INTEGRATING THE BIOMASS SUPPLY CHAIN FOR IMPROVED EFFICIENCY

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Executive Summary

To achieve widespread commercialization, biofuels must be readily available and cost competitive with fossil-based transportation fuels. This report outlines a supply chain integration strategy to achieve these goals, using representative terrestrial biomass-to-biofuels production pathways to frame the discussion of the current state-of-the-art in supply chain integration. In this context, supply chain integration is defined as the process of understanding and managing the various parameters and components of biofuel production to holistically lower costs and improve overall efficiency and performance. This paper includes recommendations for managing parameters, developing technology, and improving federal coordination. The report will be useful in implementing the National Biofuels Action Plan.

Acknowledgements

This report is the product of an interagency working group (IWG) appointed under the Biomass Research and Development (R&D) Board. The group includes representatives from the U.S. Department of Agriculture, U.S. Department of Defense, U.S. Department of Energy,

U.S. Department of Transportation, U.S. Environmental Protection Agency, and National Science Foundation. Six of the Board's seven standing IWGs also participated:

- Feedstock Production—Genetic Improvement
- Feedstock Management and Production
- Feedstock Logistics
- Transport and Distribution Infrastructure
- Conversion
- Analysis.

The IWGs' involvement assured the inclusion of expertise and perspectives from across the entire supply chain and helped establish a foundation for enhanced and continued collaboration among the different federal agencies.

Biomass R&D Board

Congress established the Biomass R&D Board[1] in 2000 to coordinate programs within and among departments and agencies of the federal government to promote the development of a biobased industry. This interagency coordination occurs through senior executive leadership, an appointed Technical Advisory Committee, and various technical experts organized into working groups. This paper is an example of an interagency coordination effort to remove barriers toward the commercialization of biofuels, bioproducts, and biopower.

Introduction

The biofuel production supply chain involves several components: biomass production, logistics, conversion to products, product distribution, and end use. Each component of the supply chain consists of several activities. An activity within a component can be as simple as passive drying, or as complex as molecular deconstruction and re-construction. These components are combined to form what is referred to herein as the supply chain. In this report, the supply chain involves the use of biomass feedstocks in various conversion processes to produce and deliver large quantities of biofuels, bioproducts, and biopower.

Decisions concerning one component may affect other components in the supply chain. For example, changing the feedstock characteristics through genetic modification may enhance conversion performance; densifying agricultural residues into pellets rather than transporting them as bales will increase downstream handling and transportation efficiency; and enabling catalysts to perform in the presence of ash could reduce pretreatment activities during logistics and increase conversion efficiency.

Considering the interactions of supply chain components, research, development, demonstration, and deployment (RDD&D) programs have identified the need for a holistic approach to optimizing the supply chain. This integrated approach may be more efficient and more cost effective than focusing RDD&D on making improvements to individual components. Improvements resulting from integration can occur at various and multiple places along the supply chain, such as siting strategically, managing plant material characteristics for low-cost production, optimizing conversion technologies, and using existing distribution networks more efficiently. This leads to high volumes and quality of biofuels and other products while minimizing inputs and waste streams.

With the benefits of holistic supply chain approaches growing in awareness among the various agencies—and as identified by the National Biofuels Action (NBA) Plan—there is a need for better understanding of how best to integrate feedstock production, conversion,

[1] More information about the Biomass R&D Board is available at http://www.biomassboard.gov/index.html.

and distribution. Integration can improve overall system economics and thus accelerate biofuel commercialization (Huang et al. 2010; Hajibabai et al. 2013). The primary goal of this paper is to highlight key interface points along the supply chain and make recommendations for improving overall system efficiency in an integrated fashion. Another goal of the paper is to enhance coordination among the federal agencies specific to RDD&D efforts for better integration across the biofuels supply chain.

The Biofuels Supply Chain

A biofuels supply chain has several components linked through the flow of materials (see Figure 1). Components include feedstock production, feedstock logistics, conversion/upgrading, and distribution. Materials change format and characteristics as they move through the supply chain. For example, corn stover lying in the field will likely be baled, ground, and potentially pelletized before being converted into a fuel. Furthermore, processes and activities occurring along the chain will affect recovery quantities and quality.

Understanding and managing the effects of material flow; changes in material quality, quantity, and characteristics; and the performance of activities within each component can lead to better efficiency of the entire supply chain if using an integrated approach to manage across the entire chain instead of individual components.

Approaches to Integrating the Supply Chain

Integration requires understanding and managing the various parameters within each component of the supply chain, as well as their relationship to other components. The goal of supply chain integration is to manage multiple parameters in such a way that optimizes performance, yields, and low costs for the supply chain. Integration of supply chain components brings together the biological, physical, chemical, socioeconomic, and engineering sciences to create the fully integrated feedstock production, conversion, and product-uses pathways. A full purview of knowledge, basic and applied sciences, tools, and expertise is needed to manage the parameters that control performance, outputs, and material flows in supply chain components to maximize overall system performance.

There are numerous parameters associated with the supply chain components. Some are very specific to a particular component, but many are transferable along the chain and can impact subsequent component activities and performance. A full description of all the individual parameters and their impacts is beyond the scope of this paper. Instead, this paper provides a general overview of the parameters and offers examples of managing them in a more integrated manner.

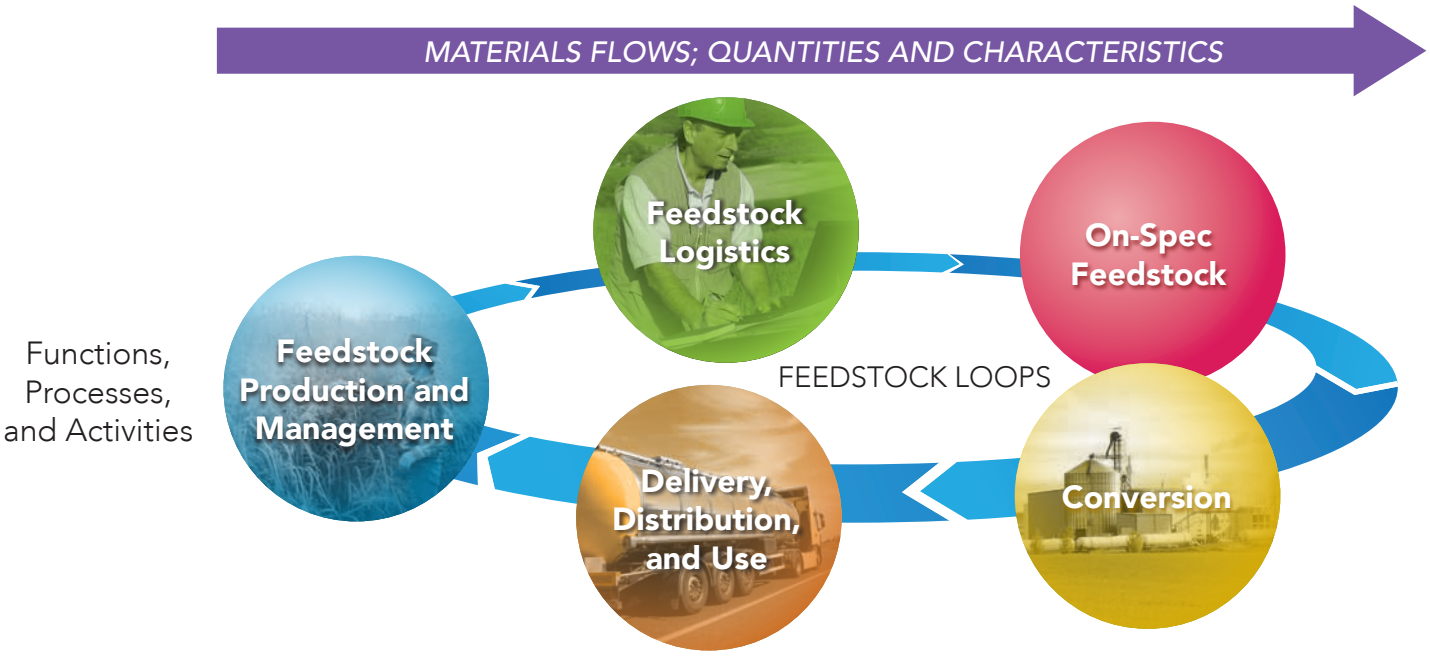

Figure 1. Overview of biofuels supply chain components.

Table 1. Examples of Parameters in the Supply Chain

Category of Areas of Impact	Example of Parameters along the Supply Chain
Quantity (inputs and outputs of materials and flows)	Feedstocks and process yield, recovery efficiency, product and co-product allocations, feedstock accessibility and availability rates, conversion process production rates, storage and queuing capacity, nameplate capacity, and material flow balance
Quality (characteristics of materials and flows along the chain)	Feedstock Interface: ash content, moisture content, composition, structure, density (mass and energy), maturity days, recalcitrance, hygroscopic (tendency to attract and hold water), formability, grindability, microbiological activity, particle size, and shrinkage Process Interface: intermediate purity; final fuel specifications
Performance of the Processes	Management of material loss, degradation recalcitrance responsiveness, depolymerization, efficiency, hygroscopicity, yield and output efficiency, process rates and capabilities, co-products, costs, and impacts
Design	Siting and location; supply area; type and blend of feedstocks; type and steps of conversion processes; intermediate and final products and co-products; balance of capacities along the chain; co-products and waste recovery systems; conversion and product pathways; conversion processes production rates; routing and delivery systems for products; transportation networks, modes, and availabilities; access to markets; and delivery points

The following are examples of integrated approaches for managing parameters.

Genetics

Altering plant genetics offers enormous promise in improving supply chain efficiency. Factors such as biomass yield, quality, and resistance to pests and disease could impact downstream operations and are current areas of research. Therefore, coordinating such research with downstream operations is not only critical, but it can even impact conversion performance (Zhou et al. 2011). Desirable feedstock characteristics, such as reduced recalcitrance, can affect the design of other aspects of the supply system, such as the use of enzymes in the conversion process. For example, increasing sugar content and decreasing anatomical ash in corn stover during plant growth would increase ethanol yield via enzymatic hydrolysis. Developing biomass species that can grow on marginal lands expands the land area available for biomass production and can reduce competition for land between plants for biofuel and crops grown for food and feed.

Mapping, understanding, and manipulating genomes have changed the way we design, deploy, and manage biofuel production systems. New approaches and tools for plant breeding and genetic modification are leading to faster, targeted development of plants with desired characteristics, such as enhanced drought tolerance, increased growing range, and cell walls that can be more easily and efficiently converted into biofuel components. Thus, science will enable living organisms to be manipulated and tailored in unprecedented ways, leading to a new bioeconomy (U.S. Department of Energy [DOE] 2012) and enabling integration of new biomass into supply systems.

Management

Capturing the potential of biomass resources for energy depends on successfully addressing major challenges, such as increasing the yield, reliability, and sustainability of feedstock supply; improving land and resource use efficiency; reducing feedstock production costs; and continuing to deliver needed levels of goods (including food supplies), services, and values—both now and into the future—while also maintaining air and water quality. These strategies and systems must meet the complex mix of objectives of land owners, producers, conversion facilities, rural communities, and the nation.

Sustainable management systems and practices integrate productivity, economic viability, and conservation of the natural resource base and its associated services. Developing sustainable, cost-effective, high-yield feedstock production practices for large-scale use of

dedicated energy crops; enhancing land productivity while meeting water quality and other environmental goals; and creating management practices that integrate energy feedstock production into conventional management systems are critical to an efficient supply chain.

Logistics

Although there are some niche feedstocks that can be relatively easily collected, transported, and used, biomass has numerous inherent logistical challenges as a feedstock for biofuels production. Generally, raw biomass is highly distributed, high in moisture, low in bulk density, low in energy density, and not compatible with high-capacity handling systems. This causes high transport and handling costs, but more importantly results in a poor-quality feedstock that promotes low conversion efficiency and low biofuel yield. Ample research is ongoing to address these challenges, including developing more efficient equipment for harvest and collection, drying, comminution, and densification. Depending on the point at which these operations take place, they could have a significant impact on the supply chain. Downstream transportation costs could be reduced by drying the biomass and increasing the dry matter bulk density, for example. Additionally, many thermochemical conversion processes show improved performance when fed a dry, dense feedstock. An example of a somewhat new technology that benefits many aspects of the supply chain is torrefaction, which increases both bulk and energy density and converts the raw biomass to a uniform, high-quality feedstock.

Storage systems are another component of logistics systems that offer an opportunity for supply chain integration. Biomass often has a high moisture content (i.e., above 20%) and low bulk density, both of which create challenges for long-term storage. Designing storage systems that reduce dry matter losses resulting from rotting reduces the amount of biomass needed for conversion; consequently, they result in a smaller draw area. Additionally, preventing quality losses that result from degradation during storage can prevent negative impacts on conversion. Coordination between supply chain components could reduce the need for longer-term storage, such as by using "just-in-time" delivery. Alternatively, long-term storage capacity allows more flexibility in supply chain and provides a supply buffer. The supply buffer could enable continuous plant operation for feedstocks that have limited harvest windows—such as corn stover—and also reduce the risk of supply chain upsets.

One concept for advancing logistics systems is developing the "uniform-format" supply system as an evolutionary progression from present-day conventional supply systems (Searcy and Hess 2010; Hess et al. 2009). The concept is to change raw biomass into a stable, flowable, dense, uniform-format feedstock that meets biorefinery specifications. In doing so, this can reduce transportation, storage, and handling costs, but more importantly, the value-added pretreatments in the logistics component reduce overall conversion costs. Finally, this concept can change design parameters in that the resource supply would not necessarily dictate location of the biorefinery.

Conversion

Many conversion technologies require the in-feed material (i.e., feedstock) to have very specific characteristics for optimal operation (see the examples Jones et al. 2013; Aden et al. 2010; and Dutta et al. 2011). In the biochemical conversion pathway, relevant feedstock parameters that impact conversion include ash content, moisture content, lignin structure, processable sugar content, and recalcitrance. Conversion of biomass into biofuels through fermentation or other metabolic pathways relies upon microbial metabolism of available sugars. Higher sugar content that can be easily released from feedstocks is advantageous for conversion. Additionally, certain biomass components, such as acetate present in hemicellulose, can be inhibitory to microbes during metabolic processes. Feedstock development, processing, and logistics can address some inherent biomass utilization difficulties; however, pretreatment methods can minimize the impacts of biomass that does not meet the in-feed specifications and optimize production.

For example, biomass can be deacetylated by treatment with dilute sodium hydroxide prior to enzymatic hydrolysis to remove the fermentation inhibitor (Humbird 2011), or microbes can be used to selectively remove or utilize fermentation inhibitors and minor sugars (Nichols et al. 2010; Hector et al. 2011). Through enhanced xylose utilization, more of the available biomass sugars can be used, which results in a higher conversion rate of feedstock to desired intermediates and end products. Other physical preprocessing activities, such as the crushing of oilseeds to extract a dense intermediate vegetable oil feedstock, are fundamental for efficient biomass conversion. Such preprocessing may be co-located with biorefinery facilities, or occur at separate nodes earlier in the supply chain.

Thermochemical conversion processes generally have different parameter requirements than biochemical conversion processes. Fast pyrolysis, for example, requires dry, ground biomass for optimal heat transfer. The very high heating and heat transfer rates at the biomass particle reaction interface in fast pyrolysis requires a finely ground biomass feed of typically less than 3 millimeters (mm) to overcome the low thermal conductivity typically seen in biomass (Bridgwater 2012). A variety of parameters impact the cost and efficiencies of logistics, as well as feedstock quality of this pathway, such as biomass dimensions and format, biomass moisture, ash and nitrogen content, transport distance (i.e., plant location), and biorefinery size/capacity. For example, because ash can foul the pyrolysis reactor, among other negative impacts, it should be removed prior to conversion.

Biorefinery Sizing and Siting

Decisions regarding the size and location of a biorefinery rely on a number of supply chain elements. The size of the biorefinery depends on feedstock availability (including seasonality) and cost, conversion technology, and capital available. For example, one may select a smaller plant size based on the availability of feedstock in the immediate area that can be procured affordably; however, that may result in a conversion facility size that does not take advantage of economies of scale, and that is below optimum size (Searcy and Flynn 2008; Jenkins 2007; Kumar et al. 2003; Larson and Marrison 1997; Nguyen and Prince 1996).

Smaller facilities may be constrained to truck transport, whereas larger facilities have additional supply and distribution options. As the biorefinery output increases, high-capacity transport modes such as pipeline, rail, and even barge may become viable options. These high-capacity transport modes have a lower cost per ton mile (i.e., lower variable cost); however, they either require significant investment in infrastructure, access to a water way (in the case of barge), or both. There would also be the additional loading/unloading/transloading cost incurred by switching from truck to the high-capacity mode. The distance after which it would be economically beneficial to transfer the biomass to a high-capacity transport mode would be a modeling exercise involving a variety of supply chain parameters. Examples of these parameters include biomass yield, which impacts transport distance; biomass bulk density, which impacts transport cost; cost of each transport mode, both fixed and variable cost; concern over roadway congestion; and availability of infrastructure.

Reliable analyses and cost projections of biofuels depends on assumptions about the supply system and biorefinery capacity. Further, the supply system and facility capacity depend on the economics, feedstock logistics, and feedstock sustainability. A previous report on biochemical refinery capacity noted that increasing the biorefinery size up to 10,000 tons per day achieved lower costs (Argo et al. 2013). Muth and others (In Press) report on thermochemical conversion and refinery sizing based on woody biomass supply systems. The overall result is that there are economies of scale when using an advanced logistics system (larger area) compared to conventional logistics. Having a greater supply of feedstocks (including by increasing transport distance) will decrease the risk of disruptions in biomass supply to the conversion facility.

A variety of factors impact the decision of where to locate a biorefinery, some of which relate to supply chain logistics and some do not. For example, state tax incentives may motivate biorefinery location. Other considerations include proximity to the feedstock resources, access to utilities (power, water), and proximity to transportation infrastructure (such as rail lines). Situating a refinery near a feedstock resource with parameters compatible with optimal conversion performance is an example of supply chain integration.

Modeling

Institutions have modeled different components of the supply chain. The data used in these models are of varying origin. For example, Oak Ridge National Laboratory (ORNL) modeled U.S. Department of Agriculture (USDA) data on crop availability, which DOE used in the U.S. Billion-Ton Study (DOE 2005) and U.S. Billion-Ton Update (DOE 2011). Idaho National Laboratory compiled a logistics database—called the Biomass Logistics Model—from various sources, including universities, other national laboratories, in-house research, and manufacturers. ORNL's Integrated Biomass Supply and Logistics[2] model provides time-dependent simulation of biomass feedstock supply operations. On the conversion end, the National Renewable Energy Laboratory and Pacific Northwest National Laboratory both analyze in-house data, as well as data collected from academia and industrial partnerships, in conversion models for such technologies

[2] http://www.biomass.ubc.ca/docs/Publications/2008-09-01%20IBSAL.pdf.

as fermentation, gasification, and pyrolysis. These national laboratories collaborate to design and model supply chain scenarios that can support DOE in meeting its biofuels production goals.

EPIC—the Environmental Policy Integrated Climate model—is a USDA Agricultural Research Service model used to generate crop and biomass yields and related impacts on soil organic carbon, soil erosion, and nutrient leaching and runoff for crop rotation, tillage system, and biomass harvest alternatives (Archer 2010). There are several other USDA economic and biophysical models[3] used to assess bioenergy production at various parts of and over the supply chains, such as the Regional Environment and Agriculture Programming Model, WholeFarm, Soil and Water Assessment Tool, FARMII, and others.

These are just some examples of models that address bioenergy supply chains. Certainly, there are many additional models with greater development of integrated models occurring. The complexity of the decisions for equipment, routes, materials, and resources will require development of computational optimization models (Shastri et al. 2011; Papapostolou et al. 2011). Mathematical programming models help to optimize the design of such integrated systems, but can also be used for daily management activities.

Representative Biofuel Production Pathways

The Biomass Research and Development (R&D) Board's Conversion interagency working group (IWG) selected three representative pathways to frame the integration/optimization discussion (see Figure 2). The selected pathways include three high-impact[4] feedstocks and three conversion routes to various products. This report discusses these three pathways in depth for purposes of illustration only. This report acknowledges that these pathways may be able to utilize alternative feedstocks, and other pathways—such as pyrolysis of herbaceous energy crops or biochemical conversion of algae—may be more optimal for a particular location.

The selected pathways are as follows (see Figure 2):

- **Pathway 1**: Agriculture residues with pretreatment hydrolysis to sugars, carbohydrates, and lignin with conversion to biofuels (hydrolysis and fermentation)
- **Pathway 2**: Woody crops with pyrolysis to sugars, carbohydrates, and oil intermediates with conversion to biofuels (pyrolysis)
- **Pathway 3**: Forest residues with gasification to syngas with biological and chemical conversion to biofuels and Fischer-Tropsch (FT) liquids (gasification).

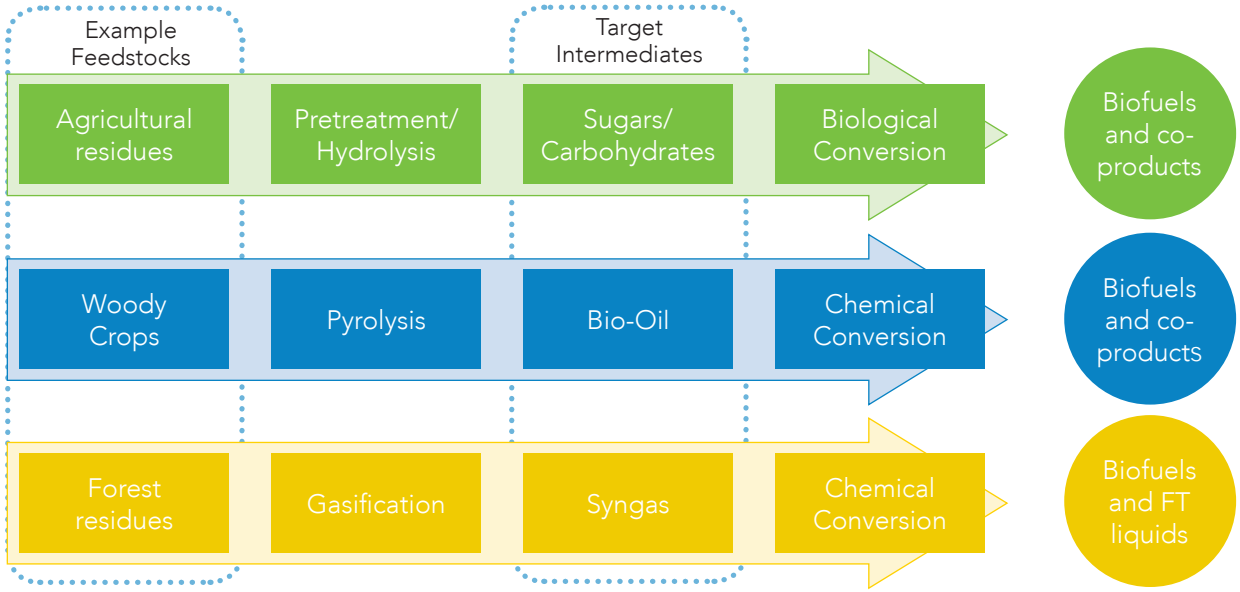

Figure 2. Three representative pathways selected for demonstrating integration opportunities throughout the biofuels supply chain.

[3] USDA Economic and Biophysical Simulations Models Useful for Assessing the Impact of Bioenergy Production: http://www.biomass.ubc.ca/docs/Publications/2008-09-01%20IBSAL.pdf.

[4] Used by DOE to mean a feedstock or multiple feedstocks compatible to a specific conversion technology that is domestically and sustainably potentially available at least 50 million dry tons annually.

The example pathways demonstrate some of the range of component options in biofuels production chains. There are a variety of potential biomass feedstocks, each with different parameter considerations and a variety of conversion technologies and resulting products.

EXAMPLE PATHWAY 1: Agriculture residues (corn stover) with hydrolysis pretreatment followed by fermentation of carbohydrates and conversion to biofuels and a lignin power co-product

This pathway has generated much interest due to the large quantities of agricultural residues potentially available from the grain industry. The U.S. Billion-Ton Update (DOE 2011) estimates that 272 million dry tons of corn stover will be available as biofuel feedstock by 2030. Due to the feedstock being a residue from a food/feed crop, there is no land competition involved. However, the amount of stover available annually is very dependent on corn market dynamics. Significant investments have been made in improving harvesting, densification, and transportation systems for agricultural residues—especially corn stover, which is the above-ground material that remains after the grain is removed, namely the stalk, leaves, and cobs (Hess et al. 2009). Issues associated with corn stover, including stover removal and its impact on long-term soil sustainability, have been addressed to some degree (Muth et al. 2012). Significant federal resources have been invested in developing cost-effective conversion technologies for agricultural residues, particularly enzymatic hydrolysis (for examples, see Aden et al. 2010; Kamireddy et al. 2013; Shekiro et al. 2012; and Tao et al. 2012). The model feedstock selected for this example pathway is corn stover (as well as other agricultural residues) due to the large amount of knowledge associated with conversion through enzymatic hydrolysis and subsequent steps.

The amount of agricultural residues (in this case, corn stover) that can be removed from the field depends on crop yield, as well as how much stover must be left on the field to maintain soil health. Therefore, biomass yield is a critical parameter that influences feedstock costs, harvest and collection costs, and transportation costs. Another critical consideration for biomass production is quality. One critical quality parameter for biochemical conversion is sugar content. Various parts of the stover have different sugar compositions, which are affected by the genetics of the corn plant and the environmental factors during production (Aden et al. 2002). Many factors can affect feedstock quality, including harvest time and equipment, storage practices, and preprocessing techniques. The resulting variation in feedstock quality can significantly affect cost through product yield, as well as pretreatment efficiency and conversion yield (Aden et al. 2002). Therefore, development of a system that minimizes differences in feedstock quality and composition will be critical future work within this pathway.

A variety of logistics system configurations are possible for agricultural residues. A typical system employs techniques and equipment developed for the agriculture industry, and generally involves harvest followed by field drying. The moisture-reduced biomass is then baled, collected, and brought to the roadside for storage until it is needed by the biorefinery. The bales are loaded onto a truck and then delivered to the biorefinery where additional preprocessing required for conversion (such as drying or size reduction) occurs. A variety of parameters impact the logistics cost and efficiencies of this pathway, including biomass yield, biomass format (i.e., bulk density, round bale versus square bales, etc.), biomass moisture content, transport distance (i.e., biorefinery location), and biorefinery size (i.e., process capacity).

The biochemical process selected for this pathway uses dilute-acid pretreatment, enzymatic saccharification, and co-fermentation to convert the feedstock into sugars prior to fermentation into alcohol (Humbird et al. 2011). The lignin byproduct, unconverted cellulose and hemicellulose, biogas from anaerobic digestion, and biomass sludge from wastewater treatment can be used to make heat, steam, and electricity. It would be more preferable to convert the lignin to higher-value biobased chemicals, such as aromatic chemicals, to subsidize the cost of fuel production.

In this case, the pretreatment uses dilute alkali followed by dilute acid. The alkali step releases acetyl groups that improve downstream metabolic conversion, while the acid step solubilizes the hemicellulose to release sugars. The solids that remain after pretreatment contain mostly cellulose and lignin. Enzymatic hydrolysis is used to depolymerize cellulose into oligomers and eventually monomers. Addition of accessory enzymes can be used to further deconstruct any remaining hemicellulose polymers that were not completely solubilized during pretreatment. The sugars derived from enzymatic hydrolysis are used

as feed for microbes that convert them to intermediates fuel molecules or final fuels. Optimization of these pretreatment and enzymatic processes can address the interface needs identified around feedstock quality and composition by being tailored for less-ideal or simply wider feedstock specifications. For example, pretreatment severity can be managed to reduce the amount of degradation products, such as furfurals, that are produced while allowing for maximum biomass deconstruction. Additionally, enzyme cocktails can be developed to hydrolyze a greater variety of hemicelluloses or to have better efficiency, resulting in greater sugar yields for downstream conversion. The solids that remain after pretreatment and hydrolysis contain mainly lignin, which can be used for steam, heat, and electricity.

Microbes are used to convert the sugars to alcohol, fuel intermediates, or hydrocarbon fuels. The example pathway produces an alcohol fuel, such as ethanol or butanol; however, other metabolic processes producing other fuels molecules would necessitate alteration of key interface parameters. Multiple pathways have been or are being developed for a range of different fuel precursor molecules, including—but not limited to—free fatty acids, terpenes, neutral lipids, and polyketides that can be upgraded to fuels by thermochemical or biochemical processes. Additionally, products from these pathways potentially can be blended into fuels for more desirable behavior over conventional biofuels, such as ethanol. These new target fuel molecules will help address the interface needs identified around specifications and distribution within the current fuel infrastructure. Current work emphasizes increasing yields and titers for these pathways for enhanced economic viability by engineering processes that utilize a greater range of sugars and other intermediates, such as lignin (currently used for power generation), as another source of carbon.

Trucks can transport biofuels and other products from the biorefinery. For small-scale biorefineries, this may always be the preferred method. As the biorefinery output increases, high-capacity transport modes such as pipeline, rail, and even barge may become viable options. These high-capacity transport modes have a lower cost per ton mile (i.e., lower variable cost); however, they either require significant investment in infrastructure, access to a water way (in the case of barge), or both. It is likely that biofuels would first be transported to a petroleum refinery or blending terminal where they would be blended with conventional fuels prior to being transported to the pumping stations.

Some factors that influence distribution and end use include stability and properties of the biofuel (flammable, hydrophilic), capacity of the biorefinery (does high-capacity transport make sense), distance to a petroleum refinery or blending/fuel terminal (where blending with conventional fuels will occur when permissible), storage requirements (capacity and duration), and compatibility of the biofuel with retail dispensing equipment and end-use vehicles and devices.

Example Supply Chain Integration Opportunities for Pathway 1:

- Generate plant varieties through genetic breeding and/or genetic engineering to maximize the sugar content of biomass, lower ash, and increase corn yields to improve conversion efficiency, thereby reducing conversion cost.
  - Abundance and availability of sugars can vary even within corn varieties. Corn varieties with higher sugar content and reduced recalcitrance to deconstruction methods would increase the overall efficiency and yield of biological conversion.
  - Anatomical ash content in stover is naturally quite high (generally from 5%–11%). High ash results in more unusable waste and can be detrimental to biological agents.
- Develop new harvest, collection, and storage techniques to preserve the quality of biomass before it leaves the field. Harvest and storage practices can have an effect on chemical compositions, potentially having an effect on product yield, as well as on pretreatment efficiency (Aden et al. 2002).
  - Developing techniques that do not entrain ash, such as conventional windrowing and bailing, could increase conversion yield and/or reduce costs associated with cleaning the feedstock.
  - Develop storage practices that minimize the impact on chemical composition and structure that could be caused by high moisture, contamination, or degradation. Due to the limited harvest window of agricultural residue systems, storage will be required for year-round biorefinery operation.

- Develop densification systems that do not impact convertibility and can be applied early in the supply chain to leverage reduced transportation cost, high-capacity transport, and handling infrastructure.
  - Bulk density can be increased by preprocessing biomass, reducing particle size (Mani et al. 2004).
  - Biomass pellets have a dry bulk density up to three to four times greater than that found in bailed biomass (9–12 pounds per cubic foot). Increasing density, combined with alternative concepts on storage, such as field depots, would benefit the stabilization of biomass for transport (see Hess et al. 2009 for more details).
- Develop robust conversion technologies with the ability to accept a broader range of feedstock physical characteristics and chemical composition.
  - Design advanced enzyme cocktails to generate the largest amount of readily fermentable sugars, which may allow for less severe pretreatment conditions and enable use of a greater variety of feedstocks (and components sugars).
  - Pretreatment processes involve the mechanical or chemical fractionation of the lignocellulosic complex in biomass feedstock into its components. Optimize pretreatment processes to efficiently convert biomass into usable carbon and limit the formation of degradation products that may inhibit fermentation.
  - Separation and recovery of desired products requires specificity and simple, cost-effective processes that can be applied for long durations at large product scales.
  - Continued organism development for effective, efficient sugar co-utilization during metabolic conversion will result in increased product yields.
  - Upgrading intermediate products to final fuels that meet the necessary specifications for blending and transportation requirements to enable product off-take and utilization.
- Develop systems that produce materials compatible with currently available distribution and end-use infrastructure.
  - Meeting fuel standards and certifications is critical in product integration and acceptance by consumers. Compatibility and ease of transition from petroleum-sourced incumbents are important considerations for hydrocarbon fuel products.
  - Market acceptability will occur with an end product that is amenable to current transportation, infrastructure, and consumer end-use needs.
  - Upgrade existing facilities by installing pretreatment process equipment to process biomass sugars.
  - Incorporate cellulosic ethanol processes into existing corn ethanol facilities, thereby increasing the range of feedstocks.
  - Co-locate cellulosic ethanol production facilities with existing plants to reduce costs.

EXAMPLE PATHWAY 2: Woody energy crops converted to hydrocarbon fuels via pyrolysis

The U.S. Billion-Ton Update estimates that by 2030 there will be between 67–126 million dry tons of biomass available from woody energy crops (DOE 2011). Potential advantages of woody energy crops include diverse habitat, enhanced conservation, and improved water quality (Blanco-Canqui 2010); however, they may incur a greater establishment cost with a lack of annual revenues. Woody crops, like other commodity crops, do compete for agricultural land. However, the economics usually dictate their establishment on the lower-quality land. In doing so, as a longer-rotation perennial crop, the environmental advantages do provide additional incentives for using the land for more intensive crop management systems.

Expected primary species for short-rotation woody crops (SRWC) are *Pinus*, *Salix*, and *Eucalyptus and Populus* hybrids. These woody crops are fast-growing and can be planted near a potential biorefinery. Trees must be grown over a several-year rotation, but this extended growth cycle also mitigates annual yield fluctuations due to drought, disease, and pest pressures, as well as other biotic or abiotic stresses. Unlike herbaceous crops that have a limited harvest window, a major advantage is that SRWC biomass is stored on the stump, and they can typically be harvested year-round. Year-round harvest reduces additional infrastructure and storage needs relative to annually harvested crops (Sims and Venturi 2004), allowing for better management of biomass supply relative to demand. In general, woody crops have high carbon content and are lower in anatomical ash than herbaceous feedstocks, making them compatible with ash-sensitive pyrolysis processes. For example, hybrid poplar has approximately 50% carbon and less than 1% ash on a dry weight basis (Phillips et al. 2007).

Harvest time for woody crops is flexible, enabling year-round supply and inventory that can be built up for expected inclement weather. Conversion processes may be sensitive to non-wood tree parts, such as leaves and bark.

Coppice regeneration systems from re-sprouting after harvest may also require dormant season harvests to ensure high yields.

There are two general types of SRWC harvest systems: (a) chip at the stump, or (b) chip at the roadside (Rummer and Mitchell 2012). The selection of an appropriate system depends primarily on stem size. Coppice systems generally have smaller stems and are more difficult to handle economically; therefore, these systems are better suited to the chip-at-the-stump approach. The development of a cost-effective harvesting system has been a barrier to the deployment of willow biomass crops (Volk et al. 2004), and research is ongoing to address this barrier. Due to the size of the shrubs, the most effective method at present is combining continuous cutting with chipping.

Single-stem systems, such as poplar, have much larger stems and use conventional harvest systems, including chipping at the roadside. These systems are usually comprised of feller bunchers, skidders to move the cut trees to the landing, and a chipper. Efforts are ongoing to optimize productivity through the interaction of bunch size, tree size, and accumulator capacity. There is also interest in using the coppice management approach for poplar with more dense plantings and shorter rotations. In that case, the harvest system would be similar to the willow system. A variety of parameters impact the logistics cost and efficiencies of this pathway, such as biomass yield and tree diameter, biomass format (single trees or coppice, bulk density), biomass moisture content, transport distance (i.e., biorefinery location), biorefinery size (i.e., process capacity), terrain conditions (slope, for example), and climate/season.

Pyrolysis produces a bio-oil that is subsequently upgraded and refined into hydrocarbon blends such as gasoline, diesel, and jet fuel. Biomass is heated to 375°C–525°C in the absence of oxygen to break down organic material into gases, liquids, and solids. The resulting bio-oil is highly acidic and unstable and requires upgrading before it can be used as a biofuel. Although there are a variety of reactor configurations for pyrolysis, residence time determines the resulting products: long residence times at low temperatures primarily produce char, whereas short residence times at high temperatures mostly produce gas products. Therefore, there are ongoing efforts focused on developing advanced fast pyrolysis processes to maximize high-quality liquid production. Some key feedstock parameters that impact pyrolysis conversion efficiency are moisture content, ash content, particle size, and carbon content. For example, as biomass moisture content to the pyrolysis reactor increases, the quality of the product liquid oil deteriorates, along with the overall performance of the whole system (Brammer and Bridgwater 2002). Pyrolysis requires dry, ground biomass for optimal heat transfer. At the biorefinery, wood chips are typically cleaned and screened prior to drying and additional size reduction. The very high heating and heat transfer rates at the biomass particle reaction interface in fast pyrolysis requires a finely ground biomass feed of typically less than 3 mm to overcome the low thermal conductivity typically seen in biomass (Bridgwater 2012). Additionally, the scale of the conversion reactor can affect conversion yield.

The same distribution and use considerations described above under Pathway 1 apply. As an additional consideration, raw bio-oil (i.e., coming directly out of the pyrolysis reactor) requires stabilization prior to transport using conventional liquid trucking equipment; otherwise, it must be transported as a hazardous material.

Example Supply Chain Integration Opportunities for Pathway 2:

- Improve planting materials for increased yield and pest/drought resistance.
  - Poplar species are a potentially ideal energy crop because they can be coppiced, established with cuttings, have a wide natural range, are inherently dense with low ash content, and can be easily genetically improved for higher yield and disease resistance (Berguson et al. 2012). Willow is also an ideal woody crop. It quickly achieves high yields, easily propagates, has a broad genetic base, has a short breeding cycle, and coppices after multiple harvests (Volk et al. 2004).
- Develop cost-effective management strategies, systems, and practices for SRWC systems.
  - Quantify relationships between management inputs and biofuel feedstock productivity in commercial-scale energy plantings and integrated feedstock production systems to develop deployment, production, and management options and practices that enhance nutrient- and water-use efficiency at the plant and/or site level.

- Develop new harvest and collection techniques to preserve the quality of biomass.
  - Current cut-and-chip techniques can entrain dirt, which is high in ash. Maintaining feedstock quality leaving the field can result in improved conversion performance.
- Develop models and other analytical tools that integrate productivity, economic, environmental, and social factors to predict the outcomes of production options and management practices.
  - Develop cost-of-production profiles under a representative variety of growing and production logistics conditions.
- Reduce moisture content early in the supply chain, thereby reducing transportation and handling costs downstream.
  - At harvest, SRWC has high moisture content (greater than 50%). Pyrolysis requires low moisture content (10%). Therefore, the biomass requires drying prior to conversion. While inherently energy-intensive and costly, drying the biomass earlier in the supply chain—at a depot, for example (see Hess et al. 2009 for more details)—would reduce transportation costs downstream.
- Select the site of the pyrolysis reactor.
  - Stabilized bio-oil is much higher in density (72–78 pounds per cubic foot without hydrotreating) than woodchips (20–25 dry pounds per cubic foot). Therefore, one option that is being explored is distributed pyrolysis units. An increase in efficiency may result from having numerous smaller-scale pyrolysis conversion units near the feedstock source, and then transporting the densified liquid. However, raw bio-oil (i.e., coming directly out of the pyrolysis reactor) requires stabilization prior to transport using conventional liquid trucking equipment; otherwise, it must be transported as a hazardous material. The scale of current upgrading and stabilizing equipment, however, is very large, so there would either be a huge excess in capacity, or new techniques/equipment would be required.
- Develop robust thermochemical conversion technologies with the ability to accept feedstock with varying physical characteristics and chemical compositions.
  - As biomass moisture content increases, the quality of the product liquid oil deteriorates, along with the overall performance of the whole system (Brammer and Bridgwater 2002).
- Develop strategies for conserving carbon and hydrogen in conversion and upgrading processes.
  - Carbon and hydrogen must be efficiently transferred from the feedstock to the finished biofuel to make biofuels cost competitive with petroleum-derived fuels.
- Reduce the cost of stabilization techniques to enable the transport of bio-oil as a non-hazardous material.
  - Bio-oil produced during pyrolysis is high in oxygen and very corrosive. If oxygen is not removed, the bio-oil is a hazardous material and additional, expensive precautions must be taken prior to transport. In addition, conventional refineries are unlikely to take an unstable product. Developing an efficient, effective means of removing the oxygen and stabilizing the bio-oil could reduce downstream transport, handling, and stabilization costs.
- Work with petroleum refiners to address the challenges of integrating bio-oils.
  - Instead of building biofuel processing facilities, it could be desirable to take advantage of preexisting petroleum refineries that are producing similar products. However, because bio-oils have much higher oxygen content than petroleum-derived crude oil, there are several barriers to integration. For a petroleum refinery to accept a bio-oil into its facility for co-processing with crude oil, it must be deoxygenated to an extent. The combined cost of preparing the bio-oil for refinery integration and then refining it in a petroleum refinery must be competitive with processing the bio-oil in an entirely separate facility.

EXAMPLE PATHWAY 3: Forest residues gasified to form syngas, which is then catalytically converted to biofuels and FT liquids

Forest residues are generally defined as the unmerchantable portion of the harvested tree remaining after the merchantable portion (i.e., the wood) has been removed—usually the treetop, branches, and small trees. Forest residues can also include trees removed for stand improvement, fuels reduction and fire resistance, and

pest management that cannot currently be marketed economically. High amounts of biomass left onsite can influence regeneration and subject the stand to fire and pest risks; however, some material must be left for soil health. Due to the feedstock being a residue from the production of timber, there is no land competition associated with forest residues. As noted, the removal and use of forest residues must be carefully managed to maintain long-term site productivity and ecological health.

There are significant potential volumes of forest residues available. The U.S. Billion-Ton Update projected that approximately 60 million dry tons will be available by 2030 for an estimated price of $60 per ton, including federal lands (DOE 2011). Forest residues are not typically recovered and utilized. Residues are of lower quality than debarked wood chips due to dirt (which is very high in ash) entrained during harvest, as well as the higher portion of non-wood parts of the tree (leaves, bark, and branches). The properties of forest residues vary depending on the species, types of tree components in the mixture, and any production or processing activities undergone.

Currently, residues have a low procurement cost, but are still relatively expensive to recover and transport. This is especially true if the residues are spread across the site instead of being collected at roadside like a conventional harvesting system. In current mechanized systems, residues are typically generated at roadside as part of commercial harvest operations. Most residues are processed with either a chipper or grinder at the forest site prior to transport. Some key parameters that impact the logistics of forest residues are location of the residues (landing versus distributed throughout forest), moisture content, density, tree type, transport distance (i.e., biorefinery location), biorefinery size (i.e., process capacity), terrain conditions (slope, for example), and climate/season. Residue harvest costs are usually charged against the merchantable wood, as the residues are the byproduct of the roundwood operation.

Flexible in-feed requirements for gasification make it ideal for forest residues. Gasification uses high temperatures (in the range of 750°C and above) to convert the biomass into gas, primarily carbon monoxide, methane, carbon dioxide, and hydrogen, in various proportions. The gas can subsequently be converted into a biofuel by removing contaminants and then passing the cleaned gas over a catalyst bed. The gas may also be burned in a turbine to produce power. Heat may be a secondary product.

Gasification is a thermochemical process in which solid or liquid carbonaceous material reacts with air, oxygen, and/or steam to produce syngas (Huber et al. 2006). The gaseous intermediate can then be converted to fuels and chemicals using catalysts or other biological processes. The conversion pathway includes technologies for improving yields from the conversion and the syngas cleanup and upgrading. Although biomass gasification is not new, new technologies are making this a more competitive option. Like the other pathways, gasification is sensitive to variations in feedstock characteristics (moisture content, fixed carbon and volatiles content, impurity concentrations, and ash content) and can benefit from pretreatment and blending of feedstocks to achieve consistent properties. Drying biomass improves heat transfer within the gasifier, and drier biomass helps control temperature (Swanson et al. 2010). Solids concentration, pH, and feedstock composition can affect the efficiency of low-temperature gaseous intermediate conversion processes. Improved feedstock quality contributes to yield increases and catalyst performance.

Gasification can use indirect heat from outside the gasifier, or direct heat generated by exothermic combustion and partial combustion inside the gasifier. The thermochemical process can be optimized to produce solid, liquid, or gaseous products depending on residence times.

There are three principles types: updraft, downdraft, and fluidized bed (Huber et al. 2006; Milne et al. 1998). The high-temperature process rapidly deconstructs the biomass. Low-temperature gaseous intermediate conversion processes include biological (e.g., landfill gas, anaerobic digestion) and catalytic deconstruction processes (DOE 2013).

Syngas from the gasifier contains contaminants that must be removed or reduced because they either clog or poison downstream processes (Swanson et al. 2010). Particulates are primarily removed by physical systems, such as cyclones or filters. Milne et al. (1998) reports on several ways of physically removing tars, including various scrubbing techniques. After cleaning, the syngas can go through methanol or hydrocarbon synthesis using the FT process or syngas fermentation. Fermentation technologies can work well with the relatively uniform intermediate from biomass gasification. Additional work is needed on improving these conversion technology interfaces (DOE 2013).

Examples of Supply Chain Integration Opportunities for Pathway 3:

- Develop options and practices that cost-effectively conserve or enhance soil, water, and habitat quality while providing adequate quantities of biofuel feedstocks.
  - Develop and test best management practices that integrate expanded biofuel feedstocks removal from conventional forestry systems.
  - Quantify costs and returns associated with integrating residual use for energy feedstocks into conventional forest management systems.
- Develop collection techniques to preserve the quality of biomass before it leaves the field.
  - When the limbs and tops of trees are removed near the stump, the residues are dragged to the landing, entraining significant dirt. Developing modified skidder heads to reduce dirt entrainment would reduce downstream cleaning costs, as well as increase conversion efficiency.
- Improve cleaning techniques for residues.
  - Techniques exist for removing bark and ash from chipped or ground residues. Current techniques are either slow (such as a trammel screen) or have other adverse effects (such as rinsing, which can increase moisture content).
- Reduce moisture content early in the supply chain, thereby reducing transportation and handling costs downstream.
  - At harvest, trees (including branches) have high moisture content (potentially greater than 50%). Gasification efficiency is higher with a lower-moisture feedstock (less than 20%). Residues may be field-dried prior to transport, which can be an effective way to reduce moisture content. However, this requires returning to the forest or landing, which may be impractical. Drying the biomass earlier in the supply chain—at a depot, for example (see Hess et al. 2009 for more details)—would reduce transportation costs downstream while performing an operation that would have to take place at the biorefinery regardless. Drying, however, is an inherently energy-intense and therefore expensive operation.
- Develop catalysts that are less sensitive to contaminants in the gas stream.
  - Although gasification can accept a range of feedstocks, the quality of gas generated is dependent on the feedstock quality (among other factors). Developing catalysts that are less sensitive to contaminants in the syngas stream could reduce the feedstock in-feed requirements, reducing logistics cost. Similarly, developing improved, cheaper syngas cleanup technologies would reduce system costs.

Conclusions and Recommendations

In the past, most bioenergy RDD&D focused on improving a single component of the supply chain as opposed to overall system efficiency. Recent efforts are focused on better understanding and managing the many parameters associated with an integrated supply chain to reduce biofuels cost. By reviewing current RDD&D efforts and identifying opportunities for supply chain integration, several conclusions can be drawn:

First, understanding the impacts that parameters have on the entire biofuels supply chain reveals opportunities for efficiency improvements. Many parameters have been identified that affect biofuels production chain efficiency and costs. Some of these parameters are the subject of current research; however, there is a need to conduct additional R&D in order to better understand the interaction of these variables throughout the production chain. Technology is changing how we control, manipulate, and manage the parameters across the supply chain to maximize outputs, reduce inputs, and lower costs. Some ways efficiency can be improved through parameter management include enhancing feedstock quality, reducing catalytic degradation and processing costs, improving the robustness of processes, maximizing transportation efficiency, and reducing system risk.

Second, although many of the supply chain components have well-established models and management tools, there is a lack of tools for analyzing and managing an integrated supply chain. System modeling is a common optimization tool, but there are opportunities to use a more structured mathematical framework for the design and tactical management of a whole supply chain. Continued use of models to better understand potential outcomes of supply chain component alternation for increased integration will be critical moving forward.

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