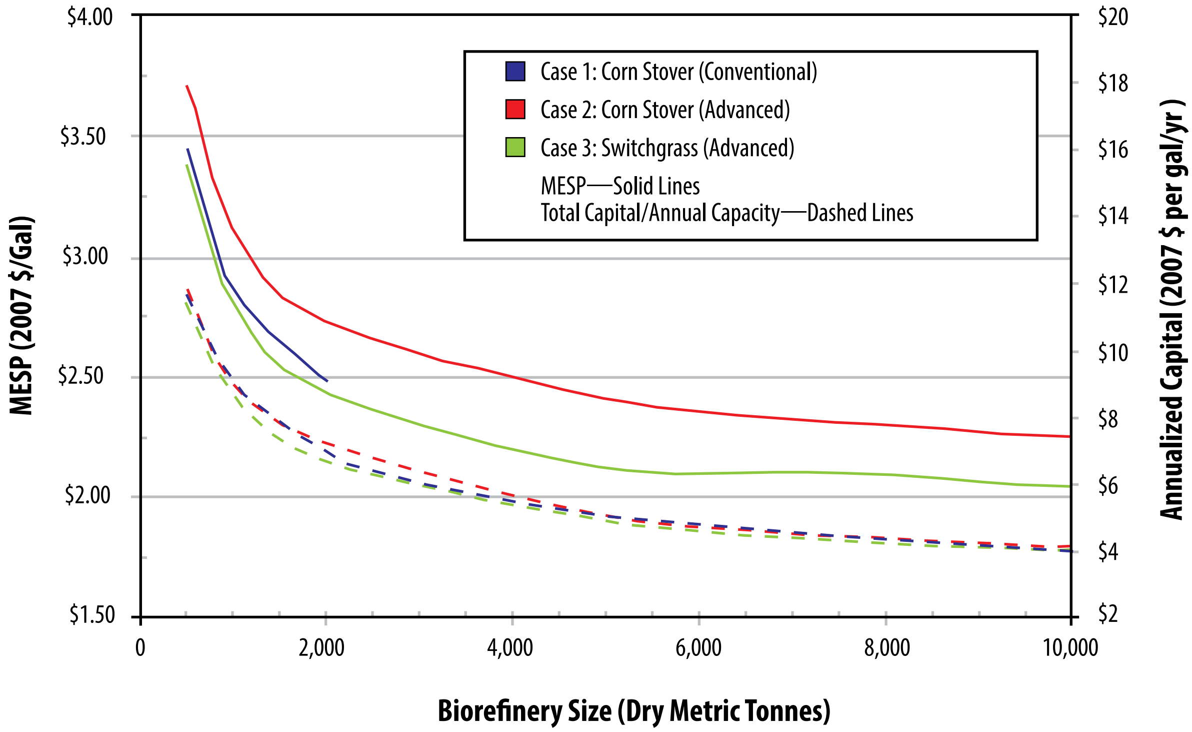


Figure 9. Minimum ethanol/fuel selling price (MESP/MFSP) as a function of plant size (Argo et al. 2013). Note: The U.S. $3 per gallon gasoline equivalent goal translates into a MFSP of $1.97 per gallon.

Realizing the Potential of Bioenergy in the United States through Feedstock Commoditization

Multiple analyses have shown that conventional biomass systems may not be able to reach cost and quality targets outside of highly productive regions and will even struggle in these highly productive regions some years due to incremental weather during production and harvest seasons or extreme events, such as flood or drought (Hess et al. 2009, Argo et al. 2013, Jacobson et al. 2014, Muth et al. 2014). These supply uncertainties tend to classify the biomass industry as a high-risk investment and limit the biorefinery concept from being broadly implemented (Hansen et al. 2015). Financial institutions translate high-risk ventures into higher interest rates, which have a profound impact on the overall costs to a biorefinery over its operational life span. Jacobson and Cafferty (2013) calculated a U.S. $350 million reduction in interest paid over a 20-year lifespan for a U.S. $500 million dollar facility if the investment loan rate dropped from 10 to 5%. This roughly translates into U.S. $ 0.07/liter (U.S. $0.25/gal) of fuel produced. The Advanced Feedstock Supply Systems developed by Hess et al. (2009) and Searcy et al. (2010) provide a method for reduce feedstock volume, price, and quality supply uncertainties. The system is based on a network of depots (Eranki et al. 2011 that use one or several biomass types to generate uniform feedstock 'commodities.' These commodities are intermediates with consistent physical and chemical characteristics that meet conversion quality targets and, at the same time, leverage spatial variability in supply quantity and cost by improving flowability, transportability (bulk density), and stability/storability (dry matter loss reduction).

Currently, biorefineries located in high-yield areas are designed to handle a single feedstock of similar format such as corn stover or wheat straw bales (Carolan et al. 2007, Hess et al. 2009). These vertically integrated systems limit potential biorefinery location and do not consider other business issues (e.g., labor, taxes, proximity to distribution centers, or end-use markets). However, more recent insights indicate that with the support of depots, biorefineries could be built almost anywhere, including lower-yield areas (Argo et al. 2013), where a network of depots would supply biorefineries with sufficient feedstock, possibly from different biomass in a variety of forms (e.g., square and/or round bales, chopped, bundled, and raw). As a result, a depot could take on many forms. For example, a depot could include particle size reduction, moisture mitigation, and densification to achieve the supply system benefits discussed in earlier studies (Hess et al. 2009, Eranki et al. 2011, Kenney et al. 2013). Emerging cellulosic biomass conversion approaches are designed around pristine feedstocks composed of clean, homogeneous structural tissues of single-species woody or herbaceous plants. A number of factors prevent raw, "as-harvested" biomass from meeting these specifications and include low flowability, low bulk density and energy density, and degradation during storage. More severe feedstock quality issues and intolerant specifications at the biorefinery could provoke depots to include additional processing steps (e.g., leaching, chemical treatment, or washing).

The biorefineries would benefit from a depot system through risk reduction and quality control; however, biomass producers would also see benefits. The ability to stabilize raw biomass and convert it into a commodity at the depot would allow the producer to sell excess material into a market. For example, if the biomass producers were contracted to supply 5,000 tons, but they had a good crop year that produced 7,500 tons, they could send the additional 2,500 tons to the depot, stabilize and densify it, and sell the newly formed commodity to other users through a market. If the depots were farmer-owned co-ops, the producers would also benefit from the value-add performed at the depot.

Building a Sustainable Industry[6]

Nascent biorefineries that rely on local agricultural residues generally only process a single feedstock species. Therefore, crop rotation within the supply radius of a biorefinery dictates what residues are being produced. What crops will be grown the next year can shift quickly due to financial or environmental forecasts, which threatens a consistent or predictable feedstock supply. Furthermore, sustainability constraints can limit the amount of residue that can be removed from any given field, further limiting a biorefinery's options for contracting its feedstock. Through careful contracting and interaction with land managers, biorefineries dependent on agricultural residues can develop sustainable management plans; however, this is done at the cost of reducing resource availability in their immediate draw area. Incorporating advanced resource production and procurement concepts, which become possible when using Advanced Feedstock Supply Systems, could facilitate sustainable land practices and allow biorefineries to be efficiently sited. By processing locally available feedstocks at depots, various feedstocks from a wider sourcing range could be made available at greater quantities for biofuel production. In addition, if such depots were made available and provided market access to growers, alternative feedstock production systems could become financially attractive.

Incorporation of dedicated energy crops into row crop landscapes (e.g., corn) is one potential option for expanding the biorefinery feedstock supply, while at the same time benefiting soil and water quality and increasing biodiversity. The conservation benefits of perennial energy crops have been well studied; however, their current production in low quantities has prevented serious interest from biomass end-users. This apathy prevents growers from committing sizable portions of land necessary to generate marketable quantities. Bonner et al. (2014) has suggested that subfield variability within row crop fields can be used to produce dedicated energy crops in a manner that is beneficial for the grower's profitability and soil quality. The study integrates switchgrass into subfield landscape positions in central Iowa where corn grain is modeled to return a net economic loss. Results show that switchgrass integration has the

[6] Portions of this section were taken from Jacobson, J., P. Lamers, M. Roni, K. Cafferty, K. Kenney, B. Heath, J. Hansen, and J. Tumuluru, Techno-Economic Analysis of a Biomass Depot, INL/EXT-14-33225, September 2014.

potential to increase sustainable biomass production by up to 99%, while promoting progressive conservation standards and improving field-level profitability. In doing so, the diversity of feedstock production is increased up to a 5050 split of corn stover and switchgrass. This reduces dependency on any one crop and gives growers and refineries a biomass source even in non-corn years. However, handling a diversified feedstock portfolio introduces logistical challenges. The advanced handling and processing capabilities of local depots can overcome these challenges and remove barriers facing the adoption of sustainable multi-feedstock production systems.

Industry Perspective: Cost and Quantity

Workshop participants were presented with a series of barriers to guide the discussion in Session 1 (Table 3). Comments captured during the workshop were reviewed and consolidated into the "Industry Perspective" sections of this report. Numbers in square parentheses (i.e., [1.2.3.4], correspond to comments or a group of comments located in Appendix A).

Table 3. Barriers to Cost and Quantity Presented to Participants of the Advanced Feedstock Supply System Validation Workshop During Session 1.

Assumption: Feedstock supply systems limit biorefinery economies of scale.	
Cost & Quantity	Barriers: 1. Uncertainty in biorefinery scaling trends 2. Transportation costs limit size 3. Variability and uncertainty in biomass availability – Weather, climate, and extreme events – Competition from other markets 4. Scale will require biorefineries to use a diversity of feedstocks 5. High resource costs will make low cost / niche resources desirable as supplemental feedstocks

Feedstock Handling

Raw biomass is often cohesive, has large particle size variations, low density, and is highly compressible; this causes arching over hopper openings and plugging mechanical and pneumatic conveying systems. Designing handling and feed systems to accommodate this variability is possible, but as handling systems become more robust, they also get more expensive. Preprocessing, including densification, is another option for enhancing biomass feeding and handling properties. A combination of advanced feeding and handling systems and feedstock preprocessing to control feeding properties will be the most likely approach to successfully balancing cost and performance.

Conventional systems can be effective in supplying biomass to local facilities in high-yielding regions [D1]. However, the most significant barrier to assembling feedstock supply chains is feedstock prices: high biomass prices make competing with fossil fuels (at current oil price levels) difficult [1.3, 1.9, 1.12, 1.16]. Yet, reducing feedstock prices will reduce availability because the market prices that biorefineries and other end users are willing to pay for feedstock is often lower than the costs to supply biomass [1.1, 1.2, 1.18, 1.19]. Producer profits must be competitive with other available opportunities to attract participation [1.8, 1.13, 1.15]. Also, risks of supply disruptions due to weather and competing uses can drive up prices, making biomass unattractive to industrial users [1.11, 1.14].

Reducing the delivered costs of feedstocks will require technology improvements along the supply chain. The distributed nature of biomass and its low bulk density can make feedstock transport expensive and resource intensive [2.2, 2.13, 2.15, 2.10, 2.22]. Furthermore, current road infrastructure, weight limits, and truck traffic limit the total amount of biomass that can be transported [2.7, 2.8, 2.9, 2.17]. In addition, the perishable nature of biomass, especially when moisture is high, renders long-term storage cost prohibitive [2.3, 2.8, 2.11, 2.14]. Engineered feedstocks could potentially address challenges with transportation and handling costs and degradation during storage, which could be handled similar to grain to achieve a commercial-scale industry [2.1, 7.1, 7.3]. New equipment with higher capacities, higher efficiencies, and increased durability for harvesting and handling biomass are needed [2.12, 2.16, 2.19, 2.20, 2.21, 3.3, 3.5, 3.12, 3.19, 3.25], although investment is required for equipment development [D17]. Variability in biomass quality due to location may warrant a need to implement systems for tracking biomass from source to destination [7.2].

Risks to feedstock availability are a significant barrier to developing commercial-scale bioenergy industries. Risks of obtaining adequate supply within a local region include grower adoption [3.2, 3.17], weather [3.8, 3.23], and inconsistent political policies [3.6, 3.13, 3.26]. Competition for biomass resources can be viewed as a risk that will increase feedstock cost [3.1] or an opportunity to establish and grow the feedstock supply industries [3.14, 3.14]. Variable feedstock quality [3.2, 3.10, 3.11, 3.18, D18] and high moisture [3.20, D18] in many bioenergy feedstocks are also major challenges for current supply chains.

Feedstock supply chains should be developed to distribute risk in order to attract investment [2.5, 2.6, 3.7, 3.21, 3.22]. The current biomass supply industry is immature and experience is needed for innovation [3.15].

Key components of biomass supply risk are land owner and producer acceptance to bioenergy feedstocks. Education for producers and landowners is needed to describe opportunities for biomass production and harvesting, clarify sustainability implications, and demonstrate new equipment [4.1, 4.14, 4.12]. Growers also need financial incentives to produce and harvest biomass [4.4, 4.10, 4.13, 4.16]. The profitability of growing biomass crops must be competitive with other land uses [4.5, 4.7, 8.1] and those with experience engaging in developing biomass supply chains would emphasize that managing relationships with a large number of producers is complex and resource intensive [4.3], especially because a significant fraction of farmland is leased [4.4, 4.8].

A major obstacle to production of bioenergy feedstocks is sustainability. Public education, including for local land owners [D19], on the sustainability advantages of biomass is needed for broader acceptance and feedstock production [5.7, 5.8]. To do this, improved analytic tools and datasets are needed to demonstrate the impacts of the sustainability constraints [5.1, 5.3, 5.4, 5.5]. Looking beyond environmental sustainability to consider the social implications could be a boost to local economies. Laborers needed for biomass harvest may not be available locally [5.2] and the impacts of drawing labor beyond the local area were unclear.

The impacts of markets and technologies beyond the feedstock supply chain are important drivers of feedstock supply chain growth. In particular, demand and price uncertainty for products derived from biomass reduce producer adoption and commercial investment [6.2, 6.3, 6.4, 6.5, 6.6, 6.11, 6.12, 6.14, 6.16]. Also, improvements in conversion technologies are needed to relieve feedstock cost targets [6.7, 6.9].

Because of the supply risks and uncertainty in prices of biomass-derived products, feedstock supply systems capable of accepting multiple biomass sources and producing multiple products are needed, because alternative uses of biomass will reduce costs and enable improved quality control [9.1]. Also, supply chains that are designed to utilize multiple feedstocks reduce risks [9.2].

Commodity Feedstocks

Merchandise is defined as goods bought and sold in business (i.e., commercial wares). Biomass is merchandisable in the form of a good/product that can be sold and bought. Typically, this would imply a minimum form of processing such as cutting, chipping, or baling, and some requirements to storability and transportability. A good becomes tradable when it can be sold in a different location than production. This is practiced by the wholesale and retail business. At this stage, the product (i.e., biomass) will need to comply with more strict requirements of storability and transportability. As a commodity, the good will adhere to a standard quality, which enables physical interchangeability and pricing. A commodity market is highly liquid (in terms of quantity) and competitive (i.e., numerous suppliers and buyers). Thus, it is often a supraregional market.

Industry Perspective: Solutions to Cost and Quantity Challenges

Developing multiple markets for biomass feedstocks is the most promising strategy for building a commercial-scale biomass supply industry. Expanding the use of biomass for other markets, such as heat and power, will enable growth and development of feedstock supply chains [1.1]. However, while multiple markets for biomass are important, they should be part of a pathway toward more liquid fuels because that pathway is the area of greatest national need and vulnerability [1.1.1]. One way to revolutionize the feedstock supply industry is to develop facilities (i.e., depots) that can accept any biomass and convert it to usable products [1.2]. These depots would be able to handle variable quantities of feedstock in a way that farmers and producers could sell excess material into the commodity market from a "banner" year [D4].

The best path for biorefinery success for is for the feedstock supply industry to work together with biorefineries and conversion researchers as advances in conversion technologies affect the design of the supply chain [2.1, D20]. The needs of future conversion technologies should be considered when designing future feedstock supply chains [D7, D20]. Likewise, new conversion technologies should be developed to address feedstock variability through more robust, feedstock agnostic conversion technologies [1.3] to achieve economic success. In addition, tying farmgate contracts to an industrial index would allow both conversion and feedstock investors to reap the benefit (and, conversely, take the hit) when, for example, oil prices are high, rather than only one party benefiting [D5].

Government incentives for biomass supply chain development would reduce new biorefinery startup costs, reduce investment risk [3.1, 3.2, 3.4], promote industry to improve efficiency, and reduce costs along the supply chain [3.4]. Consistent funding from government is critical [D21]. In addition, there is a critical and immediate need for biomass production incentives to support an expanding industry. Existing second generation biorefineries need continued government support (e.g. tax credits) to enable continued success [3.2]. The creation of a carbon tax would encourage adoption of bioenergy technologies [3.3].

Too much emphasis is put on technological issues that are decades away. An incremental strategy over time to help near-term biorefineries and feedstock suppliers operate more profitably would be more effective [4.1, 4.2].

Enabling multiple biomass value chains with depots that can process biomass into a variety of products, similar to municipal solid waste recyclers, will reduce risk and improve profitability of feedstock supply chains [5.1, 5.2, 5.3, 5.4, 5.5]. However, it is possible that feedstock suppliers would opt to produce and sell higher-value products rather than "subsidize" biofuel production [5.1.2].

Stakeholder Feedback on Sizing

Opinions vary regarding the size of future biorefineries by the year 2030. Although a majority (i.e., 14/24 polled) expect that typical biorefinery demand will be 2 to 10 K tons/day, projected biorefineries sizes of ≥ 10 K tons/day (6/24 polled) or even ≤ 2 K tons/day (4/24 polled) are not uncommon. Like other industries, such as diary [43], there may be a range of biorefinery sizes depending on the available harvest technologies [42], regional conditions [40, 50], and product(s) [41, 50].

Municipal Solid Waste

Municipal solid waste is more commonly known as garbage or trash. Typical municipal solid waste compositions in the United States are 27% paper and paperboard, 14% food waste, 14% yard trimmings, 13% plastics, 9% metals, 9% rubber, leather and textiles, 6% wood, 5% glass and 3% other. However, these compositions can change considerably depending on location, season, and from day to day. Municipal solid waste-derived paper, yard trimmings, wood, and plastics could potentially be used to produce lower-cost blends while additional value could be obtained for the biorefinery through recycling metals and glass.

Densification at or near the field or forest edge is needed to reduce the size of storage areas, improve stability during storage, enable rail or barge transport, and improve access to economically stranded biomass [6.1, 6.2, 6.3, D22]; there is some debate about whether the value added by densifying biomass is offset by the high energy requirements and costs of densification [6.5, 6.7]. However, short-term storage of biomass is critical; the appropriate amount of storage and economic impact must be considered when developing advanced concepts [D6]. Additional research is needed to more clearly and accurately assess energy balance along the supply chain, especially for advanced processing technologies [6.1.1]. Conversion of biomass to liquid intermediates at a depot should be more carefully evaluated [6.6]. Another key consideration is the energy source: any field operation requires operation of a diesel engine and the liquid fuel price is set by the transportation industry. It is usually cheaper to use electric power for an operation [D8]; however, access to electricity is required. In addition, field operations are weather and daylight dependent; therefore, it is always better to perform an operation at a stationary location where there is the potential for 24/7 operation [D8].

Advanced preprocessing at depots to create a commodity feedstock is required for scale-up of the biorefinery industry [6.4]. Metrics for assessing these Advanced Feedstock Supply Systems must go beyond the delivered feedstock cost to minimum ethanol selling price to account for the impact of feedstock quality (i.e., physical and chemical) on conversion performance [7.2]. Biomass supply chains will evolve as the biorefinery industry matures, and solutions for improving near-term profitability will not necessarily solve all challenges facing the n^{th} plant [7.6]. However, larger biomass companies maybe have an easier time absorbing costs associated with meeting biorefinery and commodity specifications. If advanced systems are to be successful, provisions for small and intermediate-sized farmers are critical, including securing farmgate contracts [D2].

Creating a solid or liquid feedstock intermediate at a depot located on a rail line will enable cheaper long-distance transport to a biorefinery [8.3]. However, the value of rail transport must be considered, because it is likely to be more expensive than expected [8.1]. It is often assumed that biomass must be converted to a flowable, densified feedstock (e.g., pellets) for rail transport; however, bales may also be reconfigured to fit centerbeam lumber rail cars and enable fast loading and unloading systems [8.2].

Session 1 Conclusions

The following were key takeaways from Session 1:

- Price is the biggest barrier to achieving a commercial biomass supply industry capable of delivering a billion tons annually. However, there are various perspectives on the causes and most effective solutions to addressing feedstock price. For example, some participants suggested that large-scale biorefineries are required to overcome economies of scale and Advanced Feedstock Supply Systems, including depots, are required to achieve a commercial-scale bioenergy industry capable of competing with fossil fuels.
- In general, Advanced Feedstock Supply Systems would overcome barriers in supplying one billion tons of biomass annually, but the high costs and energy use of advanced preprocessing technologies must be weighed against the benefits.
- Current large-scale biomass suppliers are more concerned about availability of biomass at the farm and forest than technology issues.
- Biomass producers and land owners need adequate financial incentives, lower risk, and clearer messages about the sustainability impacts of feedstock production and collection.
- The lack of clarity on an appropriate path forward is indicative of the near vs. long-term challenges facing the biomass supply industry.
- The needs of future conversion technologies should be considered when designing future feedstock supply chains.

References

Aden, A., M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace, L. Montague, A. Slayton, and J. Lukas, 2002, *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover*, NREL/TP-510-32438, pp. 154.

Argo, A. M., E. C. D. Tan, D. Inman, M. H. Langholtz, L. M. Eaton, J. J. Jacobson, C. T. Wright, D. J. Muth, M. M. Wu, Y.-W. Chiu, and R. L. Graham, 2013, "Investigation of biochemical biorefinery sizing and environmental sustainability impacts for conventional bale system and advanced uniform biomass logistics designs," *Biofuels, Bioproducts, and Biorefining* 7(3): 282–302.

Bonner, I. J., K. G. Cafferty, D. J. Muth, M. D. Tomer, D. E. James, S. A. Porter, and D. L. Karlen, 2014, "Opportunities for Energy Crop Production Based on Subfield Scale Distribution of Profitability," *Renewable Energy for Agriculture* (7)1.

Carolan, J., S. Joshi, and B. E. Dale, 2007, "Technical and Financial Feasibility Analysis of Distributed Bioprocessing Using Regional Biomass Pre-Processing Centers," *Journal of Agricultural & Food Industrial Organization* 5(2): 1203–1230.

DOE, 2011, U.*S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*, R. D. Perlack and B. J. Stokes (leads), ORNL/TM-2011/224, August 2011, p. 227.

Eranki, P. L., B. D. Bals, and B. E. Dale, 2011, "Advanced Regional Biomass Processing Depots: a key to the logistical challenges of the cellulosic biofuel industry," *Biofuels, Bioproducts, and Biorefining* 5(6): 621–630.

Hansen, J., J. Jacobson, M. Roni, 2015, "Quantifying Supply Risk at a Cellulosic Biorefinery. In K. Chichakly, & K. Saeed (Eds.)," Proceedings from the 33rd International Conference of the System Dynamics Society. Albany, New York: System Dynamics Society.

Hess, J. R., K. L. Kenney, L. P. Ovard, E. M. Searcy, and C. T. Wright, 2009, *Commodity-Scale Production of an Infrastructure-Compatible Bulk Solid from Herbaceous Lignocellulosic Biomass. Uniform-Format Bioenergy Feedstock Supply System Design Report Series*, INL/EXT-09-17527, April 2009.

Jacobson, J., P. Lamers, M. Roni, K. Cafferty, K. Kenney, B. Heath, J. Hansen, and J. Tumuluru, 2014, *Techno-Economic Analysis of a Biomass Depot*, INL/EXT-14-33225, September 2014.

Jacobson, J. and K. Cafferty, 2013, *Define Approach and Metrics for Optimizing Feedstock Production*, Idaho National Laboratory, ID#: 4.1.2.20ML1.

Kenney, K. L., W. A. Smith, G. L. Gresham, and T. L. Westover, 2013, "Understanding biomass feedstock variability," *Biofuels* 4: 111–127.

Kenney et al., 2014, *Feedstock Supply System Design and Economics for Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels-Conversion pathway: Biological Conversion of Sugars to Hydrocarbons*, INL/EXT-13-30342, February 2014.

Muth, D. J., M. H. Langholtz, E. C. D. Tan, J. J. Jacobson, A. Schwab, M. M. Wu, A. Argo, C. C. Brandt, K. G. Cafferty, Y.-W. Chiu, A. Dutta, L. M. Eaton, and E. M. Searcy, 2014, "Investigation of thermochemical biorefinery sizing and environmental sustainability impacts for conventional supply system and distributed pre-processing supply system designs," *Biofuels, Bioproducts, and Biorefining* 8: 545–567.

Perlack, R. D., L. L. Wright, A. F. Turhollow, R. L. Graham, B. J. Stockes, and D. C. Erbach, 2005, *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, DOE/GO-102005-2135, ORNL/TM-2005/66, April 2005, pp. 25–50.

Perlack, R. D., and B. J. Stokes (leads), 2011, *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*, ORNL/TM-2011/224, August 2011, p. 227.

Searcy, E. and J. R. Hess, 2010, *Uniform-Format Feedstock Supply System: A Commodity-Scale Design to Produce an Infrastructure-Compatible Biocrude from Lignocellulosic Biomass*, INL/EXT-10-20372, September 2010.

Bioenergy Feedstock Library

The Bioenergy Feedstock Library, within INL's Biomass Feedstock Program, provides a robust mechanism for storing, tracking, and retrieving various feedstocks for research and demonstration purposes. The Library is comprised of two primary components: the physical storage of feedstock materials (tracked through global unique identifier) and the archive database system. The extensive analytical capabilities at INL are a key part in determining the quality characteristics. The Bioenergy Feedstock Library allows subsequent quality analyses to be tracked back to the original sample, such that one could relate the impact of initial biomass quality on various conversion processes. Therefore, the Library plays a key role in interface tasks between conversion and feedstocks. The Bioenergy Feedstock Library also gives researchers a broader dataset for their data. Although measured parameters vary, typical parameters include feedstock compositional data (i.e., extractables, ash, lignin, glucan, and xylan) and proximate/ultimate analytical data (i.e., CHNS & O, thermogravimetric, and calorimetric data).

SESSION 2: QUALITY

Feedstock Quality and Variability in Biofuels Production Systems[7]

Emerging biomass supply systems are built on a foundation of experiences drawn from agriculture and logging industries. These supply chains carry with them a range of industry-specific assumptions about materials quality and performance; however, these assumptions may not reflect the specific needs and sensitivities for biofuel and bioenergy applications. To-date, industrial biomass feedstock supply systems have largely focused on cost reductions, with relatively less emphasis on feedstock quality. This oversight has resulted in problems in acquiring, handling, and feeding material during startup and operations.

The biomass cost-to-value relationship has been a major driver behind biomass logistics engineering research. Progress has been made in improving the biomass collection and preprocessing machinery performance and efficiencies (Shinners and Binversie 2003; Yancey et al. 2009), reducing material losses throughout the supply chain (Darr and Shah 2012, Shinners et al. 2007), and expanding harvesting and storage operational windows (Shinners et al. 2010). However, an emphasis on feedstock quality is still lacking; conventional supply systems merely attempt to offset quality-related issues by driving down feedstock supply or purchasing costs.

The emphasis of cost over quality is clearly demonstrated by the current pricing structure for biomass that assesses value on a dollar per dry ton basis (Sokhansanj et al. 2002). Otherwise, valuations based on dollar per clean, dry carbohydrate or dollar per clean, dry unit of energy would exist. The overwhelming need for a low cost, sustainable supply of feedstock is the

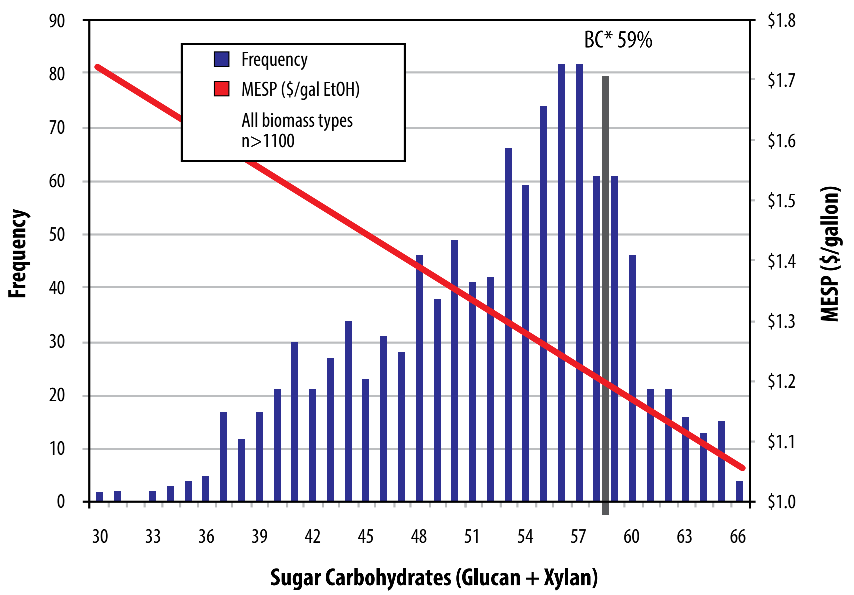


*Figure 10. An example of quality valuation of biomass feedstocks: minimum fuel selling price (MFSP) in relation to initial sugar carbohydrate content. Current biochemical conversion pathway assumption is 59% (presented by Kenney, sourced from Kenney et al. 2013).*Note: BC stands for current biochemical conversion design case.*

[7] Portions of this section were taken from Jacobson, J., P. Lamers, M. Roni, K. Cafferty, K. Kenney, B. Heath, J. Hansen, and J. Tumuluru, 2014, Techno-economic analysis of a biomass depot, INL/EXT-14-33225, September 2014.

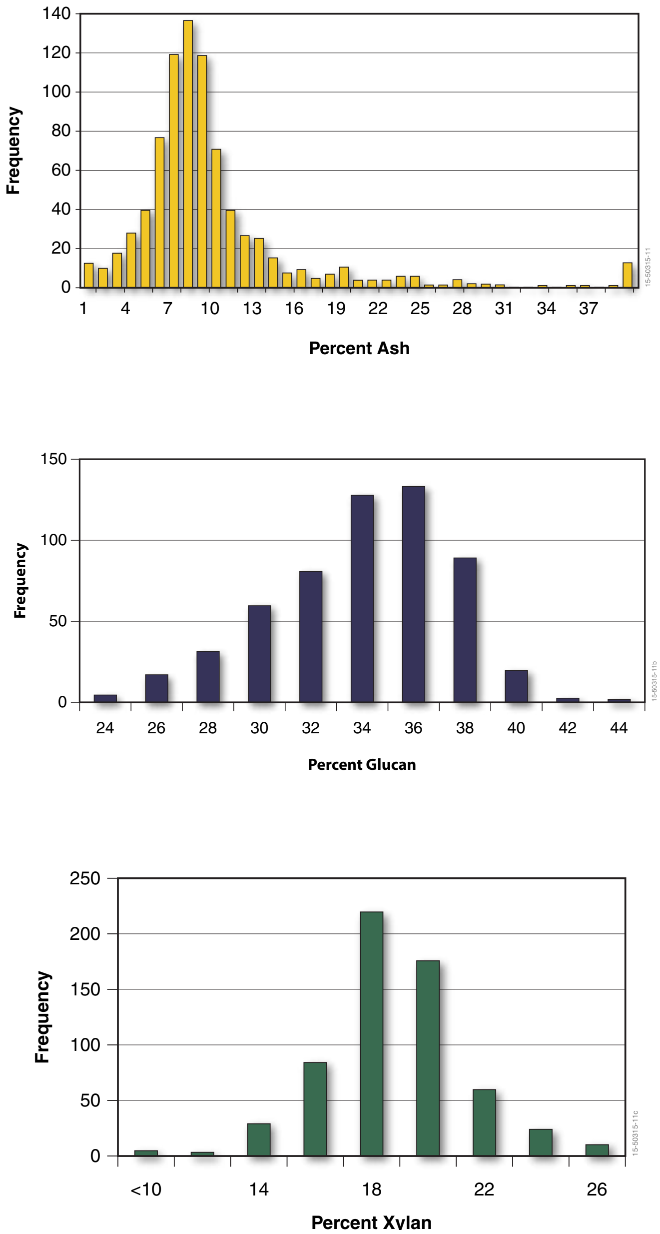


Figure 11. Example of the spatial and temporal variability of corn stover characteristics such as percent ash content, percent glucan content, and percent xylan (Jacobson et al. 2014).

driver behind this valuation; however, research and pilot-scale use of "pristine" feedstock composed of clean, homogeneous structural tissues certainly contributes to a lack of understanding of feedstock quality and specifications. Conversion processes that have scaled up to pilot-scale operations, requiring larger quantities of feedstock, have experienced vast differences between pristine and "field-run" feedstock (Humbrid et al. 2011) (Figure 10).

The quality of field-run biomass is impacted by inherent species variability, production conditions, and differing harvest, collection, and storage practices, which often differ from pristine laboratory feedstocks that are handled very carefully from field to laboratory (Figure 11). Even just cutting biomass and laying it on the ground before collecting it introduces ash and other contaminants that can affect its chemical composition. Until then, the lack of specifications should not encumber or delay feedstock development from moving in this direction. A focus on supplying a feedstock of consistent quality attributes will go a long way in enabling specifications, removing barriers to accessing our nation's vast supply of biomass resources, reducing biofuel production costs, and enabling a national-scale biorefining industry.

There are many possible approaches to mitigating variability and low-quality, passive controls (i.e., leave the bad stuff) and active controls (including blending and formulation).

Increasing Access to Biomass Resources

Blending is a common practice in many industries. For example, blending is used in the U.S. grain industry to adjust quality (Hill 1990). Similarly, different grades of coal are blended to achieve compliance with regulations regarding sulfur and nitrogen emissions in the power generation industry (Shih and Frey 1995, Boavida et al. 2012). Furthermore, the animal feed industry uses a range of feedstocks blended together to meet the specific nutrient requirements of the target animal (Reddy and Krishna 2009). Finally, relatively high-ash content biomass sources are mixed with low-ash coal to allow economical use in co-fired biopower generation (Sami et al. 2001).

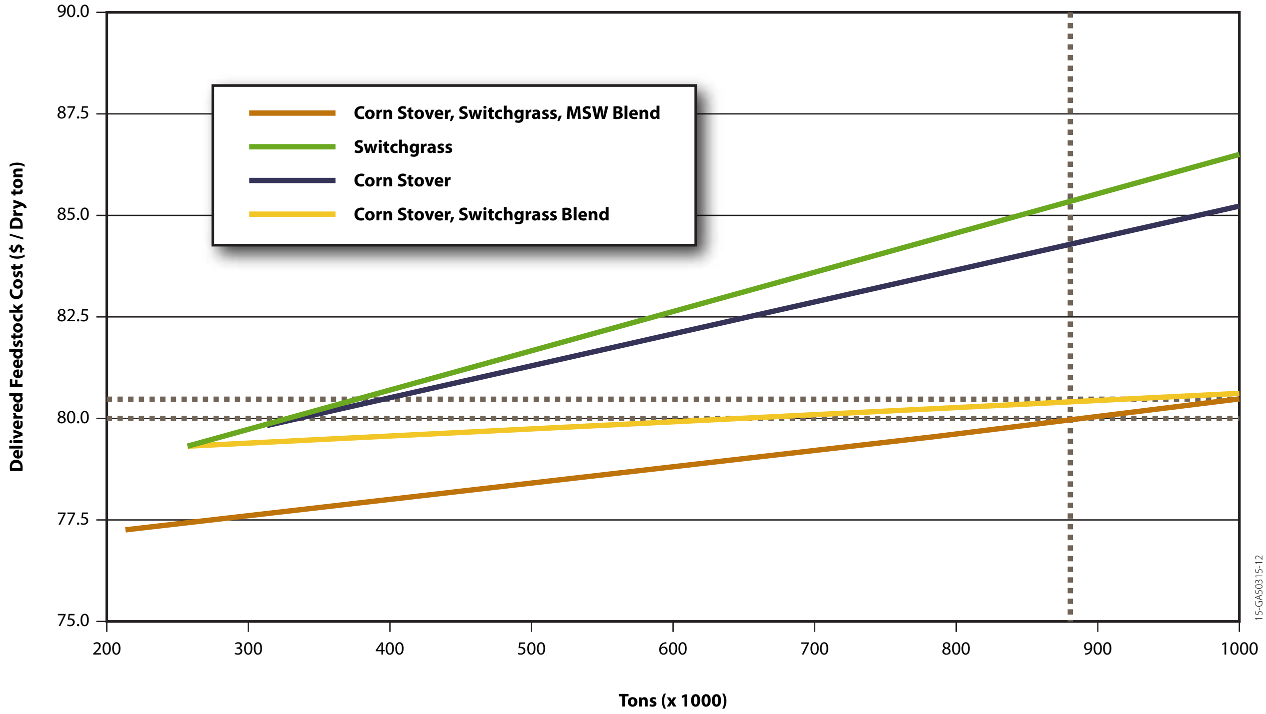


Figure 12. Comparison of individual and blended feedstock costs for one county. A blend of 60% corn stover, 35% switchgrass, and 5% municipal solid waste is needed to hit the U.S. $80/dry ton feedstock cost target for 880,000 dry tons. The two blended lines are weighted-average cost curves of the amount of each feedstock with associated delivered feedstock cost. Note that these curves would vary by county, by region, and by state. Also note that the dotted lines indicate the cost and quantity lines for both feedstock blends at a total delivered quantity of 880,000 dry tons (i.e., 800,000 dry tons plus a 10% buffer) (Jacobson et al. 2014).

By combining analyses using average farmgate price assumptions with quality information obtained from the Bioenergy Feedstock Library (see Appendix D), gains in the projected quantity available at cost and the conversion in-feed specifications are being realized by transitioning to a blended feedstock approach. Feedstock blending allows a biorefinery to collect less of any one type of biomass by collecting a variety of biomass (e.g., corn stover, switchgrass, and sorghum); which moves down the cost vs. supply curve and results in paying a lower average price for each feedstock (Figure 12). Note that this does not change the supply vs. cost curves for each resource; instead, it describes a system where purchasers are using a combination of least-cost resources and blending them to meet the bioenergy application's desired feedstock specification.

Biomass quality is a key aspect to consider when analyzing cost and quantity availability. Formulating a designed feedstock through blending and other pre-processing logistical methods allows low cost and, typically, low quality biomass to be blended with biomass of higher cost and, typically, higher quality to achieve the in-feed specifications at the conversion facility. In combination with densification, wider sourcing areas can be tapped (including resources that are considered stranded using conventional supply systems). Bringing various feedstock streams into the supply system reduces overall grower payments (Jacobson et al. 2014).

Ash is not beneficial to conversion processes and will result in additional costs for the biorefinery in terms of reducing pretreatment efficacy, machine wear, disposal, and reduced conversion performance. Ash comes in several forms, including dirt and soil on the outside and structural ash or physiological ash internal to the plant. External ash is much easier to remove through washing or best management practices in harvesting and collection. Physiological ash requires more extensive mechanical or chemical processes to remove. When ash content increases, especially due to the addition of a non-biomass constituent (e.g., soil), the convertible biomass content decreases (Kenney et al. 2013). Any increase in non-carbohydrate constituent reduces the proportion of structural carbohydrates present. Also, ash increases the neutralization capacity of corn stover during dilute-acid pretreatment, which reduces conversion yields (Weiss et al. 2010).

As biorefineries emerge, move from technology development and deployment to operation, and their focus changes to process optimization, experience with field-run biomass will move quality and specifications to the forefront. As the importance of feedstock quality is realized, quality-based valuations, which include devaluation for moisture, non-carbohydrate content (e.g., ash content), and other contaminants or conversion inhibitors, will evolve. This valuation is also necessary to incentivize farmers and suppliers to implement best management practices that preserve biomass quality, for biorefineries to enforce best management practices, and, ultimately, for biomass to be a traded as a commodity with definable and consistent quality measurements (e.g., specifications).

Industry Perspective: Quality

Workshop participants were presented with a series of barriers to guide the discussion in Session 2 (Table 4). Comments captured during the workshop were reviewed and consolidated into the "Industry Perspective" sections of this report. Numbers in square parentheses (i.e., [1.2.3.4]), correspond to comments or a group of comments located in Appendix A.

Table 4. Quality assumption and barriers presented to participants of the Advanced Feedstock Supply System Validation Workshop during Session 2.

Assumption: Quality is limiting to the biorefining industry and must be managed in the feedstock supply system.	
Quality Constraints	Barriers: 1. Variability exists and will be important at the scale of a single biorefinery (due to weather events, flood, drought and rain) 2. Variability increases biorefinery cost and risk 3. Quality attributes must be managed to achieve expected performance 4. Specification targets are ever moving and evolving 5. Cost to value added

The Limits of Physical and/or Chemical Characteristics

Physical and chemical variability exist and are unavoidable [1.1]. Natural variability due to factors such as different growing conditions (e.g., soil types and microclimates) and growing season characteristics is difficult to address [1.1.7]. However, variability in ash (e.g., ash introduced from soil) develops at the first harvest steps and carries downstream [1.1.4, 1.1.7]. Variability due to introduced ash can be addressed and minimized via best management practices [1.1.4, 1.1.14].

Variability directly influences the biorefinery's profitability and risk and impacts every unit operation in the feedstock supply chain (e.g., storage, handling, preprocessing, and yield) [1.3, 1.3.2, 1.8, D10]. There is a balance between investing in feedstock upgrading and inherent variability and determining the acceptable level of variability [1.1.15]. Obviously, different end users will value quality specifications differently; there will not be a single set of quality attributes for which the industry can target [1.1.10]. Understanding what is realistic, given the cost-benefit ratio of testing and product value, becomes critical

Sustainable Residue Removal

Though large quantities of agricultural residues are produced within the United States, only a fraction can be collected without negatively impacting soil resources and the productivity of our agricultural lands. Residues play an important role in limiting soil erosion from wind and water and in maintaining soil organic carbon, both of which are key players in soil productivity. Making sustainable residue removal decisions requires consideration of the full range of factors that can potentially limit the amount of residue that can be removed to replace a barrel of oil or bushel of grain.

Impact of Feedstock Specification

For a conversion process to handle a variety of feedstocks, it is necessary to understand the quality attributes that affect conversion efficiency and their impact. When developing feedstocks specifications, key considerations include the inherent quality characteristics of the biomass, requirements for optimal conversion performance necessary, selection of appropriate analytical methods, and incorporation of general classification descriptions and terminology that is clear to both the supplier and the end-users.

[1.1.6, 1.1.17, 1.1.27, 1.1.28]. If the conversion impacts of a range of parameters related to feedstock variability are better understood, variability specifications can create incentives and/or penalties, with management of variability enhancing product value and justifying testing costs [1.1.8, 1.1.9, 1.1.18]. Therefore, essentially, a quick, reliable, and accurate test is needed for feedstock quality attributes such as moisture and ash [1.1.12, 1.1.13]. Another question is where in the supply chain and what testing and management should occur (e.g., farmgate or biorefinery gate) [1.1.30]? Upstream processes that are distant from the biorefinery may not have the information and/or education needed to deliver a product that meets biorefinery specs [1.1.31]. At the same time, highly variable products will receive less remuneration/market value. Thus, clear trade-offs to addressing certain specs at certain supply chain stages exist [1.1.23]. Potentially, feedstock could be graded through limited characterization early in the supply chain, whereas a more detailed testing should occur later in the supply chain [1.1.17]. This would align testing scope with feedstock value.

A simple grading system, including off-spec dockage, base prices, and premia, could be helpful in limiting variability [1.3.1, 1.3.3, 1.3.10, 1.3.11]. However, development of industry or national standards is questionable [1.3.12]. Feedstock in-feed specifications are highly dependent on the conversion strategy [1.3.14] and each facility may need to negotiate its own set of specs with the suppliers [1.3.15]. Monetizing the cost of quality variables is difficult and unique to each conversion pathway [1.10]. A related challenge is the inability to accurately, quickly, and economically measure quality [1.7, 1.7.1, 1.7.2, 1.7.4] because you cannot change or improve what cannot be measured [1.7.3].

Biorefineries can adapt to feedstock variability over time [1.1.25], but variability will be important at the resolution of a single biorefinery due to the limited draw radius [1.2, 1.2.8]. Biorefinery processes are less flexible to feedstock variability on a day-to-day operational basis [1.1.25], unless they include preprocessing options within the biorefinery gates [1.3.4]. Years of experience and know-how are required to produce a consistent end-product [1.1.26, 1.2.9, 1.3.9]. However, not all variability needs to be dealt with regardless of cost [1.1.20, 1.1.21, 1.3.9] and some conversion processes will be more tolerant of variability in certain parameters than other processes [1.2.1, 1.2.9]. At the biorefinery, feedstock compositional variability can be better managed via specifications and the biorefinery's willingness to pay for specific sets of attributes [1.2.3]. If the market is strong for end-products, quality standards may even be relaxed in challenging years [1.2.10]. Seed breeding and selection may help in narrowing quality variability across the years, seasons, and regions [1.9].

Storage is a key barrier and includes considerations of feedstock degradation (e.g., due to weathering layer and mold in the center of a bale) and spontaneous combustion [1.4, 1.5, 1.6]. Establishing fire codes and standards for feedstocks to de-risk the market may be necessary [1.4.1, 1.4.3]; however, the party responsible for insurance would need to be determined [1.4.1]. Additional unsolved barriers include a lack of equipment to process biomass to exacting specs [1.11] and a lack of knowledge on material properties to control equipment that process the materials [1.12].

Drivers of Feedstocks Specifications

Feedstock specifications are constantly moving and evolving [2.1, 2.8], but will be different for different processes (e.g., cellulosic conversion pathways, bioproducts, and biopower) [2.3.1, 2.3.4, 2.3.6] and different markets [2.3.13, 2.3.15]. Cellulosic biofuel plants may further define their specs with increasing operational time [2.1.1, 2.3.11, 2.3.14, 2.3.16, 2.5.1, 2.5.2] and continuous process improvements [2.1.2]. Potentially, different grades of feedstock could be matched to different conversion processes [2.3.9]. However, it may not be beneficial to have tight control requirements that are region specific (i.e., that are not applicable beyond a certain geographic boundary).

Too narrowly defined or too many specs may constrain commoditization of the feedstock [2.3.3, 2.3.10]. Yet, having multiple markets will generate a larger pull for biomass mobilization (and ultimately commoditization), but may increase the number and variance among specifications [2.3.12, 2.3.17].

Feedstock specifications are generally considered to be ranges [2.4.2-2.4.11], potentially with a minimum or maximum and/or a threshold level. The critical point is not the individual parameter ranges but a balanced specification for multiple parameters [2.4.8]. Diversity of the conversion pathways and methods will make establishing a single feedstock spec difficult, if not impossible [2.7]. Therefore, rather than making specs for feedstock, specifications that achieve optimal reactor performance will need to be determined [2.6]. Demonstrating technical feasibility first with an "optimal" feedstock shows how robust the technology is and could be used to down-select technology pathways [2.6.3].

Conversion process optimization and economics will set the desired material spec. The feedstock supply chain, including harvest through preprocessing, must be capable of delivering that spec (or as close as possible to it) [2.6.2]. A significant improvement in certain key specs (e.g., ash) can be achieved through a combination of cost-effective techniques throughout the supply chain [2.6.4].

Defining and maintaining specifications always involves tradeoffs [2.6.1, 2.9, 2.10, 2.12]. At this stage, little is known about the response curves for most of the parameters that can be specified, and feedstock specifications are essentially an economic decision [2.11]. To control specs, early checks in the supply chain are required [2.3.7]. Active control mechanisms in the supply system can also help balance specs [2.3.2].

Requirements for Feedstock Parameter Measurements and Enforcing Biorefinery Specs

A wide range of feedstock measurements is desirable, including ash (composition) [3.1, 3.9, 3.12], moisture [3.3], carbohydrate content [3.4, 3.11], handling properties [3.5, 3.19], degradation [3.6], storability [3.7], particle size distribution [3.8, 3.10, 3.13, 3.15], harvest location [3.16], heating value [3.14], inhibitors (e.g., acids, molds) [3.22], and other impurities such as paint [3.23]. Ash is of particular interest [3.1] for the thermochemical platform [3.1.6]. However, feedstock specs vary greatly between each conversion process, even among thermochemical pathways [3.1.8]. Rapid near infrared techniques are being developed and demonstrated for measuring numerous parameters (such as moisture, ash, and carbohydrate content) [3.2]. Much more work in this area is needed to broaden industry-wide applicability [3.2] that is facilitated by increased collaboration [3.2].

Biomass degradation [3.6] is important because it changes chemical and physical characteristics [3.6.1]. A better understanding of how feedstock degradation impacts processability is needed, particularly with respect to challenges associated with conversion and feeding [3.6.2]. At the same time, degradation will only affect the owner of the biomass, not the ability to measure properties that will define the biomass value [3.6.4].

Passive & Active Quality Controls

Control over biomass variability ensures feedstock quality is on-spec. "Passive" quality control is the first and simplest method and typically refers to best management practices during harvest, collection, and storage. These passive methods serve as a means for preventing quality loss before it can occur. "Active" controls, on the other hand, serve to repair or significantly alter the course of quality loss. Active controls may remove ash from feedstocks by physical or chemical processes or alter feedstock format to improve storage properties.

A range of options are available to enforce feedstock specs, but generally a mix of penalties and incentives is required, including, but not limited to, dockage, product rejection, and premia [4.1-4.6]. Once feedstock specs are defined, biomass can be bought based on content and characteristics [4.7] such as energy content [4.10]. This is consistent with other agricultural industries and would be expected for the biomass industry [D11].

Providing upstream information on best management practices and quality control could also incentivize performance in growing and harvesting and could build relationships [4.3, 4.11-4.13]. Increased competition could also drive spec enforcement [4.14, 4.15]. Other supply chain strategies could include contracting and upstream/vertical integration of biorefineries [4.8, 4.9].

Additional Quality Considerations

Additional points to consider include competitive uses for biomass [5.1], cost trade-offs (e.g., yield per acre) [5.2], and major regional supply disruptions [5.3]. Biomass harvest and collection infrastructure should receive more attention; essentially, it will be many farmers or a custom harvest operation controlled by the biorefineries [5.4]. A quick screening should be undertaken to determine whether or not some approaches to managing different quality attributes are economically and/or environmentally sustainable [5.5]. Finally, biomass producers would likely be very supportive of producing a higher quality feedstock, provided the market is willing to compensate for any additional costs and efforts [D9].

Industry Perspective: Solutions to Quality Challenges

Best Management Practices

Best management practices are a good start for addressing quality aspects [1.1.3], but their economics need to be demonstrated [1.7]. Best management practices are part of a series of options, including active and passive quality management techniques [1.3]. An example of active measures is bale breaking plus screening and ash separation, re-baling, and potentially blending across multiple source bales to homogenize moisture content [1.6].

Preserving Quality During Storage

Consumption of valuable structural sugars by microorganisms during storage results in dry matter loss and enrichment of other components (such as lignin and ash). These other components have low or no value within a sugar-based conversion process. The goal of storage is to preserve the valuable qualities of the feedstock until they can be fully utilized within the conversion process.

National User Facility at INL

DOE is working with collaborators from across industry to develop the science and technologies needed to transform diverse forms of biomass into consistent, quality-controlled commodity products that can be efficiently handled, stored, and transported to biorefineries for processing. INL has developed the capabilities to perform these investigations through the Biomass Feedstock Process Demonstration Unit (PDU), a group of pilot to full-scale preprocessing equipment that can be operated onsite or deployed to the customer. The PDU is a preprocessing research system for demonstrating production of advanced biomass feedstocks at a pilot scale. Onsite operations are supported by laboratory-scale units for initial development, including thermal and chemical preprocessing systems, full characterization, and analytical capabilities. INL has established this set of capabilities as the INL Biomass Feedstock National User Facility. The National User Facility will advance U.S. energy security by meeting the needs of researchers for an easily accessible, state-of-the-art, and affordable capability. The INL Biomass Feedstock National User Facility is the premier facility in the United States for scientific, technical, and engineering investigation for transforming biomass feedstocks into consistent, quality-controlled commodity products that can be efficiently handled, stored, and transported to biorefineries in support of biomass-based energy security applications.

Best management practices appear to be particularly valuable for harvest, collection, and storage [1.1, 1.8]. They can certainly address aspects such as moisture and ash mitigation to a certain level [1.1]. When industry is unable to afford proper quality measurements, best management practices may be the most viable option [1.2]. At the same time, field-level quality control can support, but not replace, the control at the biorefinery inlet [1.5].

Physical and Chemical Preprocessing

The primary physical and chemical preprocessing approaches used to address feedstock quality will be densification, ash mitigation, moisture management, and blending [2.1, 2.2, 2.3, 2.4]. All approaches to mitigating feedstock quality will require a better understanding of the respective cost-benefits and life-cycle impacts [2.6]. In particular, densification may require a detailed cost-benefit analysis [2.1.1] to show that it adds more value to the feedstock, beyond just compensating for additional equipment costs through reduced handling and transport costs. However, some benefits of densification will be difficult to quantify such as overall feedstock supply risk mitigation [2.1.4]. Furthermore, densification will need to be justified from an energy balance perspective [2.1.7].

In addition, the cost-benefit necessity stays true for ash mitigation. Separation technologies exist [2.2.1, 2.2.2], including those employed by the cotton industry [D12]; however, there is little understanding of the market value of feedstock at various ash contents [2.2.5]. Cost-effective leaching technologies are needed, but this must be accompanied by a detailed understanding of the liquid stream treatment that extracted species from the biomass [2.2.3, 2.2.6].

For agricultural residues, ash mitigation may be limited by the farmer's willingness to adapt harvesting patterns [2.2.4], because cellulose is not the primary crop, the grain is. Similarly, moisture management is, to some degree, outside the control of the farmer [2.3.1]. Plus, although a critical component of current commodity systems, active moisture management is expensive [2.3.2]. Rather, approaches similar to field drying of hay may be exercised [2.3.4].

Blending feedstock is an option that could be incorporated into the depot concept [2.4.1, 3.6] and present a low-cost strategy for managing some key parameters; however, this could create conflicts with other parameters [2.4.2]. Generally, blending could potentially provide a mechanism for reducing seasonal quality variability across regions [2.4.3]. A critical question is where in the supply chain preprocessing (such as active quality control and blending) should occur? An understanding of the entire supply chain is required to determine where processing is most economical and how cost-benefits are distributed across the supply chain [2.5.1, 2.5.2, 2.9].

Other options for mitigating feedstock quality include storage techniques that allow for passive chemical modification during storage [2.8], use of additives that might stabilize and/or improve quality during storage/transport [2.10], anatomical fractionation and pure stream intermediates [2.11], and adaptation of collection systems to perform some preprocessing during harvest [2.13].

Conversion Technology

Feedstock quality impacts on downstream conversion processes are a real concern. Economically viable and successful conversion technologies will need to be more robust with respect to quality variation [3.1, 3.7]. At this point, a better understanding of process variability and process control is needed to reduce the current over-engineered processes in pioneer biorefineries [3.1.4]. As strategies are developed to address feedstock variability and quality, risk mitigation strategies through process flexibility may need to be developed to improve overall performance independent of feedstock variability [3.3].

Fractional Milling

Size reduction of feedstocks is very energy intensive, yet it is necessary for conversion in-feed. When performed prior to arriving at the biorefinery, it can enable more efficient handling and transport. One approach to reducing energy required for size reduction is fractional milling. In fractional milling, size reduction occurs in stages and various screens are employed such that only material requiring further size reduction enters secondary grinders. By separating the material that already meets size specification, energy consumption for the drying and second stage grinding are significantly reduced and throughput is effectively increased, resulting in lower processing cost.

In-plant preprocessing operations will use blending or fractional processing approaches to address quality [3.10]. Most industries have an in-feed cleaning unit operation; the cellulosic ethanol plants will need to adapt to this as well [3.9, D13]. As part of this, there needs to be improved incoming feedstock monitoring technologies/data collection [3.4, 3.8]. To offset preprocessing costs (at the biorefinery or outside), alternative uses for side streams/co-products (such as ash) may be beneficial [3.13].

Cost Benefit Concerns About Quality

A foreseeable challenge for biorefineries is securing a sustainable supply of sufficient feedstock and not just narrow quality specs. Quality concerns may be a secondary aspect to quantity variations across years and feedstock [4.12, 4.13]. However, conversion pathways will be more or less susceptible to feedstock quality variation, which is reflected in the respective pathways performance, risk rating, and ability to attract financing [4.8, 4.8.1]. Ash, for instance, is of higher concern to the thermochemical pathway than the biochemical conversion pathway [4.1.5, 4.1.6]. Biorefineries are expected to vary the price paid for feedstock, depending on how the quality parameters cause added costs through additional processing [4.10]. Also, when quality becomes a variable in a dedicated supply chain, contracting dynamics (and costs) are expected to ensure sufficient high-quality supply [4.7].

Near-Infrared Spectroscopy

Near-infrared spectroscopy has become a cornerstone technique for developing robust predictive models for rapidly and cost-effectively screening feedstocks for many quality attributes. Currently, work is being done to develop near-infrared spectroscopy models that can accurately predict ash and volatiles using calibration samples for a range of feedstocks, harvest years, and locations. Other efforts focus on developing models to determine quality attributes at specific transaction points in the feedstock supply chain process, from field level analysis to pretreated samples.

Where ash is a concern, dockage costs have been calculated to be around $2.25/ton/% ash [4.1]. At the same time, it is not clear whether this dockage value is applied broadly [4.1.4, 4.5]. Nevertheless, higher ash content not only has the potential for dockage costs, but also reduces corn stover yield per acre (and thus revenues) for the farmer [4.3]. In addition to dockage, costs related to dry matter loss and ash relate to disposal and backhauling of sludge and broken and wet bales. [4.6]. As for moisture, losses and dockage due to moisture are similar to grain shrinkage cost [4.4].

Session 2 Conclusions

The following were key takeaways from Session 2:

- Biomass' variability and inherent physical attributes, such as high moisture and high ash, can make its use as a feedstock for energy production challenging.
- Variability directly influences the biorefinery's profitability and risk and impacts every unit operation in the feedstock supply chain. Biorefineries need to clearly define incoming feedstock properties and quantify the impact of any variation in these specs on conversion performance.
- Key barriers to consistent biomass feedstock quality at the biorefinery include natural biomass variability, induced variability, the need for enhanced methods for quality measurements, defining feedstock specifications, the need to better understand the impact of biomass quality parameters on various conversion processes, and devising appropriate quality enforcement methods.
- Although the barriers for delivering high-quality feedstock are numerous, many innovative solutions could address these challenges, including active feedstock quality management (i.e., preprocessing), passive management (e.g., selective harvest and collection techniques), more robust conversion technologies, and cost vs. value-added analysis-based solutions.

References

Boavida, D., P. Abelha, I. Gulyurtlu, B. Valentim, and M. J. L. D. Sousa, 2012, "A study on coal blending for reducing NOx and N2O levels during fluidized bed combustion," *Clean Air* 5: 175–191.

Darr, M. J. and A. J. Shah, 2012, "Biomass storage: An update on industrial solutions for baled biomass feedstocks," *Biofuels* 3(3): 321–332.

Hill, L. D., 1990, *Grain Grades and Standards: Historical Issues Shaping the Future*, Chicago, IL, USA, University of Illinois Press.

Humbird, D. A. et al., 2011, *Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol--Dilute-acid pretreatment and enzymatic hydrolysis of corn stover,* NREL/TP-5100-47764, May 2011.

Jacobson, J., P. Lamers, M. Roni, K. Cafferty, K. Kenney, B. Heath, J. Hansen, and J. Tumuluru, 2014, *Techno-economic analysis of a biomass depot,* INL/EXT-14-33225, September 2014.

Kenney, K. L., W. A. Smith, G. L. Gresham, and T. L. Westover, 2013, "Understanding biomass feedstock variability," *Biofuels* 4: 111–127.

Kenney, K. et al., 2014, *Feedstock Supply System Design and Economics for Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels-Conversion pathway: biological conversion of sugars to hydrocarbons*, INL/EXT-13-30342, February 2014.

Reddy, D. V. and N. Krishna, 2009, "Precision animal nutrition: A tool for economic and eco-friendly animal production in ruminants," *Livestock Research for Rural Development* 21(3).

Sami, M., K. Annamalai, and M. Wooldridge, 2001, "Co-firing of coal and biomass fuel blends," *Progress in Energy and Combustion Science* 27(2): 171–214.

Shih, J.-S. and H. C. Frey, 1995, "Coal blending optimization under uncertainty," *European Journal of Operational Research* 83(3): 452–465.

Shinners, K. J. and B. N. Binversie, 2003, "Whole-Plant Corn Harvesting for Biomass: Comparison of Single-Pass and Multiple-Pass Harvest Systems," *Proceedings of the ASABE Annual Meeting, Las Vegas, Nevada*.

Shinners, K.J. et al., 2007, "Comparison of wet and dry corn stover harvest and storage," *Biomass and Bioenergy* 31(4): 211–221.

Shinners, K. J. et al., 2010, "Harvest and storage of two perennial grasses as biomass feedstocks," *Transactions of the ASABE* 53(2): 359–370.

Sokhansanj, S. et al., 2002, "Engineering aspects of collecting corn stover for bioenergy," *Biomass and Bioenergy* 23(5): 347–355.

Weiss, N. D., J. D. Farmer, and D. J. Schell, 2010, "Impact of corn stover composition on hemicellulose conversion during dilute acid pretreatment and enzymatic cellulose digestibility of the pretreated solids," *Bioresource Technology* 101(2): 674–678.

Yancey, N. A. et al., 2009, "Preprocessing moist lignocellulosic biomass for biorefinery feedstocks," *Proceedings of the ASABE Annual Meeting, Reno, Nevada*.

Biorefinery Financing Risk

A multitude of aspects impact a biorefinery's access to and terms of financing. First, there are macroeconomic considerations including economic, market, and policy factors. These include the general economic state, biofuel and crude oil market conditions and prices, and political framework conditions. The latter covers the existence and structure (timespan, certainty, etc.) of policy and subsidy schemes such as a carbon tax, renewable fuel mandates, federal loan guarantees, or others. On a plant scale, the terms of financing are heavily defined by the proposed business plan, including technology choice and plant layout, state-of-technology (mature vs. first-of-a-kind), legal aspects (e.g., permits and environmental considerations), and business risks (e.g., feedstock supply and experience of the company/employees/managers). Financing conditions are also influenced by the project's total capital investment, the debt-to-equity ratio, and the assets, liquidity, and credit worthiness of the debtor.

SESSION 3: OPERATIONAL AND FINANCIAL RISK

Biorefineries are affected by various aspects of feedstock risk that are predominantly linked to supply variability in terms of feedstock quality and quantity. In addition to the quality variations discussed in Session 2, feedstock quantity supply can be highly variable—both spatially and temporally—due to changing yields, inclement weather, competition, and other factors.

Securing Feedstock Supply – Reducing Operational Risk to Biorefineries[8]

Feedstock supply uncertainty contributes to feedstock supply risk; therefore, it is a critical consideration for a biorefinery. Consider the following stylized example that a hypothetical biorefinery having an annual feedstock demand of 800,000 tons might face. Relying on a conventional supply system, the biorefinery only contracts with local growers within a 50-mile draw radius, minimizing transportation cost. When relying on an Advanced Feedstock Supply System, the biorefinery can contract with local growers in addition to growers up to 400 miles, leveraging lower transport costs associated with densified material and highcapacity transport systems. We assume the biorefinery contracts with the same number of growers in the conventional and advanced systems. A model simulation informs on the feedstock quantity the biorefinery might expect in each supply system. Using parameters for yield, ash content, and dry matter loss that are representative of corn farms in the Midwest to populate the simulation model, Figure 13 shows two histograms of corn stover quantities that the biorefinery could expect.

In the conventional system (i.e., the red bars in Figure 13), the feedstock supply quantity ranges from just over 400,000 tons to slightly more than 1,000,000 tons. On average, the biorefinery would receive 751,000 tons (i.e., the mean of the simulation), but would experience considerable variation as reflected in the standard deviation (i.e., 118,000 tons). For the modeled advanced scenario (i.e., the blue bars in Figure 13), the range of possibilities is much less, with the range beginning at just over 800,000 tons and reaching slightly more than

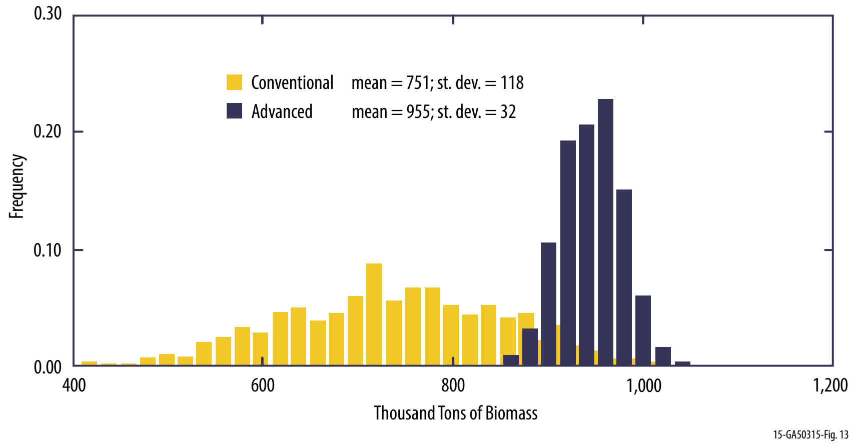


Figure 13. Histogram of the year-to-yield yield that can be expected from a conventional vs. an Advanced Feedstock Supply System.

[8] Portions of this section were taken from Jacobson, J., P. Lamers, M. Roni, K. Cafferty, K. Kenney, B. Heath, J. Hansen, and J. Tumuluru, 2014, Techno-Economic Analysis of a Biomass Depot, INL/EXT-14-33225, September 2014.

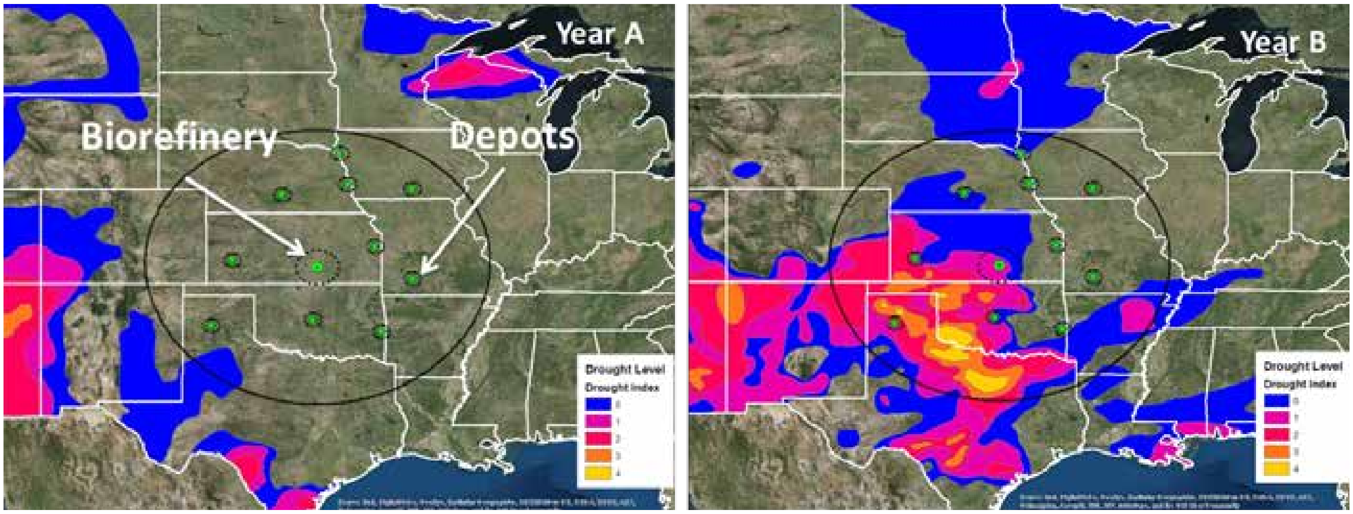


Figure 14. Impact of drought levels on an example biorefinery sourcing radius in a conventional (dotted circle) and Advanced Feedstock Supply System (wider circle, including depot operations) over 2 years (Hartley 2015).

1 million tons. On average in the advanced system, the biorefinery could expect 955,000 tons (i.e., the mean of the simulation), with much less variation than was seen for the conventional scenario (i.e., the standard deviation of the simulation was 32,000 tons). The primary reason for the difference in the two histograms shown in Figure 13 is that in the Advanced Feedstock Supply System, the biorefinery diversifies its supply portfolio, thereby mitigating feedstock supply risk. In the conventional system, all growers are impacted equally by the parameters that impact supply. That is not the case in the Advanced Feedstock Supply System, because supply is drawn from a diversity of regions. Growers are impacted by the parameters in their region only, not regions in other parts of the supply system. Therefore, unwanted events like drought, flood, or pests that impact supply may hit one (or several) regions in the supply system, but not all regions. For example, a pest is less likely to impact all biomass in a 400-mile radius than to impact all biomass in a 50-miles radius.

The extent of the impact of regional supply radius dependence is further illustrated in Figure 14, which shows the impact of rainfall in a region over two different seasons. The conventional biorefinery sourcing radius (dotted) is significantly smaller than for a system where feedstock is preprocessed at regional depots (i.e., a wider radius), representing Advanced Feedstock Supply Systems. Naturally, inclement weather will have a much more severe impact on a smaller supply radius due to its limited flexibility.

Low-density feedstock (such as bales) not only limits the sourcing radius due to high transportation costs, but also increases the storage footprint and environmental impacts, including fire hazards, rodent infestation, and localized odors normally associated with large-scale storage of non-aerobically stable feedstock.

Other than transitioning to an Advanced Feedstock Supply System, some measures can be taken within the conventional system to mitigate supply quantity risks, including over-contracting (quantity), increasing the pool of producers/farmers to source from (diversification), investments in preprocessing equipment at the plant (increased storage/buffer), or widening the feedstock base (diversification).

Impact of Feedstock Supply on Financial Risk

Mitigating feedstock supply uncertainty to the biorefinery via an Advanced Feedstock Supply System will reduce risk to financial investors, which will be reflected in the annual interest rate for the biorefinery loan. Resource uncertainties are recognized as a major investment risk by financial institutions, creating

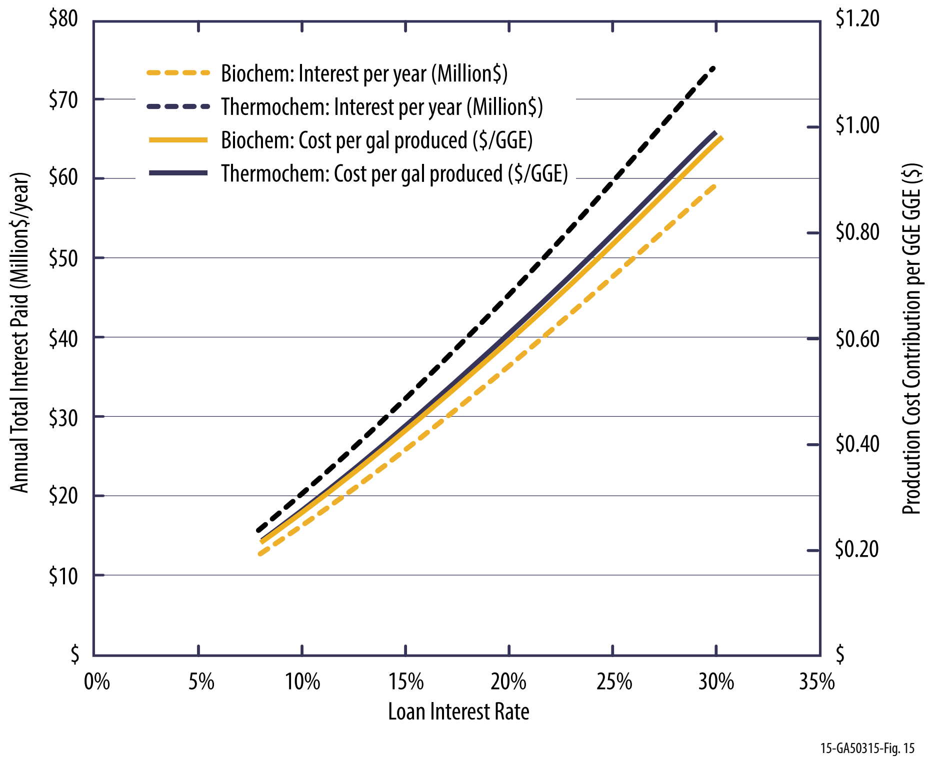


Figure 15. Annual total interest for biorefinery investments of 800,000-dry tons annual capacity facilities across varying interest rates and their respective impact on the production costs per liter of gasoline equivalent (LGE) (Lamers et al. 2015).

a barrier for new biorefineries to enter the market. Investment risk increases the cost of capital because investors in bonds and equity require a greater risk premium, directly impacting the weighted average costs of capital and annual rate of returns. Feedstock quantity and price variations are commonly identified as a key sensitivity to break even in biorefinery investments (Davis et al. 2013).

NREL biorefinery design reports assume an 8% interest rate over the course of a 10-year loan for 60% of the total capital investment of a biochemical or thermochemical biorefinery based on an Advanced Feedstock Supply System (Dutta et al. 2011, Humbird et al. 2011). Current biorefinery investments relying on a conventional feedstock supply system are assumed to face much higher interest rates due to the early industry stage and opportunity costs for investors (to invest in other, more lucrative endeavors). At the same time, n^{th}-plant assumptions, including an 8% interest rate, can also be seen as optimistic (Anex et al. 2010). A mature industry, with limited feedstock supply risks due to an Advanced Feedstock Supply System, will be able to achieve a lower interest rate than a current, conventional supply system-based biorefinery investment. Figure 15 compares the total annual interest paid for biorefinery investments over various interest rates and the respective impact per gallon of gasoline equivalent produced.

For this comparison, it is less important to identify and compare exact interest rates for current conventional vs. Advanced Feedstock Supply Systems. It is more important to observe the trend. Interest rate reductions between 2 to 15% across a range of 8 to 30% interest led to cost savings per gallon of gasoline equivalent between $0.05 and $0.51 (Table 5).

Table 5. Impact of Interest Rate Reductions Between Calculated Impacts per Gallon of Gasoline Equivalent for Interest Rates in the Range of 8 to 30% for a 10-Year Loan for 60% of the Total Capital Investment for a Biochemical or Thermochemical Conversion Facility of 800,000 Dry Tons Annual Feedstock Capacity.

Intrest Rate Reductions Between Calculated Impacts per Gallon of Gasoline	
Interest Rate Reduction	**Reduction in Unit Production Costs ($/gallon of gasoline equivalent)**
-2%	0.06 to 0.07
-3%	0.10 to 0.11
-5%	0.16 to 0.20
-10%	0.33 to 0.39
-15%	0.52 to 0.56

As demonstrated in Table 6, even interest rate reductions as little as 2% (e.g., from 17% down to 15% interest paid on debt) can result in substantial savings to investors.

Industry Perspective: Risk

Workshop participants were presented with a series of barriers to guide the discussion in Session 3 (Table 6). Comments captured during the workshop were reviewed and consolidated into the "Industry Perspective" sections of this report. Numbers in square parentheses (i.e., [1.2.3.4], correspond to comments or a group of comments located in Appendix A).

Table 6. Feedstock Supply Risk Assumptions Presented to Advanced Feedstock Supply System Validation Workshop Participants During Session 3.

Assumption: Risk is important to the biorefinery and must be managed in the feedstock supply system.	
Operation & Financial Risk	Barriers: 1. Cost 2. Transitioning from Conventional to Advanced 3. Feedstock competition

Cost and Supply Risk to Scaling Feedstock Supply Systems

The main barriers to scaling up the biorefinery industry are linked to securing sufficient feedstock at the appropriate quality and the costs associated with the respective management approaches [1.1-1.4, 1.9, 7.6]. Risk mitigation paths (such as over-contracting [1.1, 1.3] and buffer storage [1.2.1]) increase costs to the biorefinery. Hence, the challenge is to determine the lowest-cost risk mitigation tool [1.1.2]. The quality of all agricultural industries is high risk and would be vulnerable to weather events [D3]. However, many other agricultural industries leverage commodity markets and have other risk mitigation strategies in place. Grain elevators can serve as positive examples [1.2.2], because they enable supply via storage over multiple years (temporal) and across regions (spatial). At the same time, development of the grain industry required significant investment in infrastructure. Significant investment would be required for development of supply chain infrastructure to support the bioenergy feedstock industry [1.5]. The appeal of developing such a system will vary by stakeholders, including different types of financial institutions. First engaging the locallevel financiers is crucial for the initial stages [1.5.3].

To design Advanced Feedstock Supply Systems, an improved understanding is required regarding where the risks lie across the supply chain and how they could be more evenly distributed or mitigated (so that risks are not shifted from one party to another) [1.6, 1.6.3]. In current conventional supply systems, both the biorefinery and the farmer assume risk [1.6.1, 1.6.4, 1.6.5]. A potential interim solution could be the option for insuring biorefineries against risk [2.2]. However, there is a lack of data with respect to premiums for feedstock supply; therefore, this leads to a limited ability to develop respective insurance products. Insurance for inventory mitigation (i.e., crop insurance) would imply additional costs to the biorefinery operation.

Feedstock Competition and Agronomic Issues

Near-term biorefineries would very likely be located in areas of high feedstock availability, similar to the corn ethanol industry, which would lead to a high concentration of producers in specific regions [5.1.1]. This increases feedstock competition, especially under conditions of reduced harvest amounts (due to factors such as drought and pests) [5.3]. Regional sourcing dependence under the conventional supply system and the lack of feedstock diversity in a particular area are key operational risks [5.3].

Competition with other agricultural markets and changes in government regulation, such as conservation plans limiting harvest rates, are additional risks to be considered [1.9, 4.2]. Regulatory scrutiny would also be exercised in development of an agricultural residue supply stream with respect to sustainability aspects, such as soil quality and soil carbon loss. These aspects must be understood and aligned with the individual farmer at the field level to account for regional (and subfield level) differences [4.3.1]. Demonstration of sustainable practices and ongoing reporting would be an integral part of such operations [4.4].

Financing and Financial Risks

Financing aspects include access to finance and the type of finance and investors. Regional lenders may be preferable at the initial stages of future supply system investments, because they tend to be more interested in development of their local economies (i.e., "Main Street vs. Wall Street") [1.5.3]. As the industry continues to grow, more powerful financial institutions may be needed to generate sufficient capital to finance larger projects [2.3].

Because the cellulosic biorefining industry is still in its infancy, a lack of history [2.1] and price volatility in comparable markets (e.g., biopower) have increased perceived investor risk [2.1.1]. Also, as mentioned earlier, the lack of insurance and the range of operational risks, which are still not fully understood in how they expand and are balanced across the supply chain, add to the list of perceived investor risks. Other factors that add to this perceived risk include feedstock supply risk with respect to feedstock competition across multiple investments and a potential reluctance from financial institutions to take the risk to develop a density of conversion facilities (e.g., in a high-yield area). A better understanding of the project risks and priorities for investors would help increase access to capital.

"n^{th}-plant"

n^{th}-plant economics is a set of analysis assumptions and it implies that several plants using the same technology have already been built and are operating. Thus, rather than describing a pioneer plant, the analysis describes a future where a successful industry of n plants has been established. n^{th}-plant analysis avoids artificial inflation of project costs associated with first-of-a-kind plants, such as risk financing, longer startups, equipment overdesign, etc. With respect to feedstock, n^{th}-plant systems are assumed to rely on a supply system that delivers homogeneous, on-spec material at a fixed price.

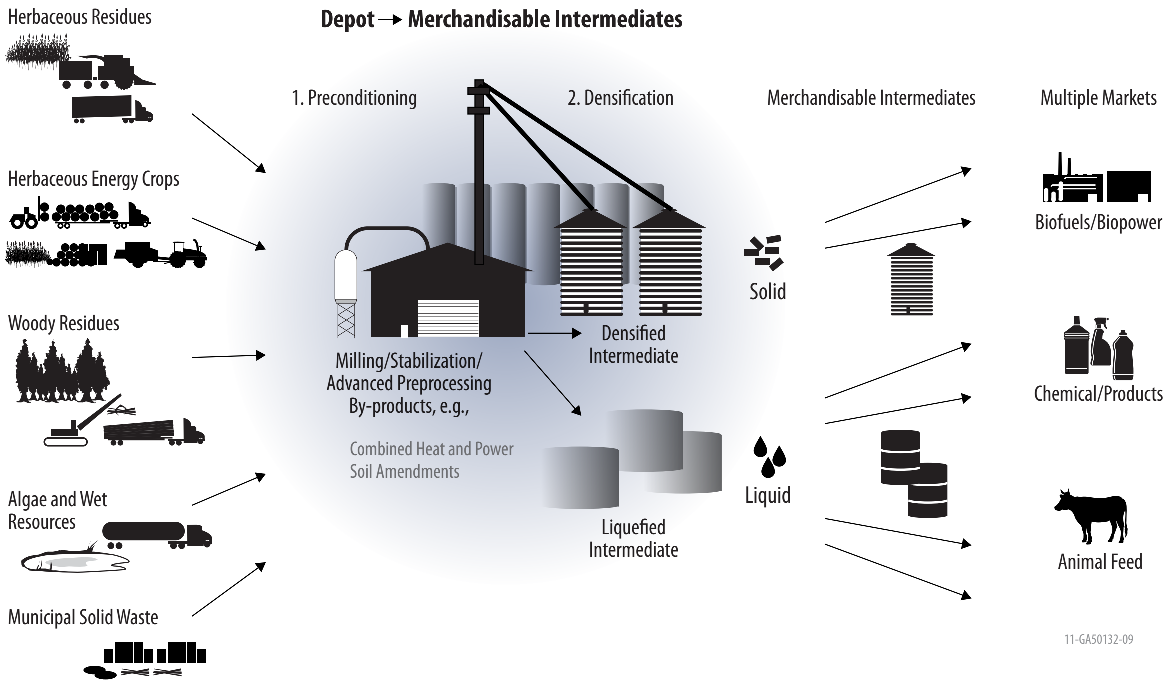


Figure 16. Schematic of an Advanced Feedstock Supply System, including distributed depots.

Business Structure and Transition Period

The path forward is built on transitioning from current, conventional biomass supply systems to future, Advanced Feedstock Supply Systems and infrastructure, which is needed to enable a billion-ton bioeconomy [6, 3]. Still, the nascent bioenergy industry would require stepping stones (e.g., demand pull from biorefineries and other biomass consumers to entice producers to get involved and build critical mass to fully commercialize the feedstock supply chain) [1.5.1]. This would involve starting with current equipment and technologies and evolving the processes into purpose-built, more effective/efficient solutions [1.5.1].

Again, the initial stages may face a chicken-and-egg situation, because it is yet unclear who should start developing the respective processes first: feedstock growers (farmers) or biorefineries. Mimicking existing grain elevator systems [6.2] (i.e., farmer cooperatives driving the depot concept) may fail due to a lack of grower acceptance. The biorefining industry may first need to commit to long-term price and quantity agreements, including a premium for preprocessed feedstock [6.1, 6.3, 6.5.2]. This also entails "captive producer risk"[9] [3.1] as long as growers can only sell into one market. At this stage, biomass producers will demand a higher price for their biomass due to the increased business risk, until there are multiple demand markets for their biomass crops to spread the risk. On the other hand, the emergence of more profitable or less risky markets for producers may result in crop-switching or a diversion of supply [D14]. This could present a major issue because the resource will go to the highest bidder [6.5.1]. Biorefineries will, in this case, demand long-term supply commitments or start integrating vertically to hedge quantity and price risks. Ideally, technologies and depot operations enhancing feedstock for the biorefining industry (such as AFEX) will also be attractive to other uses and markets [6.5.3].

With respect to the transition period, infrastructure bottlenecks (e.g., equipment availability) and a slow adoption rate of new methods and transactional schemes at the local and national level may present a barrier [1.7]. Robust extension, demonstration, and outreach to coach and support adoption at local and regional levels would be required [1.7.1].

[9] Captive producer risk describes the limitation of growers to sell feedstock to other industries rather than solely to the (regional) biorefinery.

Industry Perspective: Solutions to Biorefinery Risk

Transitioning to Distributed Depots[10]

Distributed depots, a component of Advanced Feedstock Supply Systems proposed by BETO, would create feedstock intermediates that are highly densified, flowable, stable, and allow for active quality management to meet end-user specifications (Figure 16). Distributed depots also create temporal and spatial (i.e., risk) diversification.

Depots are a component of a greater, commodity-based Advanced Feedstock Supply System; there are many possible permutations. Depots themselves can have many possible permutations, with the common factor being that they are regional preprocessing centers. However, depots could vary from simple pelleting to complex pretreatment processes [1.3]. Thus, depot outputs could be commodity solid or liquid intermediates [1.4]. These intermediates may offer different values [4.10] and requirements with respect to the connected value chain and handling system [4.10.3]. The size and complexity of depot operation would depend on a range of factors, including the owner (farmer or biorefinery), business model, and location.

A network of depots allows a more distributed and diverse feedstock supply [1.5.1, 1.5.2], which reduces business risk and costs (capital and operational) of the biorefinery [1.5.3, 1.5.4]. However, depots themselves entail investment costs and risks, which may or may not be covered by the biorefinery. The basic depot concept is based on a large-scale, multiple biorefinery system, which does not currently exist [1.1]. Transitioning from the current state of the industry to where the industry has access to depots is critical and will be part demand-pull vs. supply push [4.6].

Transition to an Advanced Feedstock Supply System will only be feasible if multiple end-use markets exist for the depot output [1.5.7, 1.5.14], whether the depot output is destined for a biorefinery or could be sold as an intermediate [1.5.21, 1.5.22]. In the short term, more attention needs to be paid to the economics and technical specifics of different depot configurations [1.5.14]. Unless the cost structure and business/market risks are better understood (i.e., the relation between costs added vs. value added and the dependence on multiple output markets), financing depots will be difficult [1.5.13, 1.5.15, 1.5.25].

Multiple output options would also increase the risk for depot clients, especially in years with regional biomass shortages [1.5.19]. As such, larger depots would face similar issues as (smaller) biorefineries in a conventional feedstock supply system, where one major event (such as a drought) could significantly impact the input stream [1.5.31]. At the same time, depot size could be minimized initially to match local markets, but still provide commercially relevant operation for review/observation by financiers and customers [1.5.16, 1.6]. Demonstration projects validating various technologies could help drive the industry forward [1.5.16].

Depot development risks (and costs) may potentially be reduced by integrating biomass depots with other, existing depots such as grain, wood, or municipal solid waste [1.5.9, 1.5.27, 1.5.30]. This would also allow an integration of larger-scale infrastructure (such as rail and barge) needed for depots to transport long distance in bulk and at low costs [1.5.8]. As such, initially integrated depots would present a transition strategy to the Advanced Feedstock Supply System [1.5.26]. Thus, the technical and business concept of the depot will evolve and change over time [1.5.23].

Ownership and financing of depots should mainly be local (i.e., "Main Street" vs. "Wall Street"), supporting communities and local economies [1.5.10, D15]. Depots would emerge to support rural economies [1.5.29] and local depot owners would be able to gain from the value added. The benefit to largescale investors of biorefineries would be a reduction of business risk, meaning both Main Street and Wall Street would benefit from widespread implementation of the depot concept.

Reducing Storage Risk

Stable, solid format intermediates that can be stored for extended periods of time and maintain quality are beneficial [2.1, 2.2]; they could replace current bulk format, bale storage, and reduce fire risk (a problem that has plagued multiple cellulosic ethanol producers) [2.1.1]. At the same time, off-gassing and dust explosions are issues with wood pellet storage. Intrinsically, dry biomass has a faster rate of combustion than coal. Coal storage yards currently turn over coal mechanically and/or water coal in the summer to reduce fire risk. Analogous strategies for biomass fire risk reduction need to be assessed [2.2.1, D16].

[10] Across the range of solutions, a network of distributed depots was the main item discussed. Solution (and barrier) categories typically received up to 10 (first-tier) comments. However, the distributed depot concept received over 30 items.

Mitigating Climate Impacts

In 2012, the emerging bioenergy industry faced enormous challenges with the drought conditions across the United States. All sectors of the bioenergy community were concerned that the drought conditions could lead to biomass harvest decisions that had long-term negative impacts on the land and the industry. These events have tremendous potential to disrupt not only the quantity of biomass available for bioenergy use, but also the quality and value of biomass. This is particularly true for end-users dependent on a single crop residue from a small geographic area. In years where catastrophic conditions exceed the control of agronomics, crop management decisions will be focused on preserving the value of primary crops and productivity of the land – often at the expense of residues for alternate markets. Mitigating this risk is crucial for reliable production of biofuels.

Multiple Markets for Commodity Feedstocks

The initial stages of depot development require flexibility with respect to sourcing (i.e., being able to handle multiple forms of biomass [4.8] and end-use markets/clientele [4.2]). Multiple off-take markets (such as energy, feed, and fodder) will be required to make a depot economical and help depots manage their profitability accordingly [4.2.1, 4.2.4, 4.2.7]. Multiple markets potentially already exist and a wider assessment may be required to better understand the entire landscape for biomass applications [4.2.2]. This could help prevent future competition for a limited feedstock resource across multiple industries. Also, additional demand pull could spur grower acceptance and help lower the initial cost of feedstock supply development [4.2.3].

Potentially, new markets for feedstock need to evolve, including spot markets [4.3] and basic standards, including contracts [4.4] that would allow hedging [4.5], which is a minimum criterion for transition to a commodity system.

Several options for depot ownership exist [D23]. In the case of vertical supply chain integration [4.7], end-use will be limited, while an independent owner would be motivated to spread his/her business risk across multiple markets (farmer cooperatives). Independent depots with multiple end-use markets may not significantly reduce a biorefinery's supply risks because producers will sell into the highest margin markets. As such, biorefineries need to be competitive across multiple feedstock markets. Prior to building new biorefineries, investors/companies need to know that the feedstock resource is secured and affordable. Upstream investment of biorefineries into depots could be a possible option for safeguarding resources.

Supporting Feedstock Development via Policy and R&D

While depots are regarded as a long-term viable solution, policy frameworks, particularly innovative risk mitigation policies, and programs (DOE and other agencies) are required in the short-term [5.2.1]. Risk mitigation tools are a means of enabling the next stages of industry development. Expanding the U.S. bioeconomy requires coherent energy policies with respect to co-firing of biomass and fossil fuels. These policies could be applied to enable logistics and industry transition. Data for identifying probabilities (i.e., frequencies and severities) on the various risk categories are needed to allow insurance companies to define rates and risk financing mechanisms [5.2]. Federal agencies could take a role to help identify risks and disseminate research results.

Messaging and education relates to dissemination and communication, where federal agencies play a critical role in mitigating different interests and enhancing the understanding of other external factors and sociological drivers. Any supply chain involves many different players with different priorities (environmental and extension people) [7.2].

Session 3 Conclusions

The following were key takeaways from Session 3:

- Risk is a major barrier to an expanding bioenergy industry in the United States, both in terms of securing feedstock supply and feedstock quality.
- Advanced Feedstock Supply Systems, including depots, could have a role in supporting the expansion of the U.S. bioeconomy by reducing risk throughout the supply system.
- Advanced Feedstock Supply Systems have many desirable features, including producing a stable product, enabling the use of high-capacity handling and transport infrastructure, and the potential of selling the biomass into various markets.
- A natural transition from current conventional feedstock supply systems to a depot-based model was not apparent. If we are to move from conventional systems to advanced, commodity-based systems, a transition strategy is required.
- Ownership and financing of depots should mainly be local (i.e., "Main Street" vs. "Wall Street"), supporting communities and local economies.
- Energy policy could play a key role in bridging the gap between these feedstock supply systems. Policy support through loan guarantees or crop insurance would be very helpful.

References

Anex, R. P., A. Aden, F. K. Kazi, J. Fortman, R. M. Swanson, M. M. Wright, J. A. Satrio, R. C. Brown, D. E. Daugaard, A. Platon, G. Kothandaraman, D. D. Hsu, and A. Dutta, 2010, "Techno-economic comparison of biomass-to-transportation fuels via pyrolysis, gasification, and biochemical pathways," *Fuel* 89 (Supplement 1): S29–S35.

Davis, R., L. Tao, E. C. D. Tan, M. J. Biddy, G. T. Beckham, C. Scarlata, J. Jacobson, K. Cafferty, J. Ross, J. Lukas, D. Knorr, and P. Schoen, 2013, *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons*, NREL/TP-5100-60223, October 2013, http://www.nrel.gov/docs/fy14osti/60223.pdf.

Dutta, A., M. Talmadge, J. Hensley, M. Worley, D. Dudgeon, D. Barton, P. Groenendijk, D. Ferrari, B. Stears, E. Searcy, C. Wright, and J. Hess, 2011, *Process Design and Economics for Conversion of Lignocellulosic Biomass to Ethanol - Thermochemical Pathway by Indirect Gasification and Mixed Alcohol Synthesis*, NREL/TP-5100-51400, May 2011.

Hartley, D., 2015, "U.S. drought map," Idaho Falls, ID, USA, Idaho National Laboratory.

Humbird, D., R. Davis, L. Tao, C. Kinchin, D. Hsu, A. Aden, P. Schoen, J. Lukas, B. Olthof, M. Worley, D. Sexton, and D. Dudgeon, 2011, *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover*, NREL/TP-5100-47764, http://www.nrel.gov/biomass/pdfs/47764.pdf, Accessed June 30, 2014.

Jacobson, J., P. Lamers, M. Roni, K. Cafferty, K. Kenney, B. Heath, J. Hansen, and J. Tumuluru, 2014, *Techno-Economic Analysis of a Biomass Depot*, INL/EXT-14-33225, September 30.

Lamers, P., E. Tan, E. Searcy, J. K. Hansen, C. Scarlata, K. Cafferty and J. J. Jacobson, 2015, "Strategic supply system design—a holistic evaluation of operational and production cost for a biorefinery supply chain," *Biofuels, Bioproducts, and Biorefining,* DOI:10.1002/bbb.1575.

WORKSHOP CONCLUSIONS

The *Advanced Feedstock Supply System Validation Workshop* brought together a variety of experts from academia and industry and the range of participant feedback reflected a diverse set of backgrounds. Nonetheless, several topics/themes repeatedly emerged from the dialogue and are summarized as follows:

There are fundamental barriers to the expansion of the bioenergy industry in the United States. Despite support from several federal agencies and other stakeholders, the numerous challenges associated with converting biomass into energy and bioproducts have led to a slow rate of industry growth. Feedstock variability and associated costs, financing challenges (i.e., access to capital and financing conditions), sustainability considerations, conversion technology scale-up challenges, the lack of a long-term national energy policy to support long-term investments in conversion facilities, and others, all constrain the rate of industry expansion. A related barrier that was commonly mentioned is business risk and its distribution across the value chain. There appears to be a clear need to identify and reduce risk to biomass producers, biorefineries, and equipment manufactures.

Conventional biomass supply systems have a limited ability to support expansion of the biofuel industry in the United States. Conventional systems have a limited ability to address and manage feedstock variability and reduce related supply risks. However, these systems can be effective under certain circumstances and they continue to have a place in supporting expansion of the bioenergy industry in the United States.

Advanced Feedstock Supply Systems and depots could play a role in addressing many of the barriers that currently hinder industry growth. Distributed biomass preprocessing centers (i.e., depots) that convert raw biomass into a stable, flowable, densified feedstock intermediate could address issues associated with variability and would reduce biorefinery supply risks. Standardized, interchangeable feedstock intermediates traded in a commodity-type market would be very desirable to biomass producers and biorefineries alike. However, a key to success is the depot provides added value and the small and mid-sized farmers can secure contracts and benefit from a commodity system, rather than get forced out by larger producers.

A transition strategy from conventional to Advanced Feedstock Supply Systems is needed. The Billion-Ton reports (Perlack et al. 2005, 2011) describe "existing" and "potential" biomass resources that could be available for biorefining, totaling approximately 1 billion tons of annual supply by the year 2030. General consensus among the participants was that a significant barrier to achieving this billion-ton bioeconomy vision would be transition from the current conventional design to the Advanced Feedstock Supply System design.

PATH FORWARD

Building on the final point, this section outlines a potential path forward for rapidly mobilizing biomass resources for expansion of the industry.

Building from Experience with Conventional Supply Systems

DOE has made significant investment in understanding and improving on conventional feedstock supply systems. For example, investments made through research at INL have enhanced the understanding of conventional feedstock supply systems in terms of equipment capacity, operational window, dry matter losses, biomass land yield requirements, sustainability, and, very significantly, their ability to support the achievement of DOE biomass cost, quantity, and quality targets (Jacobson et al. 2014, INL 2014, Hess et al. 2009, Searcy and Hess 2010, Kenney et al. 2013, Yancey et al. 2009). DOE also funded five high tonnage feedstock logistics projects (DOE 2015), with a goal of improving conventional feedstock supply systems to reduce the cost of supplying high quantities of feedstock to the refineries. Investments made in the Biomass Feedstock National User Facility have strengthened collaborations between DOE and industry, improving on existing equipment and developing new equipment to support an expanding industry. All of these advancements (and many more) have helped educate the bioenergy industry and helped guide DOE in terms of where they need to go to enable the expansion of the U.S. bioenergy industry.

The cellulosic biofuels industry in the United States is in its infancy; however, a handful of biorefineries have had to implement feedstock supply strategies for commercial facilities. The vertically integrated feedstock supply systems developed by each of these biorefineries are similar to conventional supply system designs described in DOE reports (Jacobson et al. 2014, INL 2014, Hess et al. 2009, Searcy and Hess 2010). Cost estimates for establishing the feedstock supply system on existing biomass resources (i.e., existing crops, such as corn stover, rather than energy crops) have ranged from 30 to greater than 50% of the cost of the biorefinery.

Recently published analyses show that biorefineries, cellulosic or otherwise, that are attached to an existing and fully mobilized feedstock resource (corn is the model) have a reduced risk profile that translates into 2 to 5% financing interest rate reduction (Lamers et al. 2015, Hansen et al. 2015). Depending on the size of the biorefinery, this translates into as much as a $0.20 per gal reduction in the cost of production over depreciable facility life. Additionally, evidence also suggests that facilities that do not have to develop their own supply systems can be fully operational 12 to 18 months sooner than those that must build supply systems. Combining the cost savings and faster start up time, there is great incentive for biorefineries to move beyond conventional supply systems.

Defining the Goal

The vision of the Advanced Feedstock Supply System is a mature logistical and market structure where multiple depot types and transloading terminals operate in a highly liquid and competitive feedstock market to serve multiple industries in the bioeconomy. This is essentially the vision of the upstream processes supplying n^{th}-plant type biorefineries (as described in Dutta et al. 2011, Humbird et al. 2011).

A stepwise introduction of the depot concept is seen as an organic transition toward this vision; however, depots alone do not represent the Advanced Feedstock Supply System. Initially, depots could solely entail processes for stabilizing biomass for storage and transport. They could be owned by the biorefinery to buffer supply variations and reduce storage footprint and harmonize in-feed operations. Fully independent and advanced technical designs (such as dilute acid pretreatment) may only emerge over time.

The fundamental idea of Advanced Feedstock Supply System technologies, including depot implementation, is that there are two industries (i.e., a feedstock industry and a conversion industry) for advancing the cellulosic biofuels industry, not just a single vertically integrated industry. Continuing along the path that pioneer cellulosic biorefineries have taken will constrain the bioenergy industry to very -high-biomass-yielding areas, limiting the industry's ability to increase in scale to larger plants and scale as an industry at any size of plant. Advanced Feedstock Supply Systems and depots in particular enable a bifurcated profitable feedstock supply industry that is independently viable from the biofuels industry.

Depots and, more importantly, advanced preprocessing technologies hosted at depots can mitigate many risk factors faced by biorefineries associated with conventional supply systems, such as aerobic instability (i.e., rotting and fire risk), high quality variability, inefficient handling and transportation, and supply chain upsets (due to weather, pests, etc.) to name a few. In addition to helping current biorefineries reduce feedstock supply risk, depots mobilize biomass resources into the marketplace by producing value-added merchandisable biomass intermediates that can be traded and aggregated.

Moving Feedstocks from a Biorefinery Service Industry to a ValueAdded Industry

A fundamental part of initiating depot operations is to establish a value proposition to the biomass grower, because the biomass becomes available to the market place only through mobilization. Mobilization is creating the economic drivers required for catalyzing the infrastructure investment and biomass resource development investment necessary to transition biomass from available resource (i.e., what is on the field) to a merchandisable resource (i.e., what is available for sale).

The current paradigm for developing feedstock supply systems requires a market pull (i.e., new biorefineries) to mobilize the resources. However, a feedstock supply industry that would independently mobilize biomass resources by producing value-added merchandisable intermediates creates a market push that will de-risk and accelerate deployment of bioenergy technologies. Accomplishing this would still require a market pull, but, initially, the pull comes from existing markets, leading to the need for multiple markets.

An obvious question emerges: how do you mobilize biomass into the marketplace without biorefineries to purchase the feedstock? The answer is leveraging companion markets (depots that produce valueadded product intermediates that are fully functional in both the companion market and the biofuels refining market). The stronger, established companion market mobilizes the biomass resource and that mobilization pushes the second generation biofuels market into existence.

An established animal feed industry currently exists in the United States, creating an opportunity for a companion market. AFEX creates a value-added intermediate product for livestock feed (Carolan et al. 2007). AFEX has also been found to enhance the performance of some biomass in biochemical conversion (Bals and Dale 2012, Bals et al. 2011) and could be applied at a depot. Another example of a companion market is applying thermal treatment strategies to produce oil products with acceptable "shelf-life" as a value-added intermediate for oil refining routes; this also produces valueadded products for heat, power, and specialty markets (e.g., liquid smoke and cosmetics). Technologies are being developed to support production of a stable bio-oil intermediate at depot-scale. Biopower is another example of a potential companion market. Unlike biofuels facilities that are designed to use biomass as a feedstock, existing coal plants would have to be retrofitted to co-fire significant amounts of biomass. Biopower is unique in that advanced feedstock preprocessing (such as torrefaction) to produce a bio-coal (a value add) is not an option, as is the case for biofuels, but rather is mandatory. In this respect, cofiring coal with biomass provides an opportunity to demonstrate advanced technologies and systems that could be leveraged by a growing biofuels industry (Boardman et al. 2013).

DOE's Role in Meeting National Goals

Innovative preprocessing technologies are necessary for making a depot business model profitable, some of which exist in a commercially ready form. Depots that improve feedstock stability (for storage), increase bulk density (for transport), improve flowability (for stable in-feed rates), and reduce dry matter loss are already widely applied in the wood pellet sector. However, in the herbaceous biomass sector, only small-scale, isolated operations exist.

In addition, there are many Advanced depot concepts, and a limited number of developed ideas (e.g., AFEX, torrefaction, and waste to oil). However, even these developed technologies require further investment (including piloting) in order for industry to commit sufficient resources needed to carry these technologies through to commercialization. Developing Advanced Feedstock Supply System technologies that create profit opportunities for the feedstock supply industry through added value transforms the feedstock industry from a service provider industry into an independently profitable industry producing value-added intermediate products.

The *Advanced Feedstock Supply System Validation Workshop* brought together stakeholders from many industries, the vast majority of whom acknowledged the many benefits of Advanced Feedstock Supply Systems. The obvious question is "Why doesn't industry fund the infrastructure necessary to build depotbased supply systems?" In reality, the advanced preprocessing technologies that achieve the value-added intermediates and that are needed to make this model work are not commercially ready and require substantial innovation and development. Currently, there is little understanding of the costs associated with operating a biomass depot at scale. If the advanced biofuels industry is to grow beyond the Corn Belt, Advanced Feedstock Supply System with depots must be developed and demonstrated so the technology is proven and financing for new facilities outside of this region is more easily obtained.

In reality, if a biorefinery is compelled to accept raw biomass resources, they invest only in the technologies required to make their own process operate more efficiently and would not be inclined to make investments benefiting an outside provider. Therefore, there is an ongoing need for investment from DOE to develop technologies that support expansion of the U.S. bioenergy industry.

References

Bals, B., C. Wedding, V. Balan, E. Sendich, and B. Dale, 2011, "Evaluating the impact of ammonia fiber expansion (AFEX) pretreatment conditions on the cost of ethanol production," *Bioresource Technology* 102(2): 1277-1283.

Bals, B. D. and B. E. Dale, 2012, "Developing a model for assessing biomass processing technologies within a local biomass processing depot," *Bioresource Technology* 106(0): 161-169.

Boardman, R. et al., 2013, *Logistics, Costs, and GHG Impacts of Utility-Scale Cofiring with 20% Biomass*, INL/EXT-12-25252, PNNL-22320.

Carolan, J., S. Joshi, and B. E. Dale, 2007, "Technical and Financial Feasibility Analysis of Distributed Bioprocessing Using Regional Biomass Pre-Processing Centers," *Journal of Agricultural & Food Industrial Organization* 5(2): 1203-1230.

DOE Bioenergy Technologies Office, 2015, "Accomplishments and Successes," http://www.energy.gov/eere/bioenergy/accomplishments-and-successes#2014, accessed July 2015.

Dutta, A., M. Talmadge, J. Hensley, M. Worley, D. Dudgeon, D. Barton, P. Groenendijk, D. Ferrari, B. Stears, E. Searcy, C. Wright, and J. Hess, 2011, *Process Design and Economics for Conversion of Lignocellulosic Biomass to Ethanol - Thermochemical Pathway by Indirect Gasification and Mixed Alcohol Synthesis*, NREL/TP-5100-51400, May 2011.

Hansen, J., J. Jacobson, M. Roni, 2015, "Quantifying Supply Risk at a Cellulosic Biorefinery. In K. Chichakly, & K. Saeed (Eds.)," Proceedings from the 33rd International Conference of the System Dynamics Society. Albany, New York: System Dynamics Society.

Hansen, J., J. Jacobson, M. Roni, 2015, "Quantifying Supply Risk at a Cellulosic Biorefinery. In K. Chichakly, & K. Saeed (Eds.)," Proceedings from the 33rd International Conference of the System Dynamics Society. Albany, New York: System Dynamics Society.

Hess, J. R., K. L. Kenney, L. P. Ovard, E. M. Searcy, and C. T. Wright, 2009, *Commodity-Scale Production of an Infrastructure-Compatible Bulk Solid from Herbaceous Lignocellulosic Biomass. Uniform-Format Bioenergy Feedstock Supply System Design Report Series*, INL/EXT-09-17527, April 2009.

Humbird, D., R. Davis, L. Tao, C. Kinchin, D. Hsu, A. Aden, P. Schoen, J. Lukas, B. Olthof, M. Worley, D. Sexton, and D. Dudgeon, 2011, *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover*, NREL/TP-5100-47764, http://www.nrel.gov/biomass/pdfs/47764.pdf, Accessed June 30, 2014.

Idaho National Laboratory, 2014, *Feedstock Supply System Design and Analysis*, INL/EXT-14-33227, September 2014.

Jacobson, J., P. Lamers, M. Roni, K. Cafferty, K. Kenney, B. Heath, J. Hansen, and J. Tumuluru, 2014, *Techno-economic analysis of a biomass depot*, INL/EXT-14-33225, September 2014.

Kenney, K. L., W. A. Smith, G. L. Gresham, and T. L. Westover, 2013, "Understanding biomass feedstock variability," *Biofuels* 4: 111–127.

Lamers, P., E. Tan, E. Searcy, J. K. Hansen, C. Scarlata, K. Cafferty, and J. J. Jacobson, 2015. "Strategic supply system design—a holistic evaluation of operational and production cost for a biorefinery supply chain," *Biofuels, Bioproducts, and Biorefining*, DOI: 10.1002/bbb.1575.

Perlack, R. D., L. L. Wright, A. F. Turhollow, R. L. Graham, B. J. Stockes, and D. C. Erbach, 2005, *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, DOE/GO-102005-2135, ORNL/TM-2005/66, pp. 25–50.

Perlack, R. D. and B. J. Stokes (Leads), 2011, *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*, ORNL/TM-2011/224, p. 227.

Searcy, E. and J. R. Hess, 2010, *Uniform-Format Feedstock Supply System: A Commodity-Scale Design to Produce an Infrastructure-Compatible Biocrude from Lignocellulosic Biomass*, INL/EXT-10-2037.

Yancey, N. A. et al., 2009, "Preprocessing moist lignocellulosic biomass for biorefinery feedstocks," *Proceedings of the ASABE Annual Meeting, Reno, Nevada*.

Advanced Feedstock Supply System Validation Workshop Summary Report

Available at **www.inl.gov/bioenergy**

For more information, contact:

Bioenergy Technologies Office
Energy Efficiency and Renewable Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Idaho National Laboratory
Biofuels and Renewable Energy Technologies
PO Box 1625
Idaho Falls, ID 83415
www.inl.gov/bioenergy

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

15-GA50315