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Feedstock Supply System Design and Economics for Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels

Conversion Pathway: Fast Pyrolysis and Hydrotreating Bio-oil Pathway

"The 2017 Design Case"

January 2014

Idaho National Laboratory

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EXECUTIVE SUMMARY

The U.S. Department of Energy promotes the production of liquid fuels from lignocellulosic biomass feedstocks by funding fundamental and applied research that advances the state of technology in biomass sustainable supply, logistics, conversion, and overall system sustainability. As part of its involvement in this program, Idaho National Laboratory (INL) investigates the feedstock logistics economics and sustainability of these fuels. Between 2000 and 2012, INL quantified and the economics and sustainability of moving biomass from the field or stand to the throat of the conversion process using conventional equipment and processes. All previous work to 2012 was designed to improve the efficiency and decrease costs under conventional supply systems. The 2012 programmatic target was to demonstrate a biomass logistics cost of $55/dry Ton for woody biomass delivered to fast pyrolysis conversion facility. The goal was achieved by applying field and process demonstration unit-scale data from harvest, collection, storage, preprocessing, handling, and transportation operations into INL's biomass logistics model.

The 2013 SOT was developed to highlight the barriers that are imposed by using the 2012 SOT design case but moving from a high yield area to a less productive area and implementing active quality management into the system in order to meet the in-feed specifications of a thermochemical conversion facility. The 2017 projection is the target costs that can be achieved by additional R&D in areas of densification, comminution and feedstock formulations. The 2017 design case is able to supply enough biomass to meet the RFS goals while addressing quality and sustainability targets. (See Figure ES1)

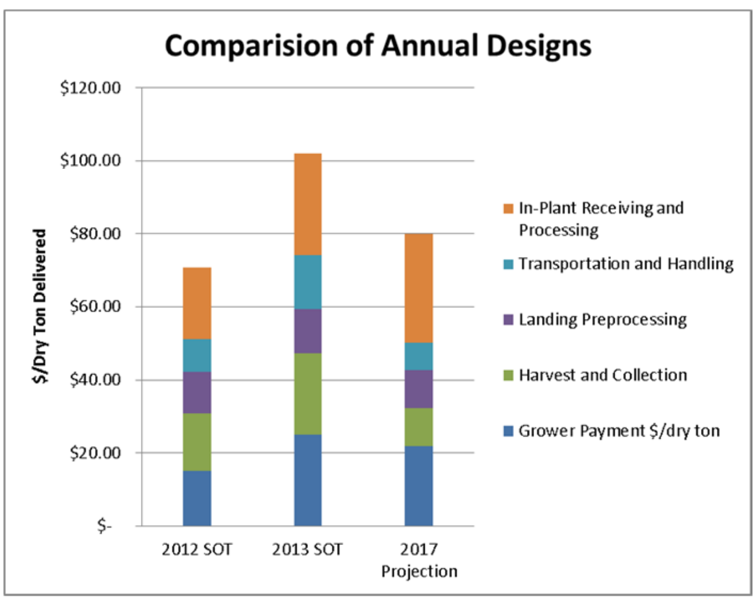

Figure ES1: This chart compares the annual feedstock logistic costs from 2012 and 2013 State of Technology (SOT) Reports and the 2017 projection. Note: 2012 SOT did not include active quality control systems or the new competition grower payment.

The 2012 SOT demonstrated that for a single biorefinery located in a high yield area with limited competition for their biomass supply that a biorefinery could reach a minimum feedstock logistics cost of $55/dry T (not including grower payment). The $56/dry T projected as 25% of the overall cost of producing biofuel at a competitive price with gasoline plus an additional $21/dry T to reduce ash to 1%. The 2012 Thermochemical SOT was instrumental in highlighting many of the barriers that would prevent the biofuel industry from reaching the aggressive Renewable Fuel Standard targets by 2022.

The goal of the 2017 Design Case is to enable expansion of biofuels production beyond highly productive resource areas by breaking the reliance of cost-competitive biofuel production on a single, low-cost, niche feedstock. To reach the volumes of the Renewable Fuels Standard, at least 350 billion tons of biomass will be needed. This volume cannot be reached using only biomass from niche, high yield areas. The 2017 programmatic target is to supply feedstock to the conversion facility that meets the in-feed conversion process quality specifications at a total feedstocks cost of $80/dry T, including both grower payment and logistics costs. The $80/dry T is the feedstock logistics contribution to the overall goal of delivering a finished biofuel for $3/. The 2012 $55/dry T programmatic target included only logistics costs (it did not include a grower payment) with a limited focus on biomass quantity and quality. The main focus was improving efficiencies of the numerous operations with in a conventional supply system.

The 2017 Design Case explores two approaches to addressing the logistics challenge of reducing cost, meeting quality specs, and decreasing ecological impacts: one is an agronomic solution based on blending and integrated landscape management, and the second is a logistics solution based on distributed biomass preprocessing depots. The two approaches are not mutually exclusive, in fact, without depots blending will have limited value. The concept behind blended feedstocks and integrated landscape management is to gain access to more regional feedstock at lower access fees (i.e., grower payment) and to reduce preprocessing costs by blending high quality feedstocks with marginal quality feedstocks. Blending has been used in the grain industry for a long time; however, the concept of blended feedstocks in the biofuels industry is a relatively new concept. The blended feedstock strategy is designed to purchase multiple feedstocks at and blend to the volumes required. By including multiple feedstocks, a lower grower payment is required for each feedstock thereby decreasing the overall feedstock grower payment. This report will introduce the concepts of blending and integrated landscape management and justify their importance in meeting the 2017 programmatic goals.

Table ES1 is a list of the 2012 State of Technology Assumptions and the changes as we move to the 2013 State of Technology and finally the 2017 Design Case.

Table ES1. Summary of assumptions underpinning progressive design implementations (INL 2017 Design Case).

	2012 SOT	2013 SOT	2017 Design Case
Feedstock(s)	Pulpwood, clean chips	Pulpwood, clean chips	Blended feedstock: pulpwood, wood residues, switchgrass, and select construction and demolition wastes (C &D)

Grower payment	Breakeven cost of Production	Increases based on marginal cost differential	Calculated and modeled according to specific location and resource blend/formulation
Moisture	Field dried to 40%	Field dried to 40%	Arrives: Pulpwood chips 30% wood residue chips 30%, switchgrass 20%, and C& D ground 20%; All dried to 9% pellets
Ash	Debark/Delimb	Debark/Delimb	Debark/delimb pulpwood Trommel screen residues Wash and sort C& D waste Blended ash content of <1% Debarked pulpwood <1%, screened wood residues 1.4%; washed and sorted C&D 1.0 %
Logistics	Uses existing systems	Uses existing systems	Pneumatics attached to hammermill High-moisture densification
Quality controls (passive)	Field drying to reduce moisture Ample available resource; quality spec manually selected	Field drying to meet moisture spec	Harvest/collection and storage best management practices for pulpwood and switchgrass More rigorous field drying of pulpwood and residues
Quality controls (active)	Waste heat dryer	Rotary drying	Multiple resource blending/formulation High-moisture densification Fractional Milling High-efficiency pellet drying Washing
Meets quality target	Yes	Yes	Yes
Meets cost target	Yes	**No**	Yes
Accesses dispersed resources	No	**No**	Yes

The biomass feedstock supply system is a combination of multiple operations that include harvest and collection, storage, preprocessing, and transportation. Each operation within the supply system incurs a cost while influencing the biomass quality. This report summarizes the improvements that are being targeted, based on the research objectives in the following five research areas: (1) blending, (2) harvest and collection, (3) storage, (4) preprocessing, and (5) transportation. Feedstock logistics research aims to reduce delivered feedstock cost, improve or preserve feedstock quality, and expand access to biomass resources. Strategies to improve logistics operations include (1) organizing logistics in innovative ways, (2) improving efficiency of existing operations, and (3) implementing new technologies to address quality issues. The result is an advanced biomass supply system that meets the $80/dry T delivered cost target. For the advanced supply system to work research and development is needed in areas such as fractional milling, high moisture densification, low cost high density drying systems, blending and formulation and characterization and utilization of municipal solid waste as a feedstock. Each of these technologies is discussed in detail in the following report.

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2017 Design Case

The U.S. Department of Energy (DOE) aims to make cellulosic biofuels competitive with petroleum-based fuels at a modeled cost of mature bio oil technology of $3/gallon gasoline equivalent (gge) ($2011) by the year 2017. The DOE Bioenergy Technologies Office (BETO) Terrestrial Feedstock Technology Area will support this goal by demonstrating a modeled delivered feedstock cost of $80/dry T (dry U.S. short ton) by the year 2017. The purpose of this report is to document a feasible feedstock supply system for the fast pyrolysis conversion pathway design capable of achieving this 2017 target. This design is referred to in this report as the "2017 Design Case."

Idaho National Laboratory (INL) has a long history of supporting BETO with techno-economic assessments and technology improvements in the area of feedstock logistics. INL was instrumental in BETO's demonstration of the cost target for bio-oil via fast pyrolysis through achievement of the 2012 $55/dry T feedstock logistics, not including grower payment (Searcy et al. 2012). The focus of feedstock logistics for the fast pyrolysis pathway was a demonstration of commercially available equipment and practices currently used in the pulp and paper industry to support pioneer (1st generation, small capacity) biofuel production plants.

The success of the thermochemical conversion pathway via fast pyrolysis from a feedstock perspective was that it demonstrated that through proper equipment selection and best management practices, conventional supply systems (referred to in this report as "conventional designs," or specifically the 2012 Conventional Design) can be successfully implemented to address dry matter loss, quality issues, and enable feedstock cost reductions that help to reduce feedstock risk and enable industry to commercialize biomass feedstock supply chains. The caveat of this success is that conventional designs depend on high density, low-cost biomass. In this respect, the success of conventional designs is tied to specific, highly productive regions such as the southeastern U.S. which has traditionally supported numerous pulp and paper industries.

The goal of the 2017 Design Case is to increase availability of affordable biomass beyond only highly productive resource areas. The 2017 programmatic target is to supply to the conversion facility with a feedstock that meets the conversion in-feed specifications at a total feedstocks cost of $80/dry T. This design document describes a feedstock logistics design capable of achieving this goal. This document begins with a discussion of the limitations of the conventional supply systems when applied outside of highly productive resource areas. Next, the discussion shows how these limitations can be resolved through integration of multiple types of feedstocks, clear definition of biomass quality specifications, and technology advancement in logistics and preprocessing.

The $80/dry T target encompasses a total delivered feedstock cost, including both grower payment and logistics, and meeting all conversion in-feed quantity and quality targets. The $55/dry T target for 2012 included only logistics costs. An estimated grower payment associated with the 2012 Conventional Design was $15.20/dry T based on the break-even cost of production (Langholtz, 2013). Adding grower payment and logistics, the total delivered feedstock cost was $70.20/dry T in 2007 dollars. Translated to 2011 dollars, the total delivered feedstock cost of the 2012 Conventional Design scales to about $80/dry T. This demonstrates that for a conventional supply system it is possible to deliver feedstock to a thermochemical conversion pathway via fast pyrolysis for $80/dry T, but only for a set of tightly coupled set of designs that require high quality, low moisture harvested material. First, the 2012 Conventional Design assumed field drying the material to 30% moisture content. Next, it was assumed that waste heat from the conversion facility would be available for further drying requirements. And finally, the design assumed that biomass was available in high yield regions, minimizing transportation distances. Each of these assumptions limits the size and location of conversion facilities. Achieving the goals of the 2017 Design Case will require innovative solutions and significant technological advancements as pivotal assumptions within the 2012 Conventional Design are removed.

This report is intended to couple with the fast pyrolysis and hydrotreating bio oil pathway design report, "Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway" (Jones et al., 2013) that describes a viable route from biomass to hydrocarbon fuels. The assumptions of scale and feedstock quality requirements are consistent with the design case assumptions used in the fast pyrolysis and hydrotreating design report and techno-economic assessments. This design does not consider the different requirements and nuances of other thermochemical conversion processes or other hydrocarbon pathways. Feedstock design reports associated with alternate hydrocarbon pathways of BETO will be published subsequent to this report.

1.1 Limitations of Conventional Supply System Designs

Conventional designs are the backbone of an emerging biofuels industry. In fact, we can expect to see conventional designs successfully implemented by pioneer (1^{st} of a kind, small capacity) biorefineries in the operation now. However, conventional supply systems have limitations (Hess et al. 2009; Searcy and Hess 2010) that prohibit them from being broadly implemented to access the diverse set of resources needed to support a national biorefining capability. These limitations, including biomass availability and feedstock quality, are discussed in this section.

Biomass availability. The viability of the 2012 Conventional Design is rooted in areas that have a concentrated supply of easily accessible, and low-cost biomass resources (i.e., termed highly productive resource areas in this 2017 Design Case). Moving outside of these select regions, the feedstock supply system must be adapted to accommodate a different supply-demand dynamic brought about by changing cost, quality, and conversion facility size constraints. When located outside highly productive areas, biorefineries that rely on conventional designs are likely to be small due to the high cost of transportation of low density biomass, limiting their ability to achieve economies of scale, because feedstock costs and risks are likely to be prohibitive (Graham et al. 2013).

Feedstock quality. Biomass is highly variable in quality (e.g., ash, moisture, and particle size). Conventional systems can only address feedstock quality indirectly through passive controls such as resource selection or best management practices, such as harvest technique. When positioned in a highly productive area, biorefineries can be selective in contracting only those feedstocks that meet their specifications. Best management practices also can be used to reduce issues of moisture and ash, but they will not eliminate them. Additional work needs to be done both on the conversion side as well as the feedstock side to identify additional quality specifications and aligning them with the various feedstocks. The new quality specifications could include breaking down total ash by species (e.g. potassium and other alkali), cellulose, hemicellulose, lignin, and other extractives. Each conversion pathway will have a select set of quality specifications that may very well dictate regions of the country that are better aligned to supply feedstocks.

Two requirements that distinguish the 2017 Design Case from the 2012 Conventional Design are first expansion beyond highly productive resource areas and second adherence to feedstock specifications. These requirements are discussed in detail in the following subsections.

1.1.1 Expansion beyond Highly Productive Regions

Expansion beyond highly productive resource areas has significant implications to the feedstock supply chain. Sparse areas, whether due to reduced yields and/or higher dispersion, typically increase feedstock logistics costs. Higher harvest and collection costs are incurred due to the need to spread machinery ownership costs over fewer tons of biomass or the need to cover more acres for the same quantity of biomass. Additionally, lower resource yields increase the supply radius and biomass transportation distances. Under the 2012 Conventional Design, higher yield areas allow refinery to be selective on the resource that they access.

Consider, for example, the scenarios depicted in Figure 1. This resource map illustrates a county-level resource assessment of pulpwood farm gate at $60/dry T prices (this includes grower payment, harvest, collection, and chipping costs). Farm gate price data were extracted from *The Billion Ton Update* (BT2) (U.S. DOE 2011) data supplied from Oak Ridge National Laboratory. It should be noted that while the data is reported at a county-level, the data should be applied at the wood shed (typically much larger area than a county) level because it was derived from the U.S. Forest Service Forest Inventory and Assessment Data (FIA) [US FS 2013] and does not equate to county levels accurately. The FIA is a woodshed level assessment and therefore to use the data correctly it is necessary to combine multiple counties.

The cost competitiveness of the 2012 Conventional Design was demonstrated by Searcy et al. (2010) in the scenario located in southern Alabama, a high biomass yielding area. We further suggest, based on the consistency of farm gate (i.e., landing) prices shown in this map, that the 2012 Conventional Design can be deployed cost effectively in South Carolina. Commercial readiness of conventional supply systems ultimately will be demonstrated by commercial-scale cellulosic ethanol plants opening in these areas in the near future.

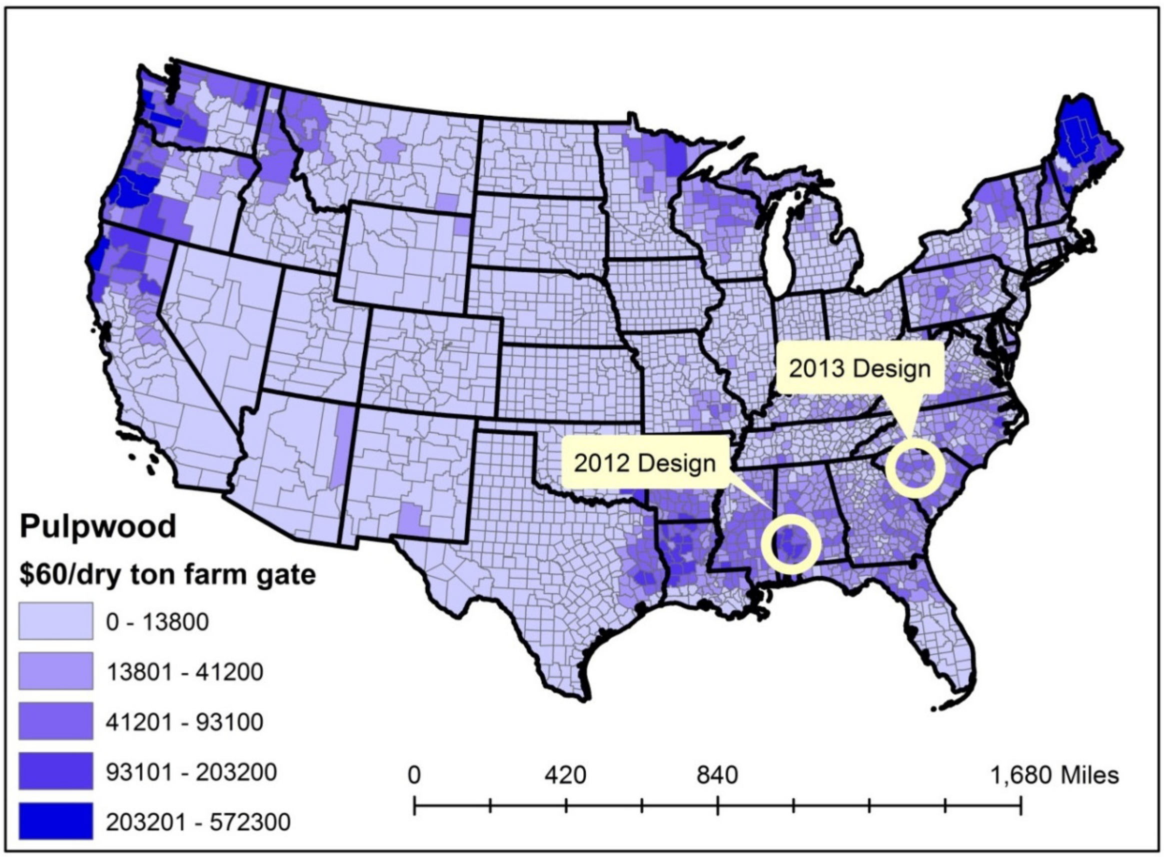


Figure 1. Total tons per county of available pulpwood at $60/dry T farm gate price. Yellow circles show areas represented in the 2012 Conventional Design and the Relocated (2013) Design Case (U.S. DOE 2011).

The map depicts a fairly steep gradient where resource available at $60/dry T rapidly decreases away from the southern area that traditionally supported a thriving pulp and paper industry. Significant county-to-county fluctuations in farm gate price are seen as well. In these areas, as in the scenario depicted in western South Carolina, sufficient pulpwood exists to support an 800,000 ton per year biorefinery; however resource selectivity to passively mitigate quality will be constrained due to the limited amount of biomass (i.e., selecting only the higher quality material and leaving the low quality material behind). In this scenario, a more dispersed pulpwood resource, due to lower yields in these regions, also results in increased harvest, collection, and transportation costs compared to the lower-cost scenario.

1.1.2 Feedstock Quality Specifications

Techno-economic models often involve process simulations wherein mass and energy balances are converged across a number of unit operations to assess the entire system as a whole. Feedstock compositions and heating values are required inputs to these balances. The fast pyrolysis and hydrotreating feedstock modeled in the design report is shown in Table 1. These assumptions were based on the composition of low ash, woody biomass delivered at 30wt% moisture (Jones et al. 2013). Currently within the feedstock logistic system the only quality specifications that are actively being managed are ash, particle size and moisture. Other components may be included in future revisions as they are identified. A combination of passive methods, biomass selection (i.e., clean pulpwood chips), and applying utilization of best management practices that preserve material, and harvest practices that minimize introduced ash (soil) comprised the solutions that were implemented in the 2012 Conventional Design for adherence to feedstock quality assumptions. However, quality “specifications” were not actively enforced in the 2012 Conventional Design. In other words, the specifications were acknowledged and attempts were made to match up the biomass with the specifications, but no active management was installed to enforce expectations.

Table 1. Delivered woody feedstock composition and processing assumptions for the fast pyrolysis and hydrotreating design report (Jones et al. 2013).

Component	Composition (dry wt. %)
Carbon	50.94
Hydrogen	6.04
Nitrogen	0.17
Sulfur	0.03
Oxygen	41.90
Ash	0.90-1.0
Heating Value (Btu/lb)	8,601 HHV
	7,996 LHV
Moisture (Bulk Wt. %)	10.0
Particle Size (inch)	1/4

These same pulpwood composition assumptions have been carried through to the current thermochemical conversion pathway design report to which this 2017 Design Case is associated. However, this 2017 Design Case introduces the expectation that the feedstock supply chain will be held accountable to these feedstock assumptions, hereby elevating these assumptions to feedstock specifications that currently define the feedstock quality associated with the fast pyrolysis and hydrotreating conversion pathway.

The passive approaches (i.e., biomass selection and best management practices) implemented in the 2012 Conventional Design Case are not sufficient to guarantee feedstock specifications. Further, passive approaches to feedstock quality assurance restrict feedstock availability and producer participation, and ultimately increase risk to biorefineries by making them dependent on limited specific feedstocks. There may be years where due to rainy weather that the biomass does not undergo any field drying, thereby increasing biomass moisture which increases dry matter loss, transportation costs, grinding costs and drying costs.

The solution to be implemented in the 2017 Design Case still includes biomass selection and best management practices; however, this design also introduces active quality controls into the feedstock supply chain. This approach enables access to the vast and diverse biomass resources available to support a national biofuels production capacity, while assuring strict adherence to biorefinery quality specifications.

A significant challenge for implementing active quality controls adding cost to an already cost-constrained system. Therefore, the insertion of active controls into the 2017 Design Case must balance the cost/benefit of mitigation in the feedstock supply chain and the cost of further biorefinery processing of off-spec feedstock. In commercial practice, this normalization function is implemented through a dockage fee.

Dockage is the penalty a feedstock supplier pays the biorefinery for delivery of off-spec feedstock. The dockage fee is established based on the additional cost the biorefinery incurs to process off-spec feedstock; the dockage fee is subtracted from the feedstock payment. If the pre-delivery cost of mitigation by the feedstock supplier exceeds the dockage fee, the dockage fee is the lowest cost option; otherwise, the feedstock supplier must implement corrective strategies to avoid the dockage penalty and remain economically competitive. For example, if ash removal is required to meet the biorefinery feedstock quality specification and mitigation within the feedstock supply chain costs the supplier $15/ton, but the biorefinery is able to mitigate the ash for $10/ton, the feedstock supplier may choose to accept the $10/ton dockage fee rather than implement ash reduction, for a net $5/ton savings. For further discussion on dockage see Appendix B.

Implementation of a dockage-based quality assurance approach, much like in the grain industry, requires accurate assessment of the cost/specification relationship(s), the practicality and cost effectiveness of the mitigation approach, and the availability of rapid and accurate analytical methods for measurement of the specifications at the point of sale. The following list describes an initial approach to establishing dockage for moisture and ash content.

- ***Moisture Specification.*** From a thermochemical processing perspective, feedstock moisture content has a strong influence on the pyrolysis process economics. High quality heat in the reactor will be required to evaporate the extra moisture which can be a significant penalty on the process depending on how it is configured (Carpenter et al., 2013).The reality is that the moisture has a high impact on both the feedstock supply system as well as the thermochemical conversion process. In addition to its implications on storage stability, biomass moisture content can significantly affect transportation, preprocessing, and feedstock handling (Kenney et al. 2013). These logistics-related costs are discussed in Section 2. Since the logistics supply system is designed to meet the moisture target there will not be a dockage assessed by the refinery for excessive feedstock moisture content.
- ***Ash Specification(s).*** Feedstock ash content has a big impact on liquid yields from fast pyrolysis. Ash in this context is a combination of inorganic material that has 2 parts – 1) the mineral matter taken up from the soil and retained as part of plant or tree; aka physiological ash and 2) inorganic material that got collected with the biomass during harvesting/collection – soil matter, dirt, etc. Both parts are not converted during pyrolysis and represent solid input that goes through the process and requires disposal. This extra inert mass causes a decrease in conversion efficiency and creates a waste stream that needs additional removal costs. Current predicted disposal costs are $18/T (Phillips 2007). The goal of the feedstock supply system at this time is to minimize the inorganic material collected during harvest/collection and not address the physiological ash in the plants therefore woody biomass is the preferred feedstock. The real question is can the feedstock with higher ash be purchased for a low

enough price to compensate for the losses in fast pyrolysis liquid yield or an added cleanup process to bring it in on spec or is the more expensive, cleaner material more cost effective. INL, in collaboration with NREL and PNNL, are researching the benefits/costs of both methods. Table 2 illustrates the effect of ash content on fast pyrolysis liquid yield. Additionally, feedstock ash content represents an additional variable operational cost to the biorefinery because it reduces pretreatment efficacy, increases wear in handling and feeding systems, and accumulates as a waste stream that requires disposal, increases water treatment costs (Raveendran et al. 1995). While ash entrained in the liquid could impact downstream catalysis, it is unknown at this time if the ash is soluble or attached to the char. There is a filtration step prior to condensed-phase upgrading then may help reduce the impacts. If the ash is soluble, it may impact the catalyst life.

We also don't know the efficiency of upgrading high-ash feedstock pyrolysis oils. Preliminary efforts indicate that oil produced from high-ash feedstocks actually performs better during hydrotreating. This would indicate that the loss of efficiency during pyrolysis is balanced by improved efficiency during hydrotreating. This might actually be an improved scenario because lost efficiency during hydrotreating is typically related to small molecular weight acids that consume hydrogen before being lost to the fuel gas. (Conversation with C. Drennen, PNNL)

Table 2. Potential Effect of Higher Biomass Ash Content. (Jones et al. 2013)

Cost and Consumption	Base Case with 0.9%wt Ash	Base Case with 1.9%wt Ash
Fuel yield, gal/dry T biomass	84	75
Natural gas usage, scf/gal	19.3	5.9
H_2 Demand, MMscfd	44.5	40
TCI, million $	700	672
MESP, $/gge	3.39	3.55

Note: TCI (Total Cost Indicator)

Forest thinnings, logging residues, and construction and demolition (C&D) wastes are low cost resources to procure, but also have unfavorable quality specifications, specifically ash content. It should be noted that the ash type and quantity may have an effect on the yield of fast pyrolysis oil as certain ash constituents can cause an increase in the gas production at the expense of condensable liquids; however more research is needed to understand the impacts of ash on conversion.

Because these biomass resources are low cost, supply chains that include active ash management preprocessing unit operations can be purchased. Prior to preprocessing, certain resources can be blended to reduce the overall percentage of ash and moisture, thereby reducing the costs and severity needed to reduce the ash to in-feed specifications. Table 3 shows an example formulation.

Table 3. Costs and specifications for woody feedstocks and blends (INL analysis).

Feedstock	Reactor Throat Feedstock Cost ($/dry T)[2]	Formulation Fraction (%)	% Ash Delivered to Throat of Conversion Reactor
Pulp	99.49	45	0.5
Logging Residues[1]	67.51	32	1.5
Switchgrass	66.68	3	4.0
C&D Wastes	58.12	20	1.0
Formulation Totals	**80.00**	**100**	**<1**

[1] residues do not include costs for harvest and collection; they are moved to landing while attached to the merchantable portion of the tree (for example, timber or pulpwood)

[2] includes ash mitigation

The C&D wastes are incorporated because of its low access fee cost and its low ash content. C&D wastes were limited in quantity due to the uncertainty of available supplies. Current research shows significant quantities of C&D but there are uncertainties with EPA qualifying C&D waste for credit for RIN's and competition from other markets. This is only an example; the actual blends will be regionally based designs that take advantage of local feedstocks and their biomass characteristics. Additionally the ability to blend feedstocks to a specification has the potential to reduce some of the risks associated with the seasonality of feedstocks.

While many factors contribute to the performance of a feedstock in a thermochemical conversion process, a large source of quantity and quality loss in the biomass supply chain is degradation during storage. Biodegradation in the most severely impacted areas of the storage pile (outer regions of chip storage piles and agricultural residue bales) results in structural sugar loss (pentosans to a greater extent than hexosans) and greater oxygen and water content of the bio-oils (Agbelvor et. al. 1994, Agblevor et. al., 1995, Casal et. al. 2010). To this extent, the moisture quality control discussed above will have a large role in minimizing dry matter loss and preserving material quality. The potential impacts and sources of this measure are discussed in Section 3.2

1.1.3 Expanding the 2012 Conventional Design

With the 2012 Conventional Design Case located in a highly productive pulpwood production area, the main constraint of the design was that the biorefinery could be selective in contracting pulpwood that was <1% ash content (Table 2). In the 2013 SOT, the assumption that the biorefinery can be selective is unlikely since there will most likely not be enough resource available to maintain the volumes required.

The feedstock supply chain unit operations modeled in the baseline case are shown in Figure 3. These unit operations are identical to those in the 2012 Conventional Design (Searcy et al. 2012), with the exception of the removal of the waste heat drying. The details of these unit operations are discussed in the design basis sections of this report.

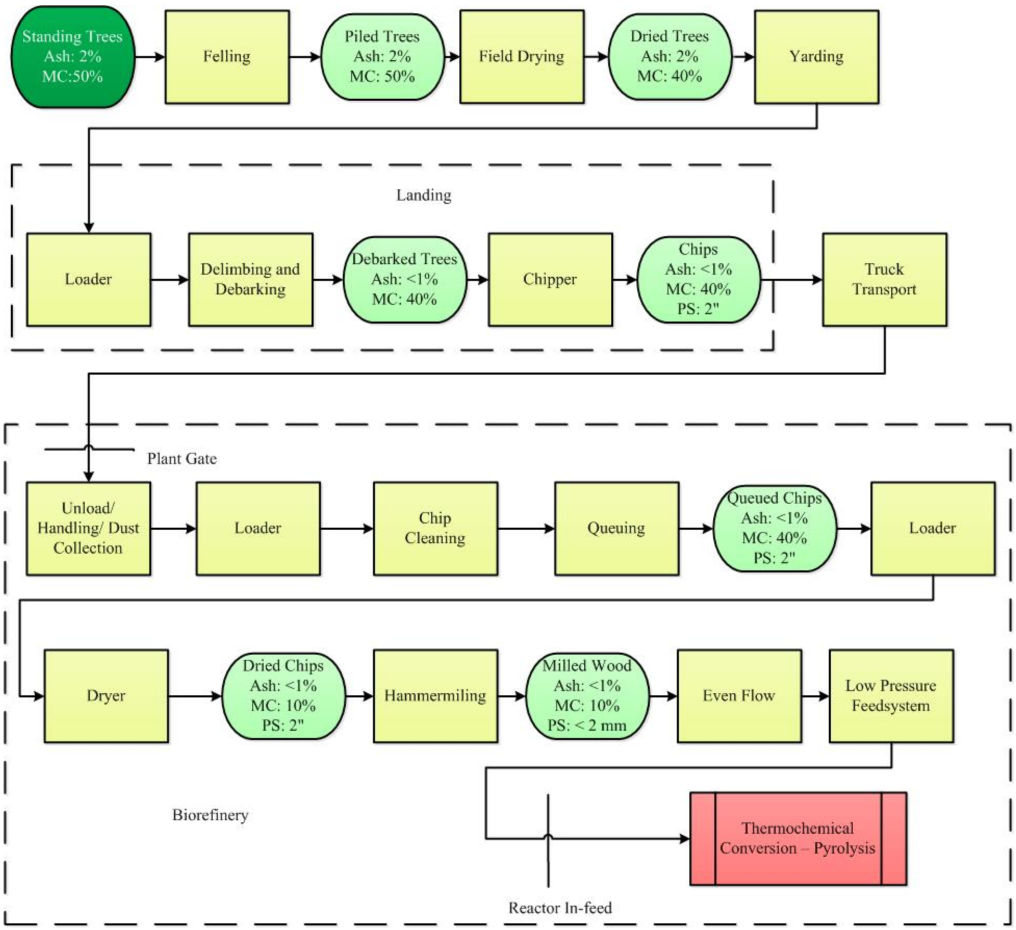


Figure 2. Flow diagram of the 2012 Relocated (Baseline) Design Case to supply thermochemical conversion refineries (Searcy et al. 2012).

The cost estimate of the baseline system (Table 4) shows a logistics costs total of $77.90/dry T, compared to $55/dry T for 2012 Conventional Design. Increased costs of the baseline system are attributed to the following:

- Cost escalation from 2007$ to 2011$ cost year[a]
- Lower resource yields (90% to 67%), which increases harvest, collection and transportation costs
- Switch from waste heat dryer to natural gas dryer due to the separation of the depot from the conversion facility which eliminates the ability to make use of waste heat.
- Increased grower payment from the $15.70/dry T to $25.00/dry T based on the BT2 data (U.S. DOE, 2011)
-

Escalation was determined from the difference in the Chemical Engineering Plant Cost Index and Producer Price Index from 2007 to 2011. The Chemical Engineering Index is published in each issue of Chemical Engineering (www.che.com/pci). The Producer Price Index includes commercial and industrial machinery and equipment repair and maintenance costs (www.bls.gov/ppi/ppinaics811310.htm).

- Table 4. 2013 SOT cost estimate (all costs are in 2011 USD).

Cost Element	Cost by Operation ($/dry T)	Cumulative Cost ($/dry T)	Report Section
Grower Payment	25.00	25.00	Section 2.1
Harvest and collection	22.20	47.20	Section 3.1
Landing Preprocessing			Section 3.1
Debark/Delimb	6.10	53.30	
Size Reduction	6.10	59.40	
Storage	3.80	63.20	Section 3.2
Preprocessing			
Size Reduction	5.40	68.60	Section 3.3
Drying	17.20	85.80	Section 3.4
Dust collection and miscellaneous equipment	0.80	86.60	
Handling	1.50	88.10	Section 3.4
Transportation	14.80	102.90	Section 3.4
Ash Dockage	0.00	0.00	Section 3.1
Total Delivered Feedstock Cost		**102.90**	
Delivered Feedstock Specifications			
Ash Content	<1%		Section 1.2.1
Moisture Content	9%		Section 1.1.2

1.2 Approach of the 2017 Design Case

The 2012 Conventional Design presented above illustrates the limitations of the conventional biomass supply system that will limit expansion of a national biorefining industry. This report will address three specific challenges for reducing the current estimated feedstock costs to achieve the $80/dry T cost target. These challenges include price of biomass resources (grower payment), feedstock quality, and the ability of the logistics system to handle increased volumes at reduced costs. First, grower payment (access costs) must be reduced. This does not suggest that the payment producers receive for biomass will decrease; rather it will be shown that the grower payments can be reduced by selecting multiple resources thereby decreasing the amount of any single resource and moving down supply curve and reducing the cost for access. Second, the current conventional biomass supply system has no mechanisms for preserving or addressing feedstock quality. Biorefinery conversion efficiency is tightly coupled to the quality of the feedstock (Jones, 2013). There are operations that can be included in the feedstock logistic supply system that can address these quality issues and deliver a feedstock that meets the in-feed quality specifications. Third, technological improvements in all supply chain unit operations must occur to reduce logistics costs and handle larger more dispersed volumes of biomass material. This section discusses the general approach of the 2017 Design Case for addressing these challenges.

1.2.1 Addressing the Grower Payment Challenge

The Billion Ton Update (BT2) (U.S. DOE 2011), which is the definitive source of national biomass supply/cost data, represents biomass access costs in terms of "farm gate" price, which includes the cost of production, harvest, collection and chipping at the landing, compensation for soil nutrient removal, and grower profit. The farm gate price includes harvest, collection, and chipping. However, feedstock logistics designs also consider harvest, collection, and chipping operations within logistics costs, therefore it is necessary to subtract harvest, collection, and landing preprocessing costs from the reported farm gate price and refer to difference as the grower payment. The grower payment would then consist of feedstock production, soil nutrient replacement, and profit margin.

Neither grower payment nor farm gate prices are constant; rather they are functions of the marginal cost of procuring the next additional quantity of biomass. BT2 scenarios provide projected farm gate prices for each county in the United States for all available feedstocks for the years 2012 through 2030. If you examine the BT2 scenario it will show that very little biomass shows up as accessible until farm gate prices reach $40/dry T. This means that farmers are not willing to allow access to their biomass until they are offered at least $40/dry T farmgate price.

Figure 4 below shows the step-wise supply curve for marginal and average feedstock costs versus supply quantities accessible from the BT2 scenario. These cost curves are used to determine the quantity of biomass that can be accessed at the different farmgate prices. The BT2 data is generated in increments of $10/T cost targets, hence the step functions. It is important to note the difference in marginal versus average costs. The width of the boxes displays the increased amount in total tons that shows up for each type of biomass as the price increases. Looking at Figure 4, at $50/dry T around 40 million dry T of woody residues could be procured and a small amount of dedicated feedstocks. At $60/dry T, an additional 160 million dry T of stover could be procured and an additional 15 million dry T of dedicated feedstocks. The average price is the weighted average of the amount of biomass at $50/dry T with the amount of biomass at $60/dry T Note that the biorefinery would not pay the marginal cost of feedstock but the average cost.

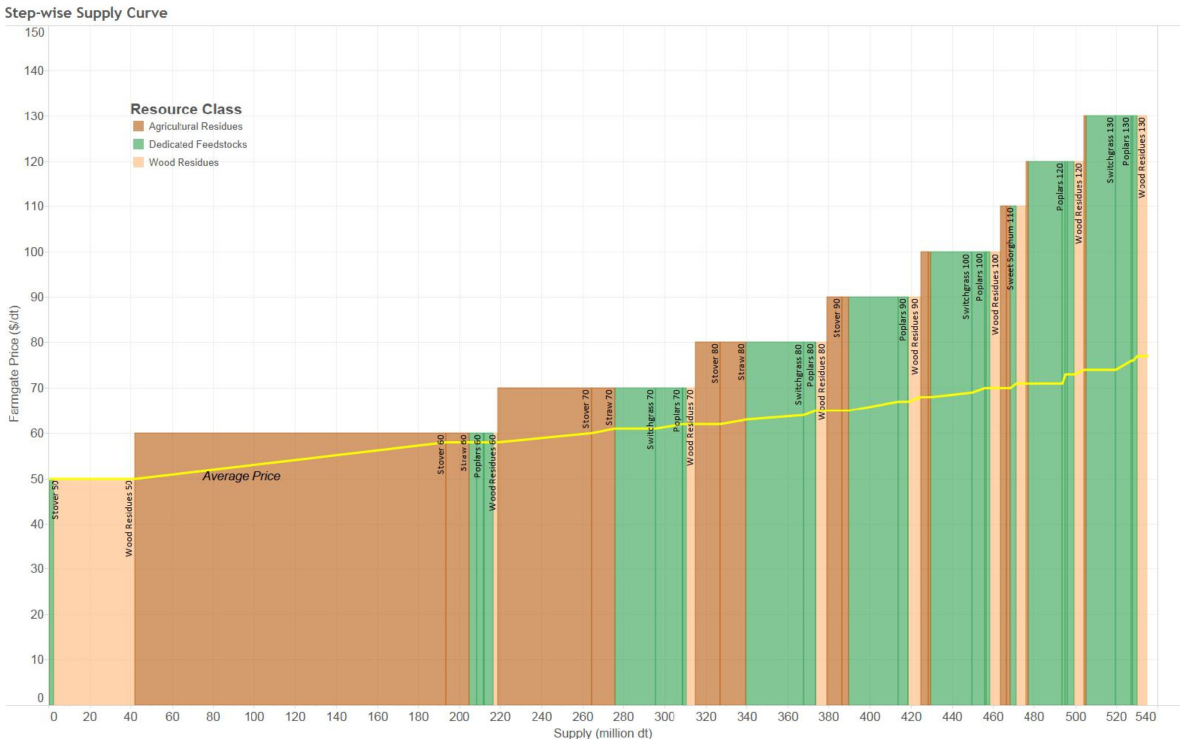
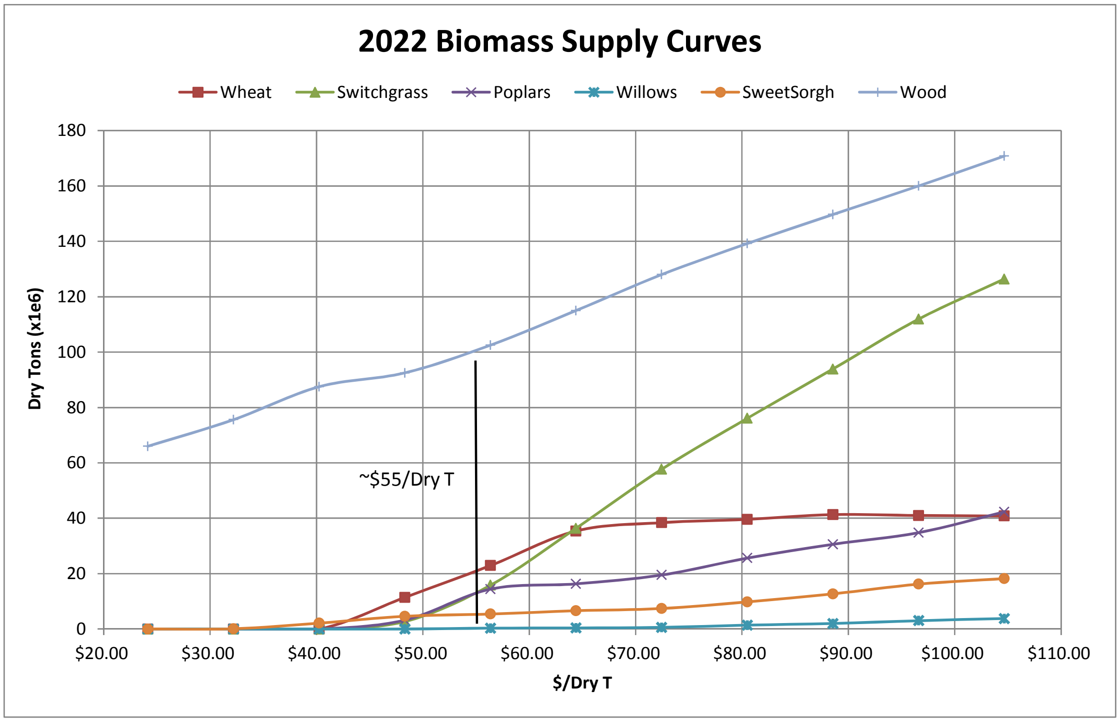


Figure 3. Marginal and average feedstock costs versus supply quantities derived from BT2 data for the U.S. predicted out to 2022 (Courtesy of ORNL).

Figure 5 below shows a national set of farmgate prices for the U.S. At $55/dry T over 100 MM dry T of woody biomass can be secured, but only about 15 MM dry T of poplar. If 100 MM dry T of biomass was required to supply a biofuel industry, one path would be to pay an average of $55/dry T for 100 MM dry T of woody biomass. A blended strategy could select 85 MM dry T of woody biomass at $50/dry T and supplement the rest with a combination of wheatstraw, sweet sorghum, and poplar at $50/dry T for an average price $50/dry T. This would decrease the overall cost of biomass by $5/dry T. What still needs to be determined is if blended feedstocks will behave like a single feedstock in a conversion facility. The testing of blends is currently underway for several conversion technologies to determine feedstock behavior from front-end through finished blendstock.



Note: In this supply, Poplars is considered pulpwood, Wood is considered woody residues.

Figure 4. U.S. Marginal Farmgate prices projected for 2022 by POLYSYS (Courtesy ORNL).

The 2017 Design Case will implement the multi-feedstock approach via a blended feedstock strategy. In this strategy, the multiple feedstocks are blended together in specific ratios determined by availability, access costs (grower payment), and composition. The specific blendstocks chosen as the scenario for the 2017 Design Case will be discussed in Section 2.

1.2.2 Addressing the Feedstock Specification Challenge

As previously stated, compliance with biorefinery in-feed quality specification has a significant impact on bio-oil yield. Using multiple types of feedstock provides an opportunity to adjust feedstock quality; given the right blendstocks, it may be possible to blend to meet a specific biorefinery in-feed specification thereby reducing the need to implement a more aggressive quality control system or purchasing only the biomass that can meet the quality specifications. Blending for such purposes is a common practice in many industries. For example, blending grain to adjust quality is standard practice in the U.S. grain industry (Hill 1990). Similarly, different grades of coal are blended to achieve compliance with regulations regarding sulfur and nitrogen emissions in the power generation industry (Boavida et al. 2004, Shih and Frey 1995). 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 their economical use in co-fired biopower generation (Sami et al. 2001). By using the blended feedstock strategy, it may be possible to develop feedstocks that conform to a desired moisture, and/or ash specification without using expensive preprocessing technologies. More research is required to understand the behavior blended feedstocks will have on overall fuel conversion. Even though it may be possible to blend to specification as measured by composition and physical properties, an additional challenge of the blended feedstock approach is to have the blended feedstock actually perform as well as or better than a singular feedstock in the conversion process. Better understanding of the interactions of blendstocks in the conversion process will require additional research and development focus to better inform blended feedstock development.

1.2.3 Addressing the Logistics Challenge

Moving beyond high yield areas reduces the quantity of resources that can be passively eliminated if not compliant with feedstock specifications. In other words, in Iowa, with high yields, only dry, low ash material can be secured while leaving the remainder of the residues for other uses. In Kansas or other lower yield areas, there may not be enough extra biomass to allow such down selection of material. The high logistics costs of the baseline case, compared to the 2012 Conventional Design Case, are mostly attributed to resource dispersion and moisture mitigation. Additionally, the elimination of waste heat in the baseline case more realistically reflects the costs incurred by the system since it is unreasonable to assume that the conversion facility and the depot will be co-located where they can take advantage of the waste heat. Therefore, improvements in supply systems are needed to reduce the sensitivity of grinding and transportation to biomass moisture and ash content. Additional quality specifications currently not addressed in these designs such as, high heating value (HHV) and low heating value (LHV), could also become important in future design cases. Solutions to these barriers could include fractional milling and high moisture densification with a cross flow pellet drying system. Finally, as multiple feedstocks are incorporated into the system, logistic solutions also are needed to reduce the cost that would occur due to the complexity of handling multiple types of biomass.

The blended feedstock strategy, which relies on the availability of multiple feedstock sources within an economical supply radius, adds an additional logistics challenge to the 2017 Design Case. The complex nature of this approach could bring in more business management overhead to simultaneously manage multiple feedstocks. However this approach could increase the total amount of biomass in an area that would traditionally not have enough of a single resource to economically supply a biorefinery. Overcoming the logistics challenge of a blended feedstock design will require system-level solutions. The 2017 Design Case explores two approaches: one is an agronomic solution based on integrated landscape management and the second is a logistics solution based on biomass depots.

Compared to traditional cropping systems that manage productivity and environmental sustainability on an overall average field scale, integrated landscape management considers subfield scale variability to substitute low productive crops with annual or perennial biomass crops (herbaceous or wood) for improved environmental and productive performance. For example, with the integrated landscape management approach, perennial energy crops may be planted in a pulpwood stand to improve biodiversity or protect sensitive waterways prone to erosion. Similarly, areas of a field that typically under-produce and result in lost revenue for the producer may be planted in a biomass crop (such as switchgrass) that is better suited to the productive potential of the soil. This approach would result in a landscape mosaic where a stand is interspersed with areas of switchgrass and willow. Successful integrated landscape management will produce both economic and environmental benefits to growers, thereby improving the biomass supply-demand dynamic and making more biomass available at lower access costs. Further, such a system alleviates the logistics challenge of dispersed resources by co-locating crops and making more biomass available within smaller supply radii than even the single feedstock scenario.

Biomass depots also may provide logistics solutions for sourcing multiple biomass resources to a biorefinery, whether these resources are largely dispersed or co-located. In this scenario, regional biomass depots may emerge as feedstock supply-chain business elements to lessen the complexity of a blended feedstock supply system. The economic advantage of a depot in this scenario may be its specialization to supply and preprocess a single blendstock. This specialization eliminates the need for a single entity to make the capital investment and establish the expertise to contract, preprocess, and supply a diversity of resources that may have different preprocessing requirements.

2. 2017 FEEDSTOCK SUPPLY SYSTEM DESIGN: ADDRESSING GROWER PAYMENT

The least-cost formulation (blending) approach to resource selection was introduced in Section 1.2.1 as a solution to the grower payment challenge (i.e., to reduce feedstock access costs). This section builds on the baseline scenario located in eastern South Carolina to illustrate the least-cost formulation approach to resource selection for the 2017 Design Case. This approach challenges the single-feedstock paradigm by allowing available resources to compete based on cost, quantity, and quality considerations. It is also shown that such an approach can contribute significant cost reductions to biomass feedstock supply.

2.1 2013 State of Technology

Most cellulosic biomass supply systems are designed around a single feedstock, typically clean woodchips for thermochemical conversion processes like fast pyrolysis. Note that these supply curves represent the projected cost (i.e., farm gate) and quantity available in 2017 based on data from the BT2 analysis. Figure 6 shows the estimated supply curve for pulpwood based on the stumpage price the buyer is willing to pay. Note that if the biofuel industry starts to require large amounts of pulpwood then the price of pulpwood will respond according to an increased demand. The price of pulpwood will increase substantially for large quantities to move into the system. The 2012 Conventional Design was developed around the concept of a single biorefinery and the supply system was designed accordingly. The 2017 Design Case is designed around supplying biomass to a developing industry and not for a single biorefinery.

The woody biomass scenarios/information in the BT2 database was developed using a different set of algorithms and models than the herbaceous biomass. The usage of the data needs to be adjusted accordingly. The woody scenarios were generated from estimates from the U.S. Forest Service Forest Inventory Model and represents estimates of large areas and not county level estimates as is the case for herbaceous biomass. Due to this difference, for estimates of grower payments for small demands (<1 Million dry tons) it is assumed that the current market price would be more appropriate to reflect local supply costs. Figure 6 shows the historical stumpage pulpwood prices for the southern U.S. The prices reflect approximately 57 million tons of pulpwood purchased each year. The stumpage price is for green biomass (as opposed to dry). If you assume around 50% moisture for pulpwood, the grower payment would be double the stumpage price and average around $20/dry T. A single biorefinery would require less than a million tons of biomass each year and hence would not significantly influence the stumpage price currently being paid. A single biorefinery could expect to pay around $20-$25/dry T when competition for the biomass is low. For the 2017 Design Case we assumed the high end for a single refinery of $25/dry T assuming that they will be competing for the biomass and thus driving the prices towards the high end.

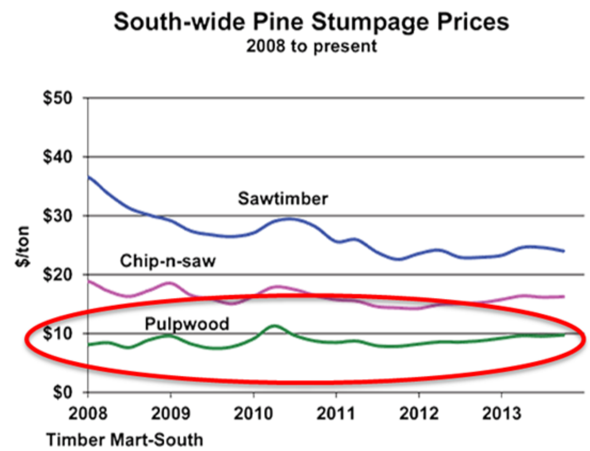


Figure 5. Historical pulpwood prices for the southern U.S. in $/dry Ton (http://www.timbermart-south.com/prices.html).

There is a significant difference in the requested amount of biomass that will be required to fuel an industry versus a single biorefinery. Oak Ridge National Laboratory in their Billion Ton Update (DOE 2011) estimated that upwards of 35 million dry T of woody biomass will be required for the thermochemical biofuel conversion industry as it matures toward the 2022 Design Cases. Based on Figure 7, the farm gate price to access 35 million tons would be around $50/dry T. It should be noted that this is based on 2022 estimates, there may in fact not be a demand as high as 35 million tons but it is important to analyze the system based on projected industry demand and identify potential barriers that will not surface when analyzing a single biorefinery supply system. What is important is to identify that as the biofuel industry grows it will begin to require large volumes of biomass that will in fact influence the supply dynamics and increase the cost to access the biomass. If the industry does grow significantly in the future then the farm gate price will increase and could be barrier that needs to be addressed.

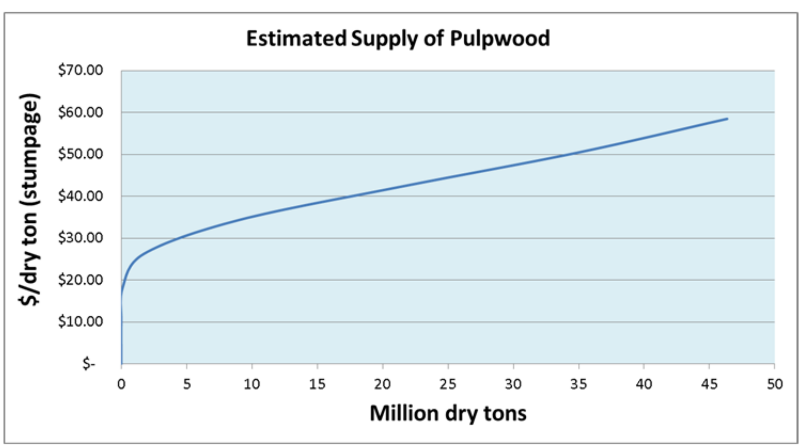


Figure 6. National estimated pulpwood stumpage prices (Courtesy of ORNL).

2.2 Resource Selection Cost Estimation

In order to represent the cost impact of the least-cost formulation approach for resource selection, it is necessary to discuss resource costs in terms of access cost, often referred to as grower payment. However, in order to avoid the misperception that with least-cost formulation in the 2017 Design Case the reduction of access cost means the growers get less, we use the term access cost.

Access costs are calculated from the grower payment cost curves shown in Figure 6, which are derived from historical prices. The 2017 Design Case basis discussion presented above provided the least-cost formulation approach for reducing access costs by accessing multiple feedstocks. With this approach, reduced quantities of each blendstock allows us to stay lower on the supply curve than if we had to supply the entire refinery with any single blendstock. The impact of this approach is shown in Table 5. The 2013 State of Technology assumes a 100% supply of pulpwood of 909,100 dry T at an estimated $60/dry T farm gate or a $25/dry T access cost. In comparison, the 2017 Design Case blend of 45% pulpwood, 32% wood residues, 20% C & D waste, and 3% switchgrass results in a weighted average feedstock cost that is nearly 15% lower than the access cost of pulpwood alone.

Table 5. Resource access cost estimate (U.S. DOE 2011, and INL MSW Data).

	2013 SOT		2017 Target	
	Access Cost (2011 $/dry T)	*Tons*	*Access Cost* (2011 $/dry T)	*Tons*
Pulpwood	25.00	909,100*	25.00	425,700*
Wood Residues	NA	NA	26.35	412,800**
Switchgrass	NA	NA	19.67	25,800
C&D	NA	NA	8.15	172,000
Totals	25.00	NA	21.90	1,036,300

*assumes 10% loss of material to debark/delimb (Walker, 2006)

**assumes 40% loss of material to clean up residues (Phanphanich, 2009)

3. 2017 FEEDSTOCK SUPPLY SYSTEM DESIGN: ADDRESSING FEEDSTOCK LOGISTICS

Feedstock logistics is a highly complex organization of operations required to move and transform biomass from the point of production to the infeed system of the conversion reactor. Feedstock logistics encompass unit operations, including harvesting and collection, storage, transportation, preprocessing, drying, and handling. Organizing feedstock logistics in a way that maintains economic and environmental sustainability, while providing necessary resource quantities, is a principal challenge that needs to be addressed before a self-sustaining industry can evolve. Feedstock logistics research aims to reduce delivered cost, improve or preserve feedstock quality, and expand feedstock access. This will be accomplished by developing new densification, and comminution processes that can handle high moisture material at reduced energy costs, improved storage options for reducing losses and preserving quality, and blending and formulation of different feedstocks that can increase biomass availability and decrease costs.

Chemical and physical properties of biomass, including moisture, ash, and carbohydrate content, are not constant throughout the feedstock supply chain. Some of these changes occur naturally with time and environmental influences (e.g., moisture and carbohydrate loss in storage), while others occur as a result of mechanical inputs during processing (e.g., moisture loss during grinding). The current 2017 Design Case does not attempt to track these changes through each unit operation as if to represent an actual scenario. Rather, the 2017 Design Case represents the likely industry standard scenario (if technology is not designed to handle it, it could represent a failure of the system).

The major assumptions of the 2017 Design Case, compared to the 2012 Conventional Design and the Baseline design developed in Section 1.1 are shown in Table 5. The implications of these assumptions on feedstock supply systems designs are discussed in this section of the report. Table 6 below summarizes the assumptions and differences between the 2012, 2013, and 2017 logistic designs. For the 2017 design case to function, there are some areas that need R&D. These include designing and improving wet densification, fractional milling, improved field storage, formulation/blending, lower access costs (grower payment), and qualifying and quantifying C&D wastes,

Table 6. Summary of assumptions underpinning progressive design implementations (INL 2017 Design Case).

	2012 SOT	2013 SOT	2017 Design Case
Feedstock(s)	Pulpwood, clean chips	Pulpwood, clean chips	Blended feedstock: pulpwood, wood residues, switchgrass, and select construction and demolition wastes (C &D)
Grower payment	Breakeven cost of Production	Increases based on marginal cost differential	Calculated and modeled according to specific location and resource blend/formulation
Moisture	Field dried to 40%	Field dried to 40%	Arrives: Pulpwood chips 30% wood residue chips 30%, switchgrass 20%, and C& D ground 20%; All dried to 9% pellets
Ash	Debark/Delimb	Debark/Delimb	Debark/delimb pulpwood Trommel screen residues Wash and sort C& D waste Blended ash content of <1% Debarked pulpwood <1%, screened wood residues 1.4%; washed and sorted C&D 1.0 %
Logistics	Uses existing systems	Uses existing systems	Pneumatics attached to hammermill High-moisture densification
Quality controls (passive)	Field drying to reduce moisture Ample available resource; quality spec manually selected	Field drying to meet moisture spec	Harvest/collection and storage best management practices for pulpwood and switchgrass More rigorous field drying of pulpwood and residues
Quality controls (active)	Waste heat dryer	Rotary drying	Multiple resource blending/formulation High-moisture densification Fractional Milling

			High-efficiency pellet drying Washing
Meets quality target	Yes	Yes	Yes
Meets cost target	Yes	**No**	Yes
Accesses dispersed resources	No	**No**	Yes

3.1 Harvest and Collection

3.1.1 Overview

Biomass harvest and collection encompass all activities required to gather and remove feedstock from the place of production to the first point of sale; this is often field side or at a nearby storage site and generally is referred to as the "farm gate." The 2012 Conventional Design focused on conventional woody harvest operations (i.e., felling and/ or skidding operations are separate from landing preprocessing operations). In addition to including switchgrass into the feedstock blend, the 2017 Design Case assumes that the immaturity of the biomass market will limit the forest and farm owner's investment in advanced equipment options for both woody and herbaceous feedstocks. Therefore, with the exception of a few proactive, early adopters, conventional forestry and farming operations will dominate the market in the regions defined by the 2017 Design Case.

Relative to the woody feedstocks used in the 2012 SOT, the 2013 SOT and 2017 Design Case are similar in many ways for harvest and collection, but the latter has two key changes to improve quality and production of woody materials. While each system is discussed in the following subsections (3.1.2 and 3.1.3), the key differences of the 2017 Design Case are first inclusion of woody residues sourced from pulpwood operations, and second in-forest drying of whole tree piles at the landing to achieve a more aggressive moisture content of 30% (Section 3.2). In this design debarking and delimbing are conducted to improve biomass quality (Section 3.3). Construction and demolition wastes are considered to enter the feedstock logistics system at the preprocessing stage (Section 3.3) and are therefore not discussed here.

3.1.2 2013 State of Technology

Conventional wood harvest and collection relies on existing forestry technologies designed for timber and pulp and paper production. Collection systems for woody material involve cutting the feedstock with a tracked feller buncher and transporting the material to the landing with a grapple skidder immediately after felling. Felling and skidding operations increase the overall ash content of harvested whole-trees by introducing soil as it is moved in contact with the ground from one location to the next (Taylor et. al, 2012). The ash type and quantity will have an effect on the yield of fast pyrolysis oil as certain ash constituents can cause an increase in the gas production at the expense of condensable liquid. The overall effects of ash through the entire conversion process (e.g., including hydrotreating) are not yet known. In both the 2013 and 2017 Design Cases active management strategies are employed during the landing preprocessing to improve biomass ash content (Section 3.3). Current forestry production of pine pulpwood is reported to yield roundwood with a moisture content of 45-55% and a whole-tree ash content ranging from 1% to 3% (Baker et al., 2012; Taylor et al., 2012; Cutshall et al., 2011; Das et al., 2011). The 2013 SOT assumes the moisture content of pulpwood to be 50% for whole-trees entering storage.

Woody residues are generated through typical commercial forestry operations on southern pine plantations where trees are harvested for pulpwood, chip-and-saw, and saw timber. Similar to the above described collection of pulpwood, these operations bring whole trees to the landing where they are delimbed and topped using a pull-through delimber. The roundwood is then loaded onto trucks for delivery to the mill while the residues are piled at the landing. While not collected in the 2013 SOT, the

2017 Design Case utilizes these materials as a fraction of the feedstock blend (Section 3.1.3). The baseline for residue moisture content is reported at 40%, while ash content has been reported to range from 2% to 4% (Dukes et al., 2013; Das et al., 2011; Baker et al., 2010).

Switchgrass harvest and collection systems use a conventional windrowing harvester and rectangular baler (3x4x8-ft). Although not used in the 2013 SOT, switchgrass under normal management and collection has been reported to yield materials with 8% to 22% moisture and 3% to 9% ash (Carpenter et al., 2010; David et al., 2010; Shinners et al., 2010; Adler et al, 2006; Dien et al., 2006). Based on these sources, the baseline switchgrass harvest and collection values have been set at a collection efficiency of 90%, a bale moisture content of 20%, and bale ash content of 6%. A delayed harvesting technique (i.e., waiting till the plant has senesced and/or overwintered) is often used to control the quality of switchgrass, and has been reported to reduce ash contents to 2% to 6%, but at the cost of decreasing yield by up to 20% (Adler et al., 2006; Dien et al., 2006; Sanderson and Wolf, 1995). Hu et al. (2010) showed the ash content of switchgrass leaves to be the greatest amongst the plant fractions, which may explain the decreased ash content and yield of delayed harvests where leaves are likely to fall off of the standing plants. Brechbill et al. (2000) reported decreasing yields of this magnitude increase production costs by as much as 10%, suggesting that the relationship between quality management and yield management must be properly assessed for development beyond the 2013 SOT.

3.1.3 Harvest and Collection Design Basis

The 2017 Design Case incorporates a chain flail debarker during preprocessing at the landing to increase the quality of the final chipped pulpwood product (Section 3.3). Therefore moisture and ash contents of material entering storage are the same in the 2013 and 2017 Designs. However, there is still impetus to increase the operational efficiency of roundwood collection for reducing costs (Hiesl & Benjamin, 2013; Smidt et al., 2009). This can be achieved through forest management shifts to short-rotation pine plantations aimed at supplying bioenergy production, increased efficiency of harvesting machinery, and increased efficiency of grapple skidder transportation. Research conducted by Auburn University for the DOE High Tonnage Forest Biomass Project has demonstrated high capacity grapplers to increase productivity by 80 tons per productive machine hour compared to traditional systems (Taylor et al., 2012) Figure 8 depicts a conventional skidder and a high capacity skidder. Further development of such operational improvements will play a key role in reducing costs of clean pulp chips for thermochemical conversion. In addition, transition of forest management to short rotation pine plantations focused reducing on energy use during harvest and collection is a promising option for increasing yields; should the economics of establishment be overcome (Jones et al., 2010).

Figure 7. Conventional (left) and high-capacity grapple skidder (right) for transporting small diameter pulpwood from the forest to the landing. Photo credit: Auburn University High Tonnage Forest Biomass Project (Taylor et al., 2012).

Wood residues (tree tops and limbs) originate from other commercial logging operations and are located in piles at the landing, eliminating the costs for harvest and collection (e.g., felling and skidding). Similar to pulpwood, the 2017 Design Case incorporates active quality controls to reduce the ash content during preprocessing at the landing (see Section 3.3).These active controls applied after storage may contain ash contents in excess of the desired specification of 0.9% for wood residues and less for pulpwood.

Switchgrass harvest in the 2017 Design Case follows conventional practices for feed and forage in terms of the equipment used, but incorporates more rigorous passive quality controls to reduce ash content. As discussed in Section 3.1.2 delayed harvest of switchgrass provides the benefits of reducing moisture and ash content, but even with the practice of delayed-harvest, it is clear the raw feedstock will not meet the final quality specification for ash. Blending of switchgrass with a low-ash feedstock is necessary to achieve ash specification of <1%. Nevertheless, it is important that best management practices for switchgrass harvest are used to reduce soil contamination during the processes of cutting and baling while respecting the relationship between delayed harvest date and collection efficiency. Research conducted by Oklahoma State University in collaboration with INL shows that switchgrass can achieve moisture contents at or below the 2017 Design Case specification (10% to 5%), though climatic variance can still introduce moisture variability in delayed harvests (Figure 9). In this same research the ash content of switchgrass was found to be low even at an early harvest (5% in August), though a decreasing trend was observed as harvest was delayed (4% by December). This work stands as an example of the effectiveness of proper harvesting techniques, and stresses the importance of establishing best management practices to cope with variability in weather conditions. Goals for the 2017 Design Case include reducing ash content to 4% through harvest timing and advanced harvesting techniques

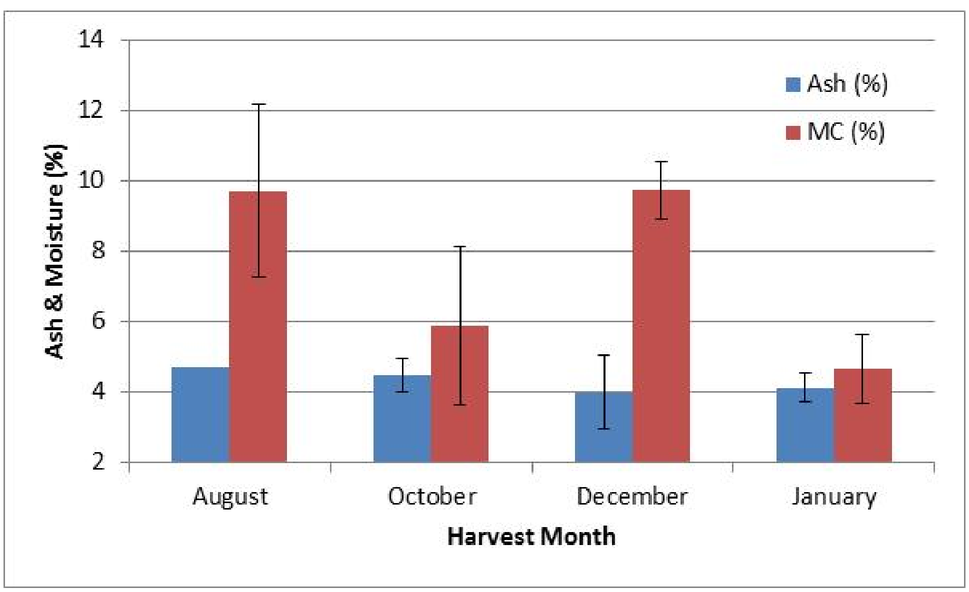


Figure 8. Ash and moisture content of switchgrass harvested in Oklahoma, 2010 by Oklahoma State University. Error bars represent one standard deviation. Ash samples for October, December, and January are three samples comprised of six individual core samples composited.

3.1.4 Harvest and Collection Cost Estimation

Harvest and collection costs assume a removal rate of 15 dry T/acre for pulpwood (Cunningham et al. 2013), 4 dry T/acre for residues (Baker et. al., 2010), and 5-dry T/acre for switchgrass (McLaughlin & Kszos, 2005). These assumptions are consistent with those used in the *The Billion Ton Update* (U.S. DOE 2011). Cost reductions from the 2013 State of Technology (SOT) to the 2017 Design Case are largely attributed to the transition from pulpwood-only in the 2013 SOT to inclusion of residues, switchgrass, and C&D waste in the 2017 Design Case shown in Table 7. The cost of ash at this point within the feedstock logistics system described in Section 1.1.2 is not yet applicable to pulpwood or wood residue, as the material will undergo active quality controls during landing preprocessing. Switchgrass may be subjected to an ash dockage at this point in the process if ash contents are greater than those needed by the feedstock blending process. Further discussion on blending and formulation follows in Section 3.3.4.

It should be noted that INL is not actively doing research in the harvest and collection area. INL has ongoing industrial partnerships with equipment manufacturers but most of that work is in densification and comminution. INL is tracking research at the U.S. Forest Service, DOE-funded high tonnage projects and other woody biomass research on new harvest and collection methods including field drying, new harvesting techniques, and hot versus cold landing processing. As some of these new techniques demonstrate clear advantages to the standard methods, they will be included in future designs as applicable.

Table 7. Biomass harvest and collection cost estimates derived from INL analysis.

Machine	2017 Target (2011 $/dry T) *Total*
Felling	15.00
Yarding	7.24
Totals	**22.24**
Mower-conditioner	4.80
Baler	7.30
Bale collection/stacking	3.31
Totals	**15.41**

3.2 Storage

3.2.1 Overview

The goal of storage is to preserve and possibly improve the valuable qualities of the feedstock until they can be fully-utilized within the conversion process. Long-term storage of organic material may lead to deleterious changes in chemical composition and feedstock loss. Wood chips with moisture contents between 25-50% support microbial growth that produces heat and results in dry matter loss especially after several months of storage (Jirjis, et al., 2005). The integration of forest residues in the 2017 Design

Case requires an improved understanding of storage behavior beyond just pulpwood-quality debarked chips, which has been the focus of most research to date. Additionally, switchgrass—an herbaceous feedstock—will be used as a component for the blended feedstock and has a whole separate set of issues with long-term storage. Storage of seasonally-harvested materials such as switchgrass requires stable long-term storage to minimize changes in feedstock availability and quality. Switchgrass also has two separate storage locations, long-term storage at field side and then short-term storage at the depot or biorefinery. For a biorefinery processing 800,000 dry T per year, or around 2,200 dry T per day, a 7 day supply is around 15,000 dry T stored on location. This minimizes the amount of space needed to store low density biomass on the refinery location.

3.2.2 Dry Matter Loss

Dry matter loss (DML) refers to both a degradation of biomass quality (i.e., sugars, lignin), but also physical loss of material. Both impact the overall yield of production at the biorefinery and need to be accounted for. Where the DML occurs is important from a cost standpoint but does not affect the overall mass balance. Each operation in the logistic supply chain adds value to the biomass. Grinding, chipping and transportation need to be accounted for with any material that is lost either physically or through degradation. Thus if 10% of the material is lost in storage at the biorefinery, we must account for all economics up to the point of loss. Therefore, material lost late in the supply chain will cost more than material lost early on.

Any DML lost needs to be tracked and the lost mass needs to be supplemented through additional acquisition and processing. Therefore, if 10% of the biomass is lost, an addition 10% needs to be acquired. DML through degradation has additional implications. This material will be processed through the conversion facility and impact the effective yields. That material will also have to be made up but that will require additional material flow through the conversion facility which will require additional infrastructure to account for the added flow capacity. Degradation has a greater impact on the overall economics than physical loss. Both are important and impact the overall economics. The INL has research in a number of areas (i.e. storage, densification, and comminution) that address minimizing DML.

3.2.3 2013 State of Technology

Unlike crop residues, woody feedstocks may be harvested throughout the year as needed in most southern US regions and therefore have less need for long-term storage. However, in-field storage may be used to reduce the moisture content of whole tree or delimbed piles (Roser et al. 2011) and stacks (Kim & Murphy, 2013) through passive drying depending upon pile configuration and local climate. The 2013 Design Case assumes 10% reduction in moisture content in pulpwood from 50% to 40% as a result of field drying prior to preprocessing at the landing. This is a very conservative assumption and therefore the 2017 Design Case assumes a 20% reduction in moisture from 50% to 30% as a result of field drying prior to landing preprocessing. Although not used in the 2013 Design Case baseline, wood residues (limbs and tops) are assumed to have a moisture content of 40% both before and 30% after storage (Section 3.1).

Current 2013 SOT and 2017 Design Case rely upon available whitewood chips from pulpwood and residues (tops and limbs) preprocessed at the landing. Dry matter losses during in-field drying of residues is expected to be low; measured losses under laboratory controlled conditions at temperatures ranging from 15° to 35° C ranged from 1% to 2% over one month (Hess et al., 2012). In a review by Jirjis (1995) storage of logging residues in windrows and bundles was reported to result in a <1% dry matter loss per month in storage; most losses were attributed to the loss of foliage. While the mechanical loss of small tops and limbs during chain flail debarking is reported to be 15% by mass (Watson et al., 2011), all costs incurred to get the material into the debarked chip format will be attributed to the mass of the chipped biomass. In this design, the flail and trommel (Section 3.3) remove material that is out of specification for ash content and is thus not a part of the marketable portion of the biomass.

Following landing preprocessing the 2012 Conventional Design relies upon limited on-site chip storage sufficient to supply three days of feedstock. Chip storage piles present favorable conditions for microbial growth, biological self-heating, and chip deterioration, which results in feedstock loss, quality changes, and risks to worker health and safety (Jirjis, 1995; Ferrero et al., 2011; Noll and Jirjis, 2012). On-site chip quantities are limited to reduce these risks. Design assumptions call for chips to be stored outdoors and handled using a front-end loader. In the 2013 baseline short-term chip storage of 40% moisture biomass is assumed to suffer 5% dry matter loss. This assumption is considered to be conservative for the timeframe in question. INL research using intermediate scale pine chip piles shows temperature increases in the range of 60 to 65°C within three to seven days of storage depending on location within the pile (Searcy et al., 2011). Extended exposure to these high-temperature conditions results in acetic acid formation and changes to color and texture of the chips (Fuller, 1985). In laboratory studies conducted by INL using fresh pine chips at 50% initial moisture, dry matter loss in storage simulation reactors reached 1.5% by three days in storage during the initiation of self-heating, 2.5% by one week when a maximum temperature of 60°C was reached, and 6% by one month as shown in Figure 10. Based on these research samples the dry matter loss assumption of 5% in the 2012 Conventional Design baseline does not account for longer storage lengths on-site beyond the three day window, potential pile wetting due to precipitation and/or moisture migration, and mechanical handling losses.

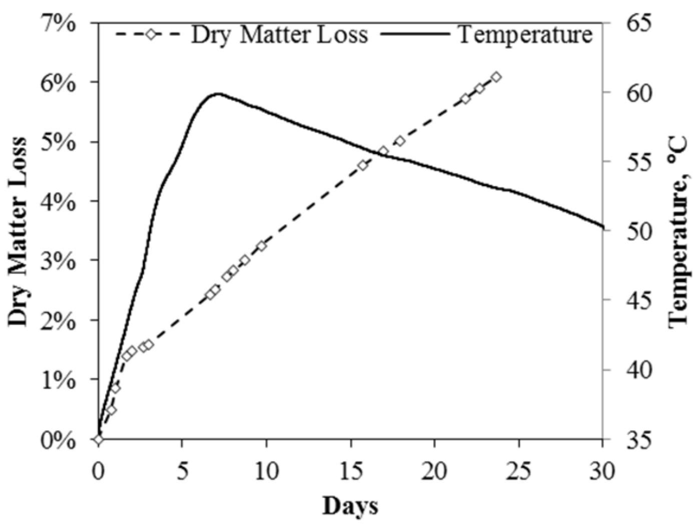


Figure 9. Dry matter loss and self-heating of 50% initial moisture pine chips stored under aerobic conditions using laboratory scale reactors at INL.

Because the 2017 Design Case utilizes a blended feedstock, switchgrass storage must be addressed. The storage of switchgrass occurs field side or at a similar on-farm unimproved storage site. As for any baled feedstock, appropriate storage sites provide adequate drainage away from the stack to prevent the accumulation of moisture around the stack, provide year-round access, and preferably allow stack to be positioned in a North-South orientation to reduce moisture accumulation on the north side of the stack (Smith et al., 2013). Tarped stacks are chosen as a balance between bale protection against moisture infiltration, which leads to dry matter loss, and storage configuration costs (Cundif and Marsh, 1996; Shinners et al., 2010). Stacks are constructed with a self-propelled stacking bale wagon and are six bales high and covered with a high-quality hay tarp. In order to prolong tarp life, it is also important that adequate year-round maintenance be provided to periodically tighten the tarps (Darr and Shah, 2012).

Biomass storage systems in the current Design Case seek to provide a low-cost, low-maintenance, moisture-tolerant solution that focus on maintaining moisture content <20%, minimizing dry matter loss and preserving feedstock composition. Table 8 shows the assumed changes in moisture content between the 2013 SOT and the 217 Design Case.

Table 8. Technical targets for biomass field storage of resources in the 2017 Design Case.

Process	After Field Drying Moisture Content 2013 SOT	2017 Target
Pulpwood	40 %	30%
Wood Residues	40%	30%
Switchgrass	20%	20%

3.2.4 Storage Design Basis

The 2017 Design Case is based on field drying for pulpwood and forest residues, both to 30% moisture at the time the material enters landing preprocessing (Section 3.3). Field studies on field drying of short rotation southern pine pulpwood and residues have shown final moisture contents of 30% to be achievable given adequate time (Dukes et al., 2013; Taylor et al., 2012; Cutshall et al., 2011). Switchgrass moisture content at the time of harvest is typically measured in the range of 15 to 20% moisture. Harvest moisture can be affected by late harvest season precipitation which will increase dry matter loss. The INL is researching new methods of storing wet biomass that will reduce dry matter loss.

Since chips are expected to enter storage at 30% moisture in the 2017 Design Case, it is reasonable to believe from the laboratory data presented in Section 3.2.2 (Figure 14) that dry matter losses will be much less (nearly negligible) within the three day holding window. The concerns of unplanned storage extensions, moisture addition, or mechanical losses could increase this number, and therefore the 2017 Design Case assumes a target chip-storage dry matter loss of 5%. Protection of chip piles with tarps could help to prevent these losses, if the additional material and labor costs are merited, and their presence does not interfere with regular loading and unloading of the piles. Storage of switchgrass is not expected to deviate from the 2013 Design Case baseline. Due to the low moisture content entering storage, the use of a tarp to protect from moisture addition through precipitation has been shown to be sufficient and cost effective (Section 3.2.2) when properly applied.

3.2.5 Biomass Storage Cost Estimation

Cost estimations for biomass storage were calculated based on literature values from recent reviews (Darr and Shah, 2012), the storage cover vendor's information, and laboratory and field level experiments (Smith et al., 2013). Storage consists of two separate components, field side storage and biorefinery storage. There is no field side storage for woody biomass, material is brought into the landing where it is delimbed, debarked and then chipped into a trailer and shipped. For switchgrass, however, there is field side storage where the baled material is stored until needed at the biorefinery. The biorefinery has a short term storage system (3 to 7 days) that buffers the daily in-feed requirements against transportation bottlenecks.

3.3 Preprocessing

Preprocessing includes any physical or chemical activity that changes the material such as chipping, grinding, drying, and densification. Preprocessing also may include necessary auxiliary operations such as dust collection and conveyors. In general, the goal of preprocessing is to increase the quality and uniformity of biomass in order to decrease transportation and handling costs further along the supply chain.

Biomass preprocessing operations of the 2017 Design Case (Figure 11) differ substantially from the current 2013 SOT. 2017 designs include improvements to size reduction (milling) and drying processes and the inclusion of new preprocessing operations (e.g., washing, pelletization and formulation) for ash reduction, stability, and feedstock blending. Biomass preprocessing begins with a coarse size reduction to break the log or bale and facilitate the subsequent separations process. The objective of biomass separations is to reduce the quantity of material that requires further preprocessing, differentiating among anatomical or size fractions based on size, material properties (e.g., moisture and density), and/or composition. Due to the nature of the woody feedstocks, preprocessing operations occur at several locations; some preprocessing occurs at the landing while further preprocessing occurs at a facility (depot or conversion facility) later in the supply chain. However, this decoupling works to the advantage of the supply chain as each individual preprocessing stage can be independently optimized and tailored to individual feedstocks. There is further discussion in Section 3.3 concerning grinding and chipping. In the 2017 Design Case, substantial cost savings in size reduction are realized by tailoring the preprocessing stages to the individual feedstock and not applying a one size fits all approach. For example pulpwood is debarked and delimbed and then processed through a chipper to optimize retention of usable material; wood residues are processed through a first stage grinder then separated by passing through a trommel screen; switchgrass is processed through a grinder while C&D waste undergoes sorting and a wash step.

Separation/sorting of C&D waste is required to remove recyclables (e.g., metal, paper, and cardboard), contaminants (e.g., plastics and concrete), and other unusable fractions to isolate only those fractions that meet the cost and quality requirements for biofuel feedstocks. In the 2017 Design Case, C&D is sorted to supply usable material for thermochemical conversion. Prior to any preprocessing the ash content of untreated C&D waste fractions is estimated to be about 6%. The application of a wash stage further reduces the ash content down to pure wood levels of about 1% (see Appendix A).

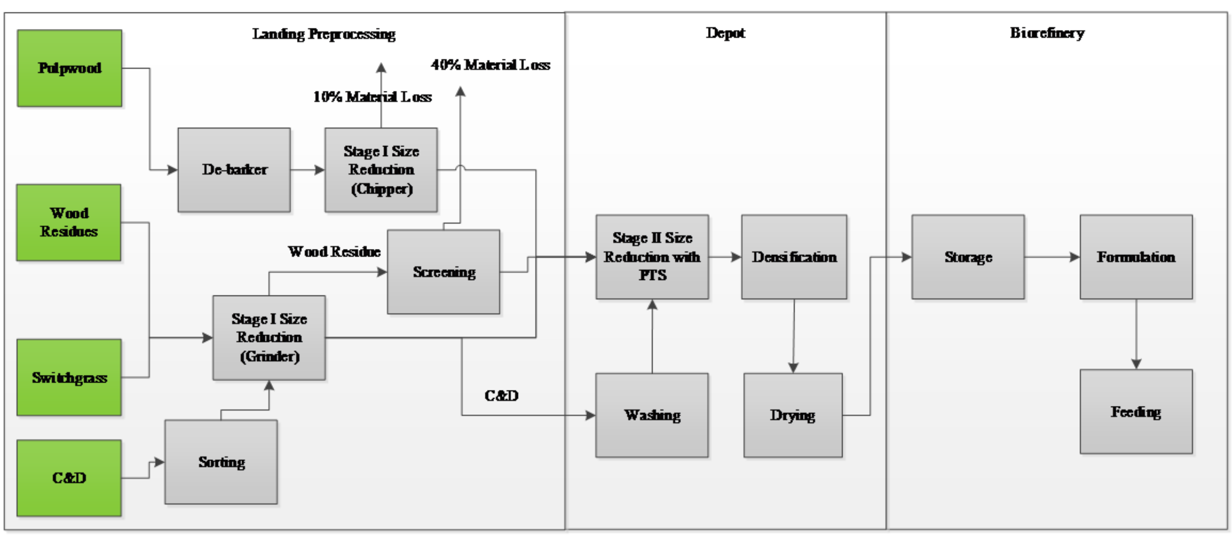


Figure 10. Material flow in the 2017 Design Case that incorporates many improvements in preprocessing, including pneumatics, fractional milling, high-moisture densification, and formulation/blending.

Following final milling of over-sized materials to the particle-size specification (i.e., 1/4-in. minus (i.e., 4-6 mm)), feedstocks are pelletized. Pelletization enables the use of more efficient dryer designs, improves stability for long-term storage, eliminates handling and feeding problems often encountered with bulk biomass, and facilitates feedstock blending. The 2017 Design Case incorporates many improvements in preprocessing, including fractional milling, high-moisture densification, and formulation/blending. Figure 15 outlines the material flow given for these improvements.

The logistics of a blended feedstock scenario are certainly more complex than a single-feedstock scenario. The 2017 Design Case assumes that preprocessing of C&D will occur at a preprocessing depot located at the source landfill or refuse transfer station, and C&D pellets will be shipped from the depot to the blending depot located within proximity of the biorefinery. Switchgrass that is formatted in large square bales will be delivered to the blending depot, where they will be processed into pellets. Pulpwood and wood residues will be initially processed at the landing for initial size reduction and ash mitigation then transported to a processing facility for pelletization. The pulpwood, wood residues, switchgrass, and C&D pellets will be queued up in blending bunkers or silos and blended to specification prior to being fed into the conversion process. The pellets of the four blendstocks (i.e., pulpwood, wood residues, switchgrass, and C&D) are then metered from the blending bunkers in the ratios required of the blended feedstock and are conveyed from the preprocessing facility/depot to the conversion facility.

3.3.1 Size Reduction

The objective of biomass size reduction, or comminution, systems is to take biomass from its as-received condition (i.e., baled, log, or coarse shredded) to the final particle size specification (<0.25 inch) required by the end user. Design and performance considerations include the size distribution of the final milled feedstock and the energy required to process the material. Each size reduction process encounters biomass loss which has a double cost associated with the process. First, the lost material must be accounted for by accruing additional biomass to make up for the loss. Second, all cost prior to the loss are lost so any losses late in the supply chain can have substantial economic impacts. For instance, encountering a 5% loss of material at the biorefinery will mean that the harvest, collection, chipping and hauling costs will be lost for that 5%.

For the 2017 Design Case, a geometric mean particle size of 0.25 in. is the target size specification for fast pyrolysis followed by hydrotreating. Particle size is dictated by a number of factors, including biomass physical and material properties, process variable of the comminution system, shear and impact forces imparted by the comminution system, and the size opening of the screen used to retain material in the system until the material is sufficiently processed to pass through the screen.

Hammer mills generally are considered the current state of art for biomass comminution due to their high throughputs and versatility in processing a wide range of materials. As a general rule of thumb, the geometric mean particle size achieved by hammer milling typically is an order of magnitude smaller than the screen size opening (Yancey et al. 2013).

3.3.1.1 ***2013 State of Technology: Sequential Two-Stage Size Reduction.***

Conventional milling operations involve two sequential size-reduction steps to arrive at the final particle size specification. The first stage of the size reduction process takes the as-received biomass and converts it (through grinding or chipping) into a product that can be further preprocessed. In the 2013 SOT scenario, the first-stage size reduction is followed by drying and second-stage size reduction. The 2013 State of Technology configuration of the first-stage grinding/chipping process uses a 2 to 3-in. screen for coarse size reduction. This size and type of screen provides enough size reduction for subsequent drying and final grinding.

The role of the second-stage grinder is to reduce the particle size further in order to meet particle size distribution requirements. Typically, second-stage size reduction process will use a 0.25 inch screen to produce a mean particle size of .05 inch. While conventional milling processes achieve the desired mean particle size, they often have wide particle size distributions, with a large percentage of undersized particles referred to as fines.

3.3.1.2 ***Optimizing Size Reduction through Equipment Selection and Pneumatics.***

Energy-intensive mechanical preprocessing operations like comminution tend to be expensive; therefore optimization of this stage of preprocessing allows opportunities to reduce the amount of equipment required and costs. Several aspects of size reduction are considered in order to optimize the system to reduce cost. First, decoupling the first and second-stage size reduction processes are primarily a function of location. The first size reduction occurs at the landing while the second occurs in a preprocessing facility. The second stage grinding requires the biomass to be much drier to prevent the equipment from plugging and in order to achieve optimal second stage grinder performance. Decoupling the two processes allows for drying of the feedstock between the first and second stage grinding.

Size reduction, reduction or comminution is an essential component of biomass logistics as downstream conversion prefers a specific in-feed particle size. Additionally, size reduction aids in downstream handling and transportation by increased load density and flowability. Comminution can be conducted with either chippers or grinders but the cutting mechanisms are quite different. Chippers use knives to cut or shear material while grinders use hammers to smash or crush material. In general, the type of material dictates the type of comminution equipment to use. In particular, grinders are used for contaminated material like C&D waste or wood residue due to their reduced sensitivity to wear compared to chippers. Size and configuration also play a role in equipment selection as chippers tend to perform better with uniform orientation of in-feed while grinders do not have an orientation preference. Forest thinnings and residues are small diameter and generally randomly oriented therefore better suited for grinding. The first stage, preprocessing step for pulpwood is generally a chipper; however equipment performance tends to be better with high moisture solid round wood material, however, when you move outside of those parameters such as drier wood or forest trimmings a grinder may be a better choice than a chipper (Mathis 2013). Additionally, chip quality, relative to uniformity of size, is more consistent when the moisture content is higher. As the materials dry out and moisture content decreases, the quality of the chips, relative to consistent size, decreases. The chipper tends to act more like a grinder and the logs shatter rather than chip as they would when the moisture is high. Hence, there is little difference between chipping and grinding of dry material, whereas chipping does provide an advantage over grinding of high moisture stems. The resulting product quality of higher moisture chips is more consistent and energy costs are also lower for chipping when the moisture is higher. In the 2017 Design Case selection of appropriate equipment per each feedstock is important to improve overall system efficiency and handling. Given these advantages, pulpwood at 30% moisture undergoes first stage size reduction through a chipper while wood residues at 30% moisture and switchgrass at 20% moisture use a grinder for first stage size reduction. C&D waste is also processed through a grinder for first stage size reduction which occurs during sorting. First stage size reduction occurs at the landing for pulpwood and wood residues.

To address the issue of quality relative to ash, pulpwood is debarked and delimbed before chipping with a flail. Bark is too high in ash content to be used economically in thermochemical conversion, and therefore should be eliminated early in the process if possible. An economic study needs to be done to determine the most economical place to address the ash issues. A 10% loss in volume is assumed due to the bark reduction (Walker 2006). Wood residues are too malleable for a flail, and therefore are passed through a trommel screen to remove bark, needles, and entrained soil losing approximately 40% of material through the trommel process (Phanphanich 2009). This is still cost effective since harvesting and collection of wood residues is costed to the commercial harvesting operation and grower payment is inexpensive (Watson et. al. 1993).

3.3.1.3 *Fractional Milling*

In addition to pneumatic separation, through a series of grinding tests conducted at the INL it was found that a significant amount of material (in this case sorghum) will already meet the specified size requirement after the stage 1 grinder. While this data was developed while grinding sorghum, the same effects are expected to be true for corn stover and all other feedstocks. Figure 12 shows the percent of material retained within 3 size fractions (less than 1/16 inch, between 1/16 and 1/4 inch and greater than ¼ inch). What is observed is that the amount of material retained in the center fraction (1/16-1/4 inch) is relatively constant regardless of the screen used, it ranges from 47-53%. However, with a larger screen (6 –in), fewer fines are produced, but more "overs" are generated compared to say a 1 inch screen. The conventional process would move all of this material through a second stage grind to ensure that nearly 100% falls below the maximum preferred size. However, if the material were screened following the first stage grind, only the oversized material would need to be sent on to the second stage grinder.

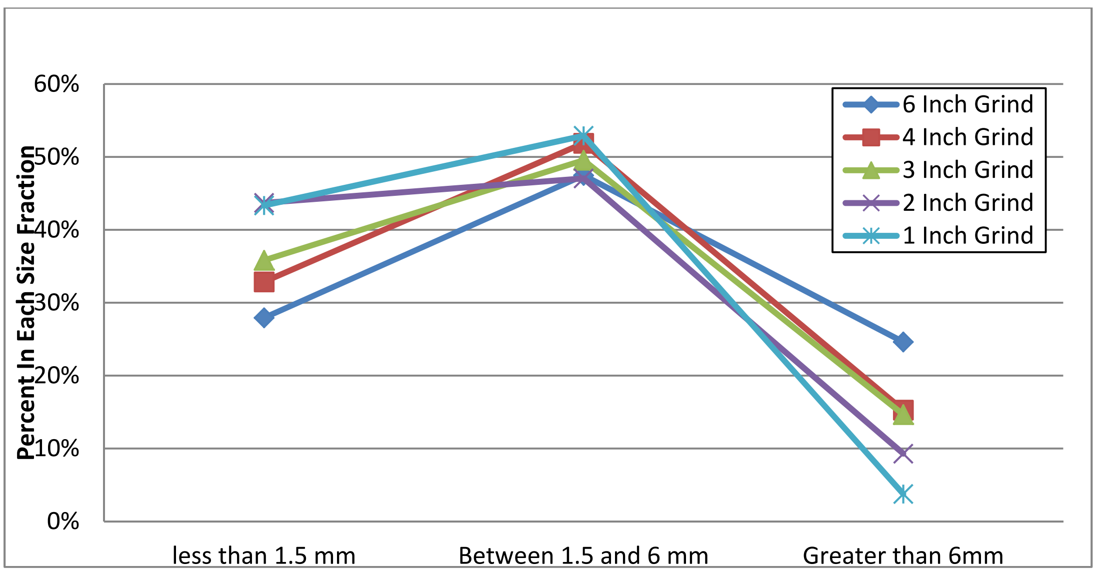


Figure 11. Percent material size retained after 1st stage grind.

Grinding energy was also measured in this study and found that as the screen size increases; grinding energy decreases (Figure 13). By going to a large screen size, less energy is consumed during stage 1 grinding. Also, the amount of material that falls into the desired screen size (in this case between 1/16 and ¼ inch) using the 6 inch screen is nearly the same as the percent in that same fraction that was generated using the 1 inch screen. The difference is that there are fewer undersized particles and more oversized particles when using the 6 inch screen.

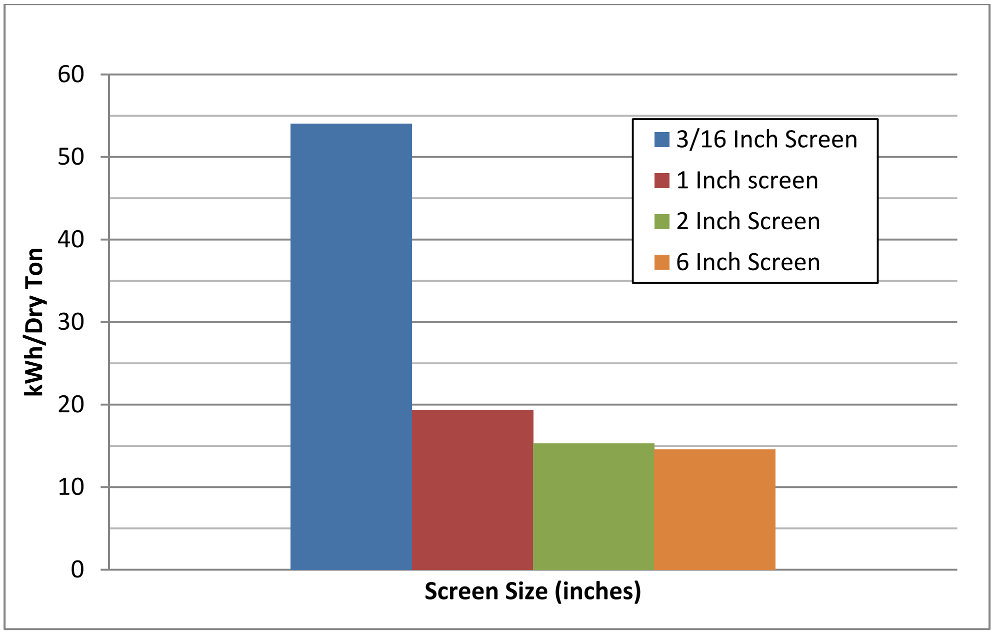


Figure 12. Energy consumption versus screen size for sorghum.

By using the fractional milling approach, the material that is not considered as overs (less than ¼ inch) will be screened from the material greater than 1/4 inch, and only the material greater than 1/4 inch will pass on to the second stage grinder. In this case, only 25% (Figure 12) of the material is greater than ¼ inch and therefore only 25% would need to be processed further by the second stage grinder. This should result in a significant reduction in the second stage grinding costs.

Finally, all remaining feedstocks undergo second stage size reduction through a hammer mill as the variability in feedstock at this point have been greatly reduced to allow a one size fits all approach. Second stage grinding at a processing facility lends well to equipment optimization through additional mechanism like pneumatic separation and drying.

Pneumatic separation has been found to be effective at increasing throughput capacities of grinders by separating out the finer particles quickly so that they do not remain in the grinder where they reduce grinding efficiency particularly with low density feedstocks like biomass. Pneumatic discharge systems can increase capacity by 3 to 4 times. Without pneumatic discharge, processed material is thrown in every direction including up the infeed. The pneumatic system helps to force the processed material quickly in the right direction – through the screen (Schutte Buffalo 2013). Figure 16 shows the improvement in comminution capacity due to the addition of a pneumatic transfer system. Additionally, pneumatics can affect the quality of feedstock by removing moisture and potentially ash illustrated in Figures 14, 15, 16. Hammer mill systems are highly sensitive to biomass moisture content, with energy consumption increasing dramatically as moisture content increases (Figure 17). The size reduction design basis is summarized in Tables 9 and 10.

Separating this material prior to stage 2 grinding will reduce downstream costs and improve product quality based on size requirements. Preliminary research shows that grinding costs can be improved by 30% by increasing screen size and separating out material that already meets particle size requirements. In FY 14, the research on size reduction will be on fractional milling, specifically on Techno-economic assessment of fractional milling for woody and herbaceous biomass as well as the comparison of different size reduction technologies based on moisture (both high and low moisture), throughput, energy consumption, and flowability.

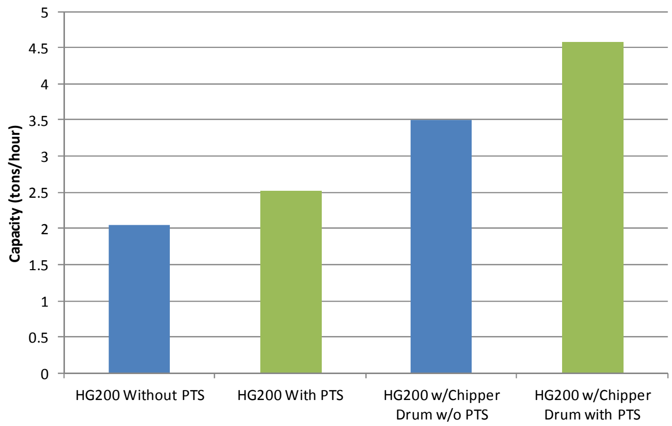


Figure 13. Comparison of comminution capacity (tons of through put per operating hour) for woody biomass as a result of adding pneumatic transfer assist (PTS) (Searcy et al., 2011).

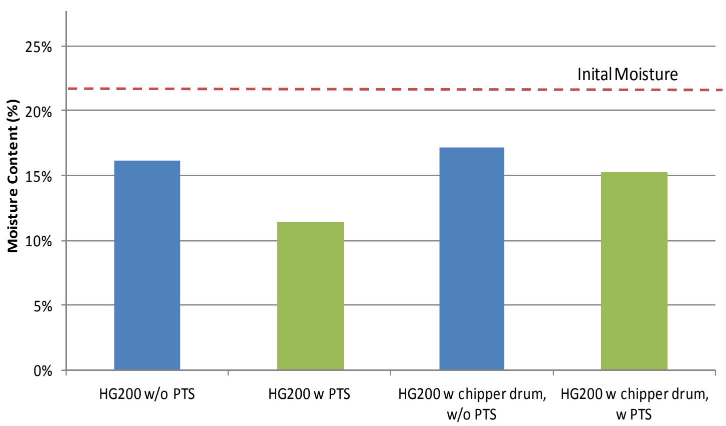


Figure 14. Change in moisture content during comminution using pneumatic transfer assist (PTS) (Searcy et al., 2011).

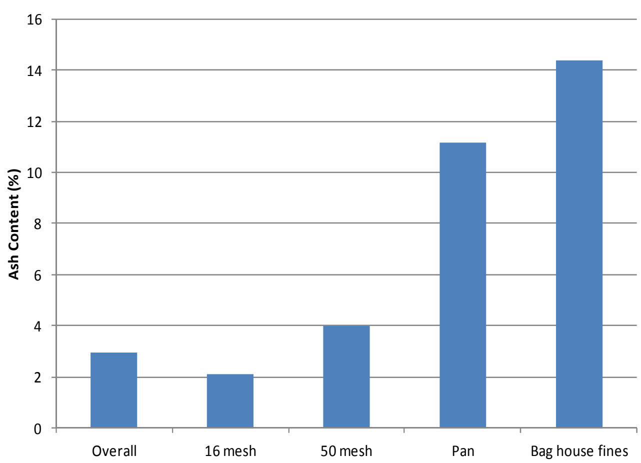


Figure 15. Ash content in various screen sizes for pinyon juniper biomass (Searcy et al., 2011).

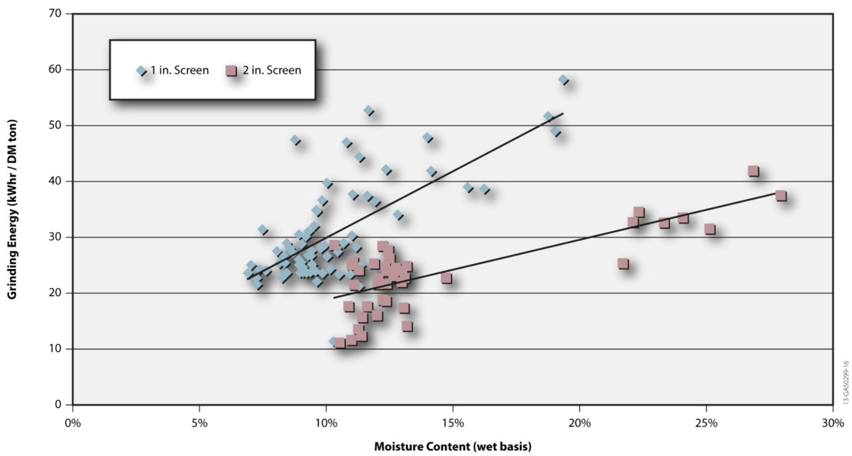


Figure 16. Hammer mill energy consumption in kWhr/dry T (DM ton) is highly dependent on biomass moisture content (INL PDU Data).

Table 9. Size-reduction design basis.

	Equipment Used	Screen Size	2013 SOT Capacity Dry T/hr	2017 Target Capacity Dry T/hr
First stage Size Reduction				
Pulpwood	Chipper	2 in.	17	17
Wood Residue	Grinder	2in.		
Second Stage Size Reduction				
Pulpwood	Hammer mill	¼ in.	5	6.5
Wood Residue	Hammer mill	¼ in.	5	6.5

3.3.2 Size Reduction Cost Estimation.

Milling cost estimation is based on vendor-supplied information and equipment performance from typical machine performance and process demonstration unit data (Table 10).

Table 10. Size reduction cost estimates.

	2013 SOT (2011 $/dry T) *Total*	2017 Target (2011 $/dry T) *Total*
Pulpwood		
Chipper	6.10	6.10
Debark/delimb	6.10	6.10

Hammer Mill	17.09	13.97
Total	29.29	26.17
Wood Residue		
Grinder	5.39	5.39
Trommel Screen	3.32	3.32
Hammer Mill	17.09	13.97
Total	25.08	22.70

3.3.3 Drying and Densification

Developing uniformly formatted, densified feedstock from a variety of biomass sources is of interest to achieve consistent properties (such as size and shape, bulk and unit density, and durability), which significantly influence storage, transportation, and handling characteristics and, by extension, feedstock cost and quality (Tumuluru et al. 2011).

3.3.3.1 *2013 State of Technology: Pelletizing.*

The biomass pellet production (Figure 18) includes initial size reduction to a 2- in. particle size, followed by drying to 10 to 12% moisture content (wet basis) using a rotary drier. The dried biomass is then passed through a second-stage grinding process to reduce the particle size to less than 3/16-in. (typically to 2 mm), steam conditioned, and pelletized. Drying is the major energy consumption unit operation in this process, accounting for about 70% of the total pelletization energy (Tumuluru et al. 2010, 2011).

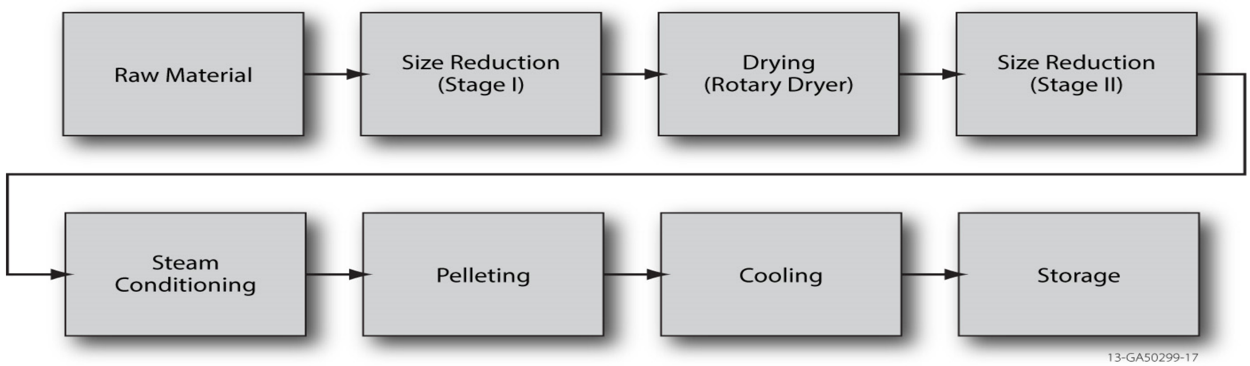


Figure 17. 2013 State of Technology pelletization process.

3.3.3.2 ***High-Moisture Densification Design Basis.*** Significant cost reductions to the conventional drying and pelleting processes are possible with a process of high-moisture densification (under development at INL) that eliminates the energy intensive rotary drying process prior to pelleting. In this process, the high-temperature (typically 160 to 180°C) drying operation is replaced with a low-temperature (approximately 110°C), short duration (typically several minutes) preheating operation. The combination of preheating with the additional frictional heat generated in the pellet die results in a reduction of feedstock moisture content of about 5 to 10 points (e.g., from 30% down to 25 to 20%) (Tumuluru 2014). The pellets produced still have high moisture (~20%) and require further drying to about 7% for safe storage and transportation. Binders will be an option in our future studies to reduce the specific energy consumption. It also is noted that higher moisture densification does not include the addition of a binder.

This process has been demonstrated at INL where corn stover, ranging in moisture from 28 to 38%, was preheated at 110°C for 3 to 4 minutes prior to pelleting in a laboratory flat-die pellet mill using both 8 and 6 mm dies. The pellets exited the mill at 20 to 30% moisture content and, after drying, exhibited densities greater than 30 lb/ft^3 and durability greater than 95%. The specific energy consumption was estimated to be in the range of 40 to 100 kWhr/dry T (Tumuluru, 2014). Preliminary studies with woody feedstocks have also exhibited similar results.

The reduction in drying energy is the key advantage of this approach (Figure 19). First, the process uses the heat generated in the pellet die to partially dry the material. Second, drying pellets offers cost and energy advantages over drying loose, bulk biomass. Loose biomass typically is dried in a concurrent-flow rotary dryer. Rotary biomass dryers are expensive to purchase (>$1M) typically operate at temperatures of about 150 to 160°C, have greater particulate emissions, greater volatile organic compound emissions, greater fire hazard, a large footprint, and often have difficulty in controlling the material moisture. With the increased density, the reduced tendency for material to become entrained in the air flow, and the increased heat transfer coefficients compared to loose biomass, more efficient drying technology options are available for drying pellets. Cross-flow dryers (common in grain drying) are much less expensive to purchase (~$50K) operate at temperatures less than 100°C, reduce the particulate and volatile organic compound emissions, and will have better temperature distribution. A comparison of pellet properties and energy balances for conventional and high-moisture pelletization processes is given in Table 11. The table shows 2017 Design Case targets to achieve a 40 to 50% reduction in the total pelletization and drying energy.

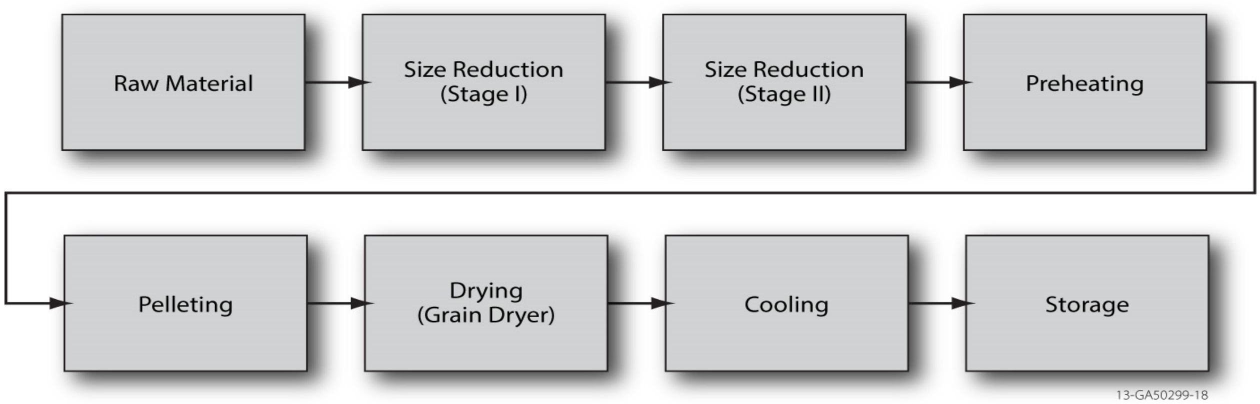


Figure 18. High-moisture pelletization process.

Table 11. Drying and densification design basis.

	2013 SOT	2017 Target
Infeed Moisture	40%	30%
Dryer Moisture Reduction	28%	11%
Densification Moisture Reduction	3%	10%
Final Pellet Moisture	9%	9%
Densification Energy	75 kWhr/dry T	50 kWhr/dry T
Drying Energy	350 kWhr/ton	100 kWhr/ton

Pellet Properties		
Unit Density	65 lb/ft^3	70 lb/ft^3
Bulk Density	35 lb/ft^3	40 lb/ft^3
Durability	Greater than 97.5%	Greater than 97.5%

The high-moisture densification design basis assumptions are as follows:

- Our preliminary studies indicated that it is possible to produce high-quality pellets with woody material; however, for our 2017 Design Case, we are assuming that the process works for other woody and herbaceous feedstocks to produce durable, high-density pellets.
- Technical and cost targets are estimated with the assumption that a grain dryer will be used to dry high-moisture pellets.
- Drying of pellets using energy-efficient driers like grain and belt driers is more economical compared to conventional rotary driers.
- Slow drying at low temperatures of less than 60°C can result in more uniform moisture distribution in pellets.

3.3.3.3 ***Cost Estimation for High-Moisture Densification.*** The cost of densification was estimated using vendor-supplied information and the capacity and energy assumptions shown in Table 12.

Rotary drying costs associated with the 2013 SOT were based on data supplied by Anco-Eaglin, Inc. Yancey et al. (2013) analyzed the cost of various unit operations in the pelletization of lodgepole pine using a process demonstration unit and indicated that a rotary dryer consumes about 70% of the energy to dry loose biomass from initial moisture content of 30 % (w.b.) to final moisture content of 15 % (w.b.), whereas pellet mill consumes about 7 %. The major disadvantages of using rotary dryer are: (a) it requires high quality heat, (b) it has greater particulate emissions, (c) it has greater volatile organic compounds (VOC) emissions, (d) has a greater fire hazard, (e) a large footprint, and (f) it is difficult to control the material moisture content (Worley, 2011).As described above, because of the similarity of pellets and grain, grain drying technology is the basis of the 2017 Design Case. Accordingly, grain drying costs were the starting point to estimate pellet drying costs. Using a grain drying calculator found at Iowa State (Iowa State University 2013), we estimate the cost of drying grain of a similar moisture content to be $10 to $14/T. Estimated pellet drying costs were reduced from these values because we assume that the porous nature of pellets and less structural heterogeneity in pellets will promote more rapid and uniform drying compared to grain that has the outer pericarp layer that limits moisture transfer.

Table 12. Drying and densification cost estimates.

	2013 SOT (2011 $/dry T) *Total*	2017 Target (2011 $/dry T) *Total*
Drying	17.20	5.60
Densification	7.70	4.40
Totals	22.90	10.00

3.3.4 Formulation/Blending

3.3.4.1 ***Overview.***

Feedstock formulation is not a new concept in many market sectors. For example, different grades of coal are blended to reduce sulfur and nitrogen contents for power generation (Boavida et al. 2004, Shih and Frey 1995), grain is blended at elevators to adjust moisture content (Hill 1990), animal feeds are blended to balance nutrient content (Reddy and Krishna 2009), and high-ash biomass sources are mixed with low-ash coal to allow their use in biopower (Sami et al. 2001). The current formulation strategy is to blend after pelletization. INL has attempted to blend raw biomass and then pelletize but found the blending process to be difficult and time consuming. The blending in the 2017 design case is performed at the biorefinery and costed under the handling operations. The pellets are blended through a series of conveyor processes and then run through a crumbler as they are fed into the conversion process.

3.3.4.2 ***Formulation Design Basis.*** To meet feedstock specifications required for various conversion pathways, formulation of specific mixtures of feedstocks will likely be required. Examples include mixing high and low-cost feedstocks to meet cost targets, mixing high and low-ash feedstocks to meet an ash target, mixing of high and low-carbohydrate feedstocks to meet a yield target, and mixing easily and poorly reactive feedstocks to meet a convertibility target. An example of blending to meet an ash and moisture specification is shown in Table 13.

Table 13. Feedstock formulation/blending of ash and moisture contents*.

Content Delivered to Biorefinery Infeed	Pulpwood	Wood Residues	Switchgrass	C&D waste	Final Blend
Ash content (wt. %)	0.5	1.0	4.0	1.0	**<1%**
Moisture content (%, wet basis)	9	9	9	9	**9**
HHV (lb/BTU)	8824	9444	7557	8824	**8984**
LHV (lb/BTU)	7255	7616	6155	7255	**7337**

*Pulpwood, wood resides, and switchgrass composition data were obtained from the INL Biomass Library. See Appendix A for C&D ash data

Assumptions for the formulation design basis are as follows:

1. Blended feedstocks will be selected and developed to achieve conversion yield specifications. It currently unknown how blended feedstocks will perform in the conversion pathways. The simplest assumption is the blended feedstocks would be the sum of performances of each individual component. There are on-going trials to test various blended feedstocks and to compare the conversion efficiencies against a single feedstocks.
2. Individual feedstocks will be pelleted at depots for shipment to biorefineries. At the biorefinery, these pelleted feedstocks will be unloaded and conveyed into individual bunkers for storage. Pellets of the different blendstocks will be metered out into the bunkers in the ratios required of the blends, crushed (using a pellet crusher), and mixed prior to insertion for the conversion process.
3. Material will be metered from individual bunkers onto a conveyer and then thoroughly homogenized through this process with no segregation. Mixing of solids occurs in many industries and is often problematic when solids of varying density, shape, and size are blended. This often leads to segregation, either during the mixing or while being transported to its destination. Mixing of solids is considered a trial-and-error process due to these issues.
4. The expected unit operations for formulation are shown in Table 14.

Table 14. Feedstock formulation design basis.

2013 SOT (2011 $	Operating Parameters Capacity	Horsepower
Pellet Pulverizer	100 dry T/hour	200 HP
Bulk Storage with Hopper	30 dry T/hour	30 HP
Conveying/Mixing System	30 dry T/hour	40 HP

Research is currently ongoing at INL to examine the compatibility of various feedstocks blends, with an initial focus on the blends reactivity versus the individual feedstocks. Blends will be developed for several regions of the United States using the least-cost formulation model as a starting point and will incorporate feedstocks with varying levels of reactivity (e.g., herbaceous, woody, and MSW). While the costs for preprocessing of feedstocks (e.g., grinding, chemical preconversion, pelleting, and drying) are addressed in other parts of the 2017 Design Case, formulation itself will require additional preprocessing options in order to work with the bio-oil conversion pathway. These processes include bulk storage, conveying systems and a pellet pulverizer to insure that the appropriate recipe of material enters the throat of the conversion reactor in the appropriate blends and sizing requirements.

3.3.4.3 ***Cost Estimation for Formulation***. Formulation cost estimation was as based on existing technology, vendor-supplied information, and equipment performance (Table 15). These costs are cursory and require more extensive research, especially in their specific application to the bioenergy industry.

Table 15. Formulation cost estimation.

	2017 Target (2011 $/dry T) *Total*
Pellet pulverizer	1.10
Bulk storage with hopper	0.20
Conveying/Mixing system	0.60
Totals	1.90

3.4 Transportation and Handling

3.4.1 Overview

Transportation includes all processes involved in the movement of material from multiple locations to a centralized location (such as a preprocessing facility). Transportation includes processes such as: loading, trucking, rail transport, and unloading. Transportation is distinguished from collection through use of existing roadways, railways, and waterways moving biomass accumulated near the production location, while collection requires use of specialized machinery capable of off-road use gathering highly dispersed biomass from a field or stand and moving it to a nearby staging location. Beyond transportation, additional biomass handling is required to move and queue material before the conversion facility. Surge bins, conveyors, dust collection systems, and miscellaneous material handling equipment such as loaders could be used.

Lignocellulosic feedstock handling operations currently operate at 40% to 50% of the design capacity. Handling operations depend on many factors, including biomass chemical composition, bulk density, particle size, and shape distribution. Lignocellulosic feedstocks inherently possess characteristics that inhibit handling (such as high cohesivity, low density, high compressibility, high variability in particle size, and shape uniformity). There are two main approaches for solving material handling problems first engineer systems to specific materials or material properties, and second engineer materials to feed into the equipment systems (Kenney et al. 2013).

Because the variability of raw biomass is inevitable given the impacts of climate, seasonality, species, and so forth, active preprocessing controls are needed to better regulate material properties. Active preprocessing controls will include technologies that provide consistent bulk solid properties while preserving valuable components (e.g., carbohydrates) and reducing problematic components (e.g., moisture and ash). Finally, feeding and handling issues due to inconsistent and to uncertain properties are estimated for reducing overall plant throughput by as much as 50%. Equipment designs capable of accommodating such feedstock variability will improve overall operation performance. Combining both improved engineered systems and material handling operation will improve capacity (Kenney et al. 2013).

3.4.2 Transportation and Handling Design Basis

As stated in Section 3.3 the 2017 Design Case includes formulation and densification meeting feedstock specifications and costs targets. Both processes of formulation and densification will improve feedstock handling operations through active controls. See Section 3.3.4 for further discussion on feedstock formulation and costs estimates for handling.

Given formulation and the specific quantities of individual feedstocks required, the average transportation distance will change based on feedstock type. In the 2017 Design Case, pulpwood will be trucked to localized depots from a draw radius of less than 50 miles while switchgrass will be trucked fewer than 15 miles. Draw radius is a function of % agricultural land, % land in crop, and % participation in bioenergy. The area chosen for the design case is considered primarily pulpwood but the participation in bioenergy is low, about 1%. While the participation for switchgrass is high >90% because the assumption as that there is not a competing industry. Therefore to accommodate this, the switchgrass draw radius is less than pulpwood. Table A-1 show sufficient C&D waste resources in the selected counties in western South Carolina therefore C&D will be transported by truck from transfer stations after processing. Current research is examining the actual availability of C&D waste, what other competition will there be for this material and what would be the implications for qualifying for RIN credits as a cellulosic biofuel. This is not a new concept, transfer stations are already used for sorting and transporting valuable material such as cardboard and scrap metal in densified forms (e.g. baled cardboard, crushed and baled scrap metal). Switchgrass will be loaded and unloaded at each location using a loader (telehandler) capable of moving 12 lb/ft^3 bales at 20% respective moisture content. A 53ft. trailer and 800,000-GVW limits were assumed in all trucking operations. Transportation for switchgrass will occur from a field side stack to a densification facility completely separate from the conversion facility, but within a minimal conveyor distance (typically <50 miles). C&D waste transportation will occur from the waste transfer station as pellets to the preprocessing facility for storage and transfer to the biorefinery. Further transportation and handling assumptions are given as follows:

1. At 20% moisture, transportation continues to be volume limited at densities of 12 lb/ft^3.
2. At 30% moisture, transportation of chips continues to be volume limited.
3. At 9% moisture, transportation of pellets is weight limited at 40 lb/ft^3.
4. There will be insignificant material losses throughout transportation and handling.
5. Densification will increase material uniformity and flowability.

3.4.3 Cost Estimation for Transportation

The cost estimation for transportation and handling was based on vendor-supplied information and equipment performance from typical machines (Table 16). Rail transportation costs were based on work from Searcy et al. (2007) using a jumbo hopper car adjusted for U.S. conditions.

Table 16. Transportation cost estimates.

	2013 SOT (2011 $/dry T) *Total*	2017 Target (2011 $/dry T) *Total*
Truck	14.84*	7.52**

*Individual feedstock therefore one transportation pathway

**Multiple feedstocks therefore multiple transportation pathways and draw radiuses.

4. SUPPLY SYSTEM ECONOMICS

4.1 Model Based Biomass System Design

The Biomass Logistics Model (BLM) is part of a versatile analysis toolset developed by Idaho National Laboratory (INL) to estimate delivered feedstock cost, energy consumption and greenhouse gas emissions for biomass supply system scenarios. The BLM is designed to work with various thermochemical and biochemical conversion platforms and accommodates numerous biomass varieties (i.e., herbaceous residues, short- rotation woody and herbaceous energy crops, woody residues, algae, etc.), resulting in a robust and flexible systems model. The BLM simulates the flow of biomass through the entire supply chain, tracking changes in feedstock characteristics (i.e., moisture content, dry matter, ash content, and dry bulk density) as influenced by the various operations in the supply chain. By accounting for all of the equipment that comes into contact with biomass from the point of harvest to the throat of the conversion facility and the change in characteristics, the BLM enables highly detailed economic costs, energy consumption and environmental impact analyses. As a result of these highly detailed analyses, areas for improvement (i.e., equipment efficiencies, operational parameters, environmental conditions, etc.) can be identified through sensitivity analyses that can be used to improve the design and performance of these systems. Finally, the BLM can be coupled to additional models as it is part of a greater modeling toolset used to assess sustainability, environmental impacts (GHGs), and feedstock quality specifications.

The BLM incorporates information from a collection of databases that provide 1) engineering performance data for hundreds of equipment systems, 2) spatially explicit labor cost datasets, and 3) local tax and regulation data (Figure 1).

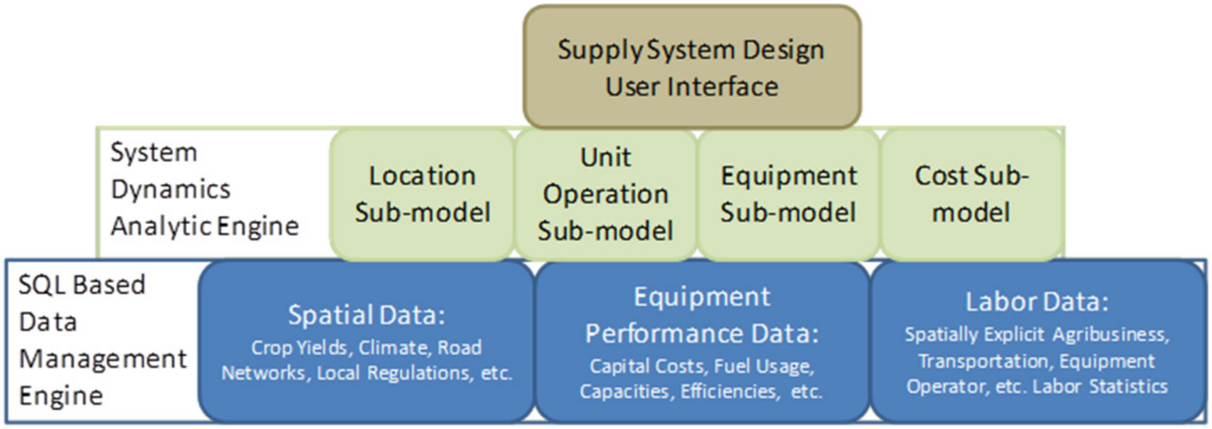


Figure 19. BLM framework.

4.2 Delivered Feedstock Costs

The cost of feedstock impacts the finished biofuel cost and how the 2017 Design Case is helping to meet the $3/gge BETO target. $3/gge would be competitive with gasoline prices. The feedstock cost of $80/dry T for feedstock logistics and assuming a conversion efficiency of 84 gallons/dry T allocates around $0.95/gge for logistics. Biofuel conversion is allocated the remainder of the $3/gge. Currently, all of the conversion technology design cases assume a feedstock cost of $80/dry T.

Two requirements for the 2017 Design Case that were established early in this report are first achieving the $80/dry T cost target when located outside the southeast U.S and second achieving biorefinery quality specifications within the $80/dry T cost target. In Section 2, feedstock curves were developed for the 2017 Design Case scenario located in western South Carolina. These curves included access costs (i.e., grower payment) and logistics costs. Using these curves, it was determined that a feedstock blend of 45% pulpwood, 32% wood residues, 3% switchgrass and 20% C&D would meet the $80/dry T delivered feedstock cost target, thus satisfying the cost criterion of the 2017 Design Case (see Table 17).

Table 17. Thermochemical feedstock design cost analysis for 2017.

Cost Element	Pulpwood	Wood Residues	Switchgrass	Construction and Demolition Waste (C&D)	Blend
Formulation Contribution	*45%*	*32%*	*3%*	*20%*	–
Grower payment/access cost	25.00[1]	26.35[2]	19.67	8.15	**21.90**
Harvest and collection ($/dry T)	22.24	0	15.41	–	**10.47**
Landing Preprocessing ($/dry T)[3]	12.17	8.73	0	9.85	**10.24**
Transportation ($/dry T)[4]	10.89	3.33	4.5	6.87	**7.52**
Preprocessing ($/dry T)	23.97	23.97	19.7	28.12	**22.79**
Storage ($/dry T)	3.23	3.23	5.5	3.23	**3.30**

Handling ($/dry T)	1.90	1.90	1.90	1.90	**1.90**
Total Delivered Feedstock Cost ($/dry T)	99.49	67.51	66.68	58.12	**80.00**
Delivered Feedstock Specifications*					
Ash content (wt. %)	0.5	1.0	4.0	1.0	**<1%**
Moisture content (%, wet basis)	10	10	10	10	**10**
HHV (lb/BTU)[5]	8824	9444	7557	8824	**8984**
LHV (lb/BTU)[5]	7255	7616	6155	7255	**7337**

[1]Per conversation with M. Langholtz based on historical pulpwood prices in Southeast (2014).

[2] The reason the wood residues are so much higher is that we waste 40% of the material therefore driving up the costs.

[3] Pulpwood uses a debarker/delimber, while residues use a trommel screen. Throughput is the same through the chipper. Debaker/delimber is an expensive piece of equipment versus a trommel.

[4] Pulpwood has a longer transport distance because we need more material and there is lower participation than the other crops. Therefore increasing the draw radius for pulpwood and corresponding costs.

[5]Not currently a quality standard but could be included in future designs.

For the 2017 Design Case scenario located in South Carolina, it worked out that both the cost and quality criteria could be achieved through blending. However, there may be other scenarios where reaching the 1% ash specification for fast pyrolysis conversion will require the removal of silica. Methods for accomplishing silica removal include both fine grinding followed by triboelectrostatic separation and alkali-based processes that dissolve silica (CENNATEK 2011). A recent analysis for non-woody feedstocks estimated a net cost of $39.93 to $60.80/dry T for removal of alkali metals (up to 95%) by leaching, followed by removal of silica (up to 75%) by triboelectrostatic separation (CENNATEK 2011). With an $80/dry T feedstock cost target, these costs are too high to allow the use of chemical preconversion as an added unit operation in the current design; the existing feedstock supply chain operations and the grower payment leave little room for added cost. A detailed discussion of a chemical preconversion for ash removal is included in Appendix B. Therefore, for this report, we have selected feedstocks that can meet the ash specification in a blend with clean pulpwood and C&D waste.

The moisture and carbohydrate content of the blended feedstock also meet the specification for moisture content (i.e., less than 20%) and carbohydrate content (i.e., at least 59%). Because each blendstock is pelletized prior to blending, the pellets are dried to about 9 to 10% during pellet production, thereby fixing the moisture content of the blend.

5. CONCLUSIONS

Figure 20 below illustrates the current State of Technology and economics to supply feedstock to a fast pyrolysis conversion facility. This report presents a design for achieving the 2017 target of delivering an on-spec feedstock to the conversion facility at a modeled cost of $80/dry T for Fast Pyrolysis conversion to bio-oils (Table 17). In order to move from the current modeled estimate of over $100/dry T, the INL is proposing changes from the conventional supply system to an advanced high-density, stable, flowable biomass supply system that will achieve the cost targets. These improvements include improvements to comminution, such as fractional milling, high moisture densification, improved storage methods, qualifying C&D wastes as a feedstock, and blending/formulation. The least-cost formulation approach presented in Section 2 illustrates the importance of cost estimates for determining the total cost of feedstock to a biorefinery, including grower payment (access costs), logistics costs, and quality/dockage cost. It also illustrates the importance of refining and updating these costs as analyses and data improve to better inform the estimates. The following conclusions are presented to document the specific areas that require additional attention to further strengthen and support the feedstock design detailed in this report.

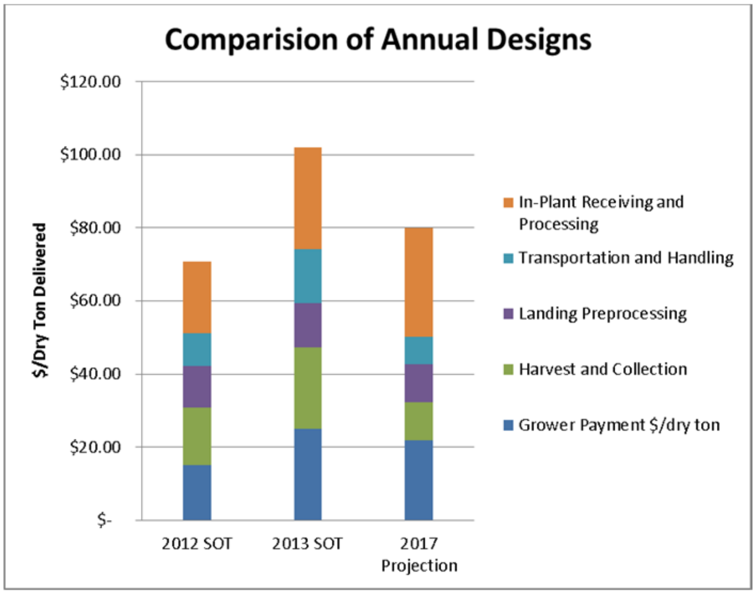


Figure 20. This chart compares the annual feedstock logistic costs from 2012 and 2013 State of Technology (SOT) Reports and the 2017 projection. Note: 2012 SOT did not include active quality control systems or the new competition grower payment.

Continued refinements of the biomass supply curves to represent the latest estimates for biomass grower payment are needed to support the least-cost formulation approach. Ultimately, translating *The Billion Ton Update* (U.S. DOE 2011) data from farm gate price to grower payment is necessary to establish better grower payment estimates. The grower payment estimates included in this report were calculated by subtracting our harvest and collection and chipping costs from the farm gate price.

Logistics costs are modeled based on field and lab data but do not include the cost of various business elements, such as profit margins for transportation, depots and field agents that would be involved throughout a biomass feedstock supply chain. This would increase the overall cost of the supply system than is demonstrated in this report. This was of little consequence to the 2012 Conventional Design Case target that intentionally focused only on logistics costs. The 2017 Design Case, on the other hand, is meant to encompass total delivered feedstocks costs. Further, the complexity of a blended feedstock approach may introduce multiple business elements into the supply chain; therefore, it is important that logistics costs be updated to include the true cost of these business elements, including a return on investment.

As the biomass logistics systems become more complex, especially with the introduction of new technologies (e.g., chemical preconversion), it may be prudent to differentiate between the current state-of-technology costs and the projected costs of mature technology (n^{th} plant costs, to be consistent with conversion platform terminology). This was not an issue with conventional feedstock designs that were intrinsically tied to current state-of-technology; however, for technology maturation, cost reductions may be worth considering for advanced feedstock designs.

Admittedly, it also is necessary to tighten the design and cost estimates around formulation and the engineering systems for crushing the pellets and blending prior to insertion into the conversion process. A better understanding of C&D availability, cost, and conversion performance is needed to solidify its position in the 2017 Design Case. Likewise, the viability of blended feedstocks as a whole depends on their conversion performance. BETO funded research is investigating the conversion performance of blends (including C&D blends) and evaluating the compatibilities and incompatibilities of blendstocks. The results of this research are critical to further development of blended feedstocks.

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Appendix A

Construction & Demolition Waste

Construction and Demolition (C&D) waste is a potential feedstock for the thermochemical pathways. This stream consists of waste materials generated during construction, renovation, and demolition from both residential and non-residential sources. In a 2009 report (EPA530-R-09-002), the Environmental Protection Agency (EPA) estimated that approximately 170 million tons of C&D waste was generated in 2003 in the United States, going to an EPA-estimated 1,900 C&D landfills, although more recently many localities are setting recycling targets for C&D projects (http://www.nyc.gov/html/ddc/downloads/pdf/waste.pdf). The composition of this waste stream is primarily wood, drywall, metal, plastics, roofing, masonry, glass, cardboard, concrete, and asphalt debris. The relative amounts of these materials vary greatly depending on the relative percentages of new construction versus renovation and demolition, as well as the type and size of structures being built, renovated, or demolished. The only fraction relevant to a biorefinery would be the woody material that consists of both untreated and treated (e.g., painted, stained, or varnished) materials. It is currently unknown whether the treated material would affect downstream processing of these materials in a thermochemical process.

C&D waste generally is not part of the residential MSW stream and is handled by construction contractors. In some locations, onsite sorting occurs by the contractors and the untreated woody fraction would be readily available. An internet survey of landfills and transfer stations showed that those facilities will only receive untreated woody material and generally compost these materials. These facilities also would be a source for this material. In areas where onsite sorting does not occur, some type of sorting to remove non-woody materials would be required. In the given study area potential C&D waste availability was determined by the South Carolina Solid Waste Management Annual Report 2012. (Table A-1)

Table A-1. Potential C&D available in select counties in western South Carolina.

County	Potential C&D Waste (tons)
Aiken	32553.2
Edegfield	2406
Fairfield	0
Greenwood	3688.4
Kershaw	13766.8
Laurens	7504.4
Lexington	52146.4
Newberry	3335.6
Richland	79640.8
Saluda	150.4
Total	195192

Table A-2. Physical parameters of solid waste.

Fraction	Moisture (%)	Ash (%)	Carbohydrate (%) (glucan+xylan)	Pretreatment Severity	Sorting Required?
Yard waste	43	28	46	More severe pretreatment may be needed3	No, if curbside recycling is in place
Food waste	37	NA	64	No pretreatment needed4	Yes
Non-recyclable paper	5	195	56	Lower severity pretreatment needed5	Yes
Untreated C&D wood	13	6.5	62	Higher severity pretreatment required6	Yes, unless onsite sorting occurs

[1]Valkenburg et al. 2008
[2]Shi et al. 2009
[3]Gustafson et al. 2009
[4]Yan et al. 2012
[5]Unpublished data generated at INL
[6]Cho et al. 2011 (includes mannan content)

The non-recyclable paper and untreated C&D wood are both below the target moisture content and can be readily blended with other herbaceous materials. With a final ash specification of <1% for the blended feedstock, only the C&D waste that has been treated by a wash stage could be used if blended with lower ash materials. It is estimated that the wash stage would reduce ash content down to about 1% and cost about $4.15/dry T making its application still cost effective.

Appendix B

Off-Spec Feedstock Dockage Approach

Ash serves no purpose in a conversion process, and in fact will result in additional costs for disposal, machine wear, and potential negative implications on the process itself. In order to mitigate these costs, they must be subtracted from the purchase payment of biomass that contains unacceptable levels of ash contamination. This milestone report demonstrates the potential impact of off-spec ash content in a traditional, well vetted liquid fuel conversion system.

The analysis below was based on the costs presented by Humbird (2011) where feedstock procurement is priced at 58.50 $/DMT. Disposal of ash was applied at 28.86 $/dry T of ash. The ethanol conversion yield of 79 gal/dry T was used to estimate non-enzymatic manufacturing costs and capital costs at 23.94 $/dry T and 13.83 $/dry T, respectively. The analysis assumes that ash content is measured at the point of sale between a feedstock supplier and refinery (exchange-point), and payout is based on the delivered material's quality compared to a baseline feedstock containing 5% ash. It was assumed that production quality and quantity must be maintained, such that the decreased yield resulting from off-spec (high ash) feedstock will require additional biomass to be purchased and processed to match the yield anticipated from baseline feedstocks. Five individually calculated dockages encompass the reduced value of off-spec materials: (1) the decrease value of above-baseline feedstocks due to mass displacement by ash; 'off-spec doc', (2) the cost of additional ash disposal; 'disposal doc', (3) the cost associated with sourcing additional feedstock; 'replacement doc', (4) the added cost of processing more material on manufacturing expenses; 'manufacturing doc', and (5) the cost of capital expansion from handling addition quantities of material; 'capital dock'.

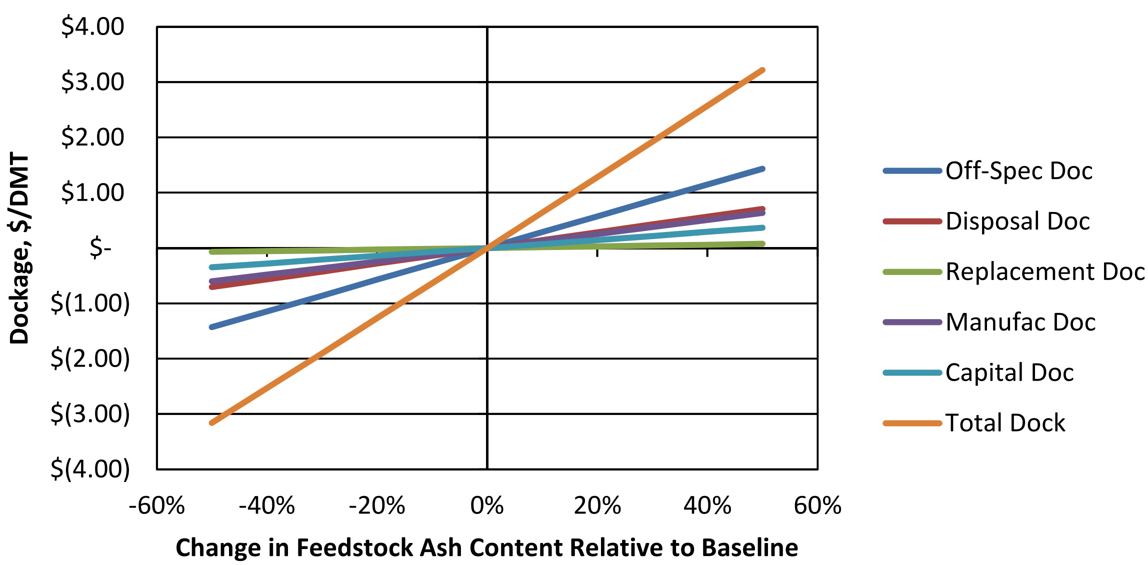

Figure B1**.** Sensitivity of dockage by altering feedstock ash content relative to the baseline ash content of 4.9% (Gresham, 2013).

The off-spec dockage was found to be the greatest contributor to the total dockage (45% of the total dockage), and the most sensitive to increases in delivered feedstock ash content followed by additional disposal (22% of the total cost; Figure B1, where a 50% relative increase in ash equates to 7.4% ash). This is important as the dockage associated with delivering off-spec material, accounting for additional disposal, and the cost of replacement are largely process independent and likely to be accounted for in the biomass supply and logistics cost basis. On the other hand, the estimates of manufacturing and capital are highly process dependent and thus subject to criticism for their inclusion in a feedstock delivery dockage. Furthermore, the argument can be made from this data that if a dockage is to be applied to material arriving above the baseline specification due to its decreased value, materials of value greater (i.e., ash content lower than the baseline) would in theory warrant a positive purchase price incentive. In the case of this data, a feedstock delivered at -50% relative ash content to the baseline (2.5% ash) would in essence qualify for a 3.16 $/dry T bonus on top of the baseline feedstock purchase price of 58.50 $/dry T. While this type of system has not yet been proposed for a commercial system, this type of financial motivation may provide further incentive for farmers to invest in single-pass technology as the material generated is truly of higher value to a conversion facility.

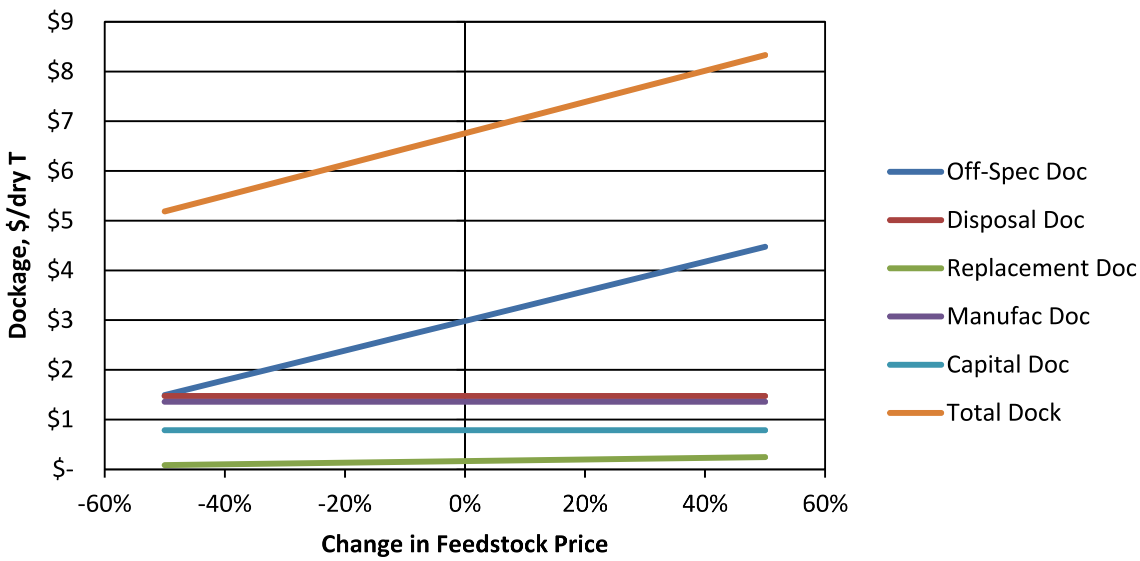

Figure B2. Sensitivity of dockage to altering feedstock price relative to the base case of 58.50 $/dry T for a delivered feedstock with 10% ash (Gresham, 2013).

To demonstrate the importance of a proper feedstock procurement cost, the analysis was conducted over a range of feedstock prices, from 29.25 $/dry T to 87.75 $/dry T (-50% to 50% change, respectively) for a delivered feedstock with 10% ash (Figure B2). The results clearly show the impact of feedstock price on off-spec dockage and ultimately total dockage, increasing the total dockage by 0.03 $/% relative change. When considering the 2017 Design Case target feedstock price of 80$/dry T (a 37%), the total dockage rises to 7.91 $/dry T for a 10% ash delivered material, where the off-spec dockage now accounts for 52% of the total dockage. This case exemplifies the ability of feedstock price to inflate off-spec dockage and potentially lead to a poor estimation of total dockage if the other costs associated with high ash are not appropriately modified as well.

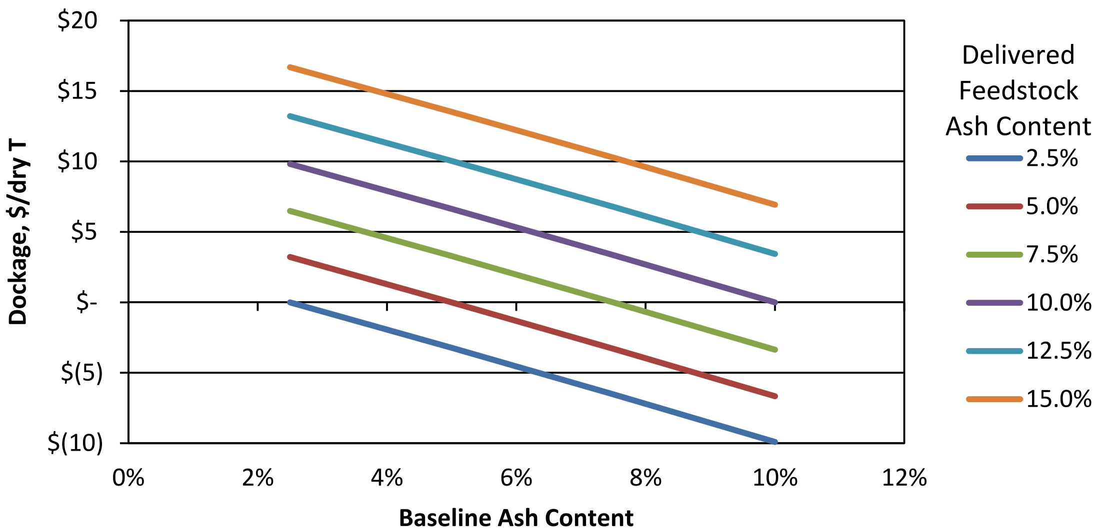

Figure B3. Total dockage based on shifting baseline ash content for a range of received materials at a feedstock price of 58.50 $/dry T (Gresham, 2013).

Finally, the analysis can be used to demonstrate the necessity of defining an appropriate baseline specification for ash content (Figure B3). Intuitively, as a baseline specification for ash content is raised, the dockage for above-spec material decreases. Figure B3 shows this rate of change at 1.30 $/% ash change for the highest ash material (15%) and increases to 1.32 $/% ash change for the lowest ash material (2.5%). This data stresses the importance of accurately determining the ash content at which the end user's process truly begins to incur additional operating costs. In the case of these examples, increasing the baseline ash content to 7.5% would reduce the dockage of a 10% ash delivered material by 50%. While it remains to be seen if the costs on material conversion are as sensitive to ash content as the current baseline suggests, this analysis shows the large financial implications to feedstock suppliers when material is compared against a strict specification.

These analyses clearly show the negative implications of off-spec ash content in the baseline conversion system chosen. That said, the variability in dockage with respect to the magnitude of contamination, the price of feedstock, and the baseline ash content highlights the importance of properly defining and assessing a particular modeled feedstock logistics and conversion system. Alternatively, because of the large variability in dockage, it is reasonable to suggest that raw feedstocks purchased by a conversion facility need only be assessed in terms of ash content and biomass content (i.e., 'material other than ash') for preliminary determination of a feedstock's value. More rigorous analysis of what the 'material other than ash' consists of is much less variable than the ash content, as discussed previously in this report, decreasing its relative importance in determining dockage and feedstock value.

Future Work

Foremost, efforts must build upon collaborative interactions with the biochemical and thermochemical conversion platforms to gain a better understanding of feedstock quality and conversion performance. Efforts must also focus on robust screening techniques and methodologies to verify feedstock quality. Relative to ash determinations, a bulk biomass screening tool that is easy to use, rugged, has low maintenance requirements and field-applicable is needed to better understand feedstock variability (temporal, seasonal), logistic and preprocessing intermediates changes and variability and options for mitigating impacts; bringing to bear all the “architectural’ requirement to support the biorefinery quality specification, and the initial and intermediate specifications that sustain those specifications.