Technical Memorandum

To:	Office of Biomass Program, US Department of Energy
Title:	Logistics Costs for the 2012 Conventional Woody Biomass Feedstock Supply for Thermochemical Conversion
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PURPOSE

The goal of this technical memorandum is to support the woody biomass logistics cost of $46.37/dry US ton, supplying biomass for the production of ethanol via gasification. The modeled feedstock is southern pine trees grown on a plantation. This cost target was achieved using a number of technologies and processes, including transpirational drying, pneumatic assist during comminution, ambient drying during storage, and a residence dryer that uses waste heat from the gasification process. Meeting this cost target of $46.37/DM ton supports the Department of Energy in meeting their 2012 cost target for biofuels production. Future designs will incorporate advanced design concepts which are required to make higher amounts of biomass available for biofuels production while meeting quality and cost targets.

BACKGROUND

To enhance energy security, the US Department of Energy (DOE) has put forth biofuels production goals, including the 20-in-10 goal (Bush 2007). When estimating biomass needs to reach this target, up to 700 million tons of lignocellulosic biomass is required annually to meet the 2017 ethanol production target (based on the conversion efficiencies cited in the biochemical and thermochemical technologies [Aden *et al.* 2002; Phillips *et al.* 2007]). To support a sustainable biorefinery industry, this biomass must be economically and reliably delivered to biorefineries at a specification appropriate for the conversion process. Pioneer refineries, which require much smaller biomass quantities than is needed in a mature biofuels industry, will rely on Conventional biomass supply chains that use existing or near-term equipment and processes. Conventional supply chains also rely on a specific, high-yield biomass scenario that is not typical in many areas. For woody biomass, the most likely woody biomass scenario for high-tonnage production is dedicated energy plantations in the U.S (Taylor *et al.* 2009).

The cost target set by DOE for the 2012 Conventional woody biomass scenario is $46.37/DM ton. The feedstock must also meet the material in-feed requirements of the modeled conversion process, gasification (Dutta *et al.* 2011). This report summarizes how this cost is achieved.

Biomass Supply Chain Design

A primary objective that drives Conventional biomass feedstock supply system design is the selection of technologies that are adaptable to existing local feedstock resources and biomass/forage infrastructures. Conventional designs represent feedstock supply system technologies, costs, and logistics that are achievable today for supplying biomass feedstocks to pioneer biorefineries. The general architecture of these designs locates the preprocessing operation inside the receiving gate of the biorefinery (Figure 1).

Figure 1. Conventional woody feedstock supply system designs rely on existing technologies and biomass systems to supply feedstocks to pioneer biorefineries and require biorefineries to adapt to the diversity of the feedstock.

Efforts are made to optimize the efficiencies and capacities of these conventional supply systems within the constraints of existing local feedstock supply, equipment, and permitting requirements. In reality, equipment, costs, and logistics could differ quite considerably from one conventional design case to the next. As such, conventional feedstock supply systems are specialty designs that are only replicable to the extent that other feedstock resources and local conditions are similar (Figure 2).

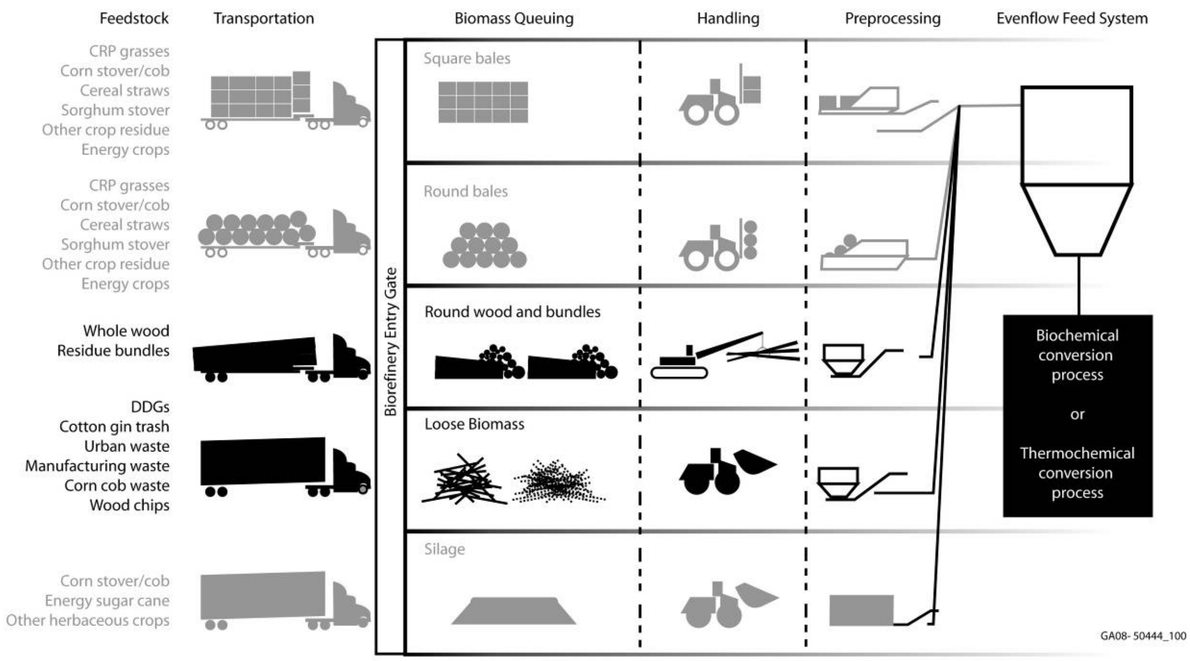

Figure 2. Conventional feedstock supply system designs are tailored for each facility and respective feedstock resource. No two are alike, and components are only replicable to the extent that feedstock sources and local conditions are similar.

These Conventional designs tend to be vertically integrated with a specific conversion facility, and the supply system infrastructure and conversion facilities are dedicated to the predominant local feedstock species and formats. In the case of biorefineries that can receive more than one feedstock or feedstock format, a feedstock-receiving system is constructed for each feedstock type and format that the biorefinery accepts. The result is duplicate supply system infrastructures that are either under-used or, if fully used, require contracting and feedstock supply delivery schedules that balance the required throughput for each feedstock format. These designs work today because they adapt to the local available biomass resources and facilitate producer participation by (1) minimizing perturbations to their present operations and (2) reducing the investment risks associated with new and unproven supply system equipment.

In Conventional designs, the burden of adapting to feedstock resources is assumed primarily by the biorefinery as each is designed for a specific feedstock or set of feedstocks. As conventional designs emerge, supply logistic operations will be performed by a co-op of land owners, federal agency managers, timber and pulpwood industry, and/or, eventually, large commodity-handling businesses. Over time, these operators will select and invest in more efficient and higher capacity equipment and technologies. The supply systems will then begin to handle more of the feedstock diversity issues, allowing conversion technology development efforts to focus on biomass compositional and recalcitrance diversity and continue working towards improved efficiencies and capacities.

Material Specification Required

An important consideration when designing a biomass feedstock supply system is the quality of material that is delivered to the biorefinery. In the case of the modeled 2012 Conventional woody feedstock supply system that meets the cost target of $46.37, the biomass is delivered to the in-feed of the conversion reactor at a specific moisture (10% (w.b.)), ash content (<1%), and particle size (2 in.). This is a very important characteristic of the biomass supply system, as conversion efficiencies rely on feedstock that consistently meets their in-feed requirements. For the Conventional woody scenario, a gasification process modeled by the National Renewable Energy Laboratory is used to determine the required material specification (Phillips *et al.* 2007). Note that by adding an additional grinding stage at the biorefinery, the biomass material produced in this design can also meet the fast pyrolysis infeed specifications (Jones *et al.* 2007). However, the second grinding stage at the biorefinery after drying the biomass down to 10% would add additional cost.

The scope of the 2012 Conventional woody feedstock supply system is restricted to currently available technologies and existing infrastructure, regardless of the geographical region in which the biorefinery operates. For this design, the modeled feedstock is woodchips derived from southern pine trees harvested on private commercial lands. The trees are delimbed and debarked, as is common in pulpwood operations.

2012 CONVENTIONAL WOODY SUPPLY CHAIN DESIGN

Woody biomass feedstock supply system costs include all logistics costs associated with the harvest and collection, receiving and handling, transport, storage, and preprocessing necessary to deliver the biomass to the in-feed of the conversion reactor at the appropriate material specification.

Several key feedstock format and machinery attributes have been identified that influence the processes within the supply system. From a cost, performance, and logistics perspective, each attribute becomes an input and/or constraint on the supply system that must be considered to design a viable supply system capable of meeting the needs of a biorefinery. The modeled feedstock system is designed to supply a biorefining facility with 800,000 DM tons of biomass annually (Table 1). The supply system design is considered appropriate for both biochemical (Aden *et al.* 2002) and select thermochemical (Phillips *et al.* 2007) conversion facility designs that depend on a year-round biomass delivery schedule. However, the feedstock is formatted to be compatible with gasification and pyrolysis conversion systems.

Table 1. 2012 Conventional woody supply system design size annual capacity assumptions for woodchips.

	Woodchips
Plant Operation Size (delivered tons[a])	800,000 DM tons per year
Acres Harvested Annually	40,800 acres per year
Participating Acres	100%
Acres Available for Contract	90%
Cultivated Acres	90%
Feedstock Draw Radius[b]	5.8 miles
Distance from Landing to Biorefinery	50 miles

a. U.S. short ton = 2,000 lb.

b. Assume an equal distance distribution of acres throughout the draw radius.

The 2012 Conventional woody system aims to provide a consistent, uniform chip to customers. Challenges in achieving a uniform woody biomass supply include, but are not limited to, developing machines for efficient harvest of trees in a range of topographies and conditions, developing machines and operating plans for comminuting biomass as near the stump as possible, developing cost-effective drying strategies to reduce losses and mold growth during woodchip storage, and quantifying environmental impacts of biomass to aid landowner decisions and policy development.

In the 2012 Conventional woody scenario, the emphasis is on cost-effective removal of trees of approximately 7 - 10" diameter. The modeled annual biorefinery capacity is 800,000 DM tons of material and all material will be acquired from southern pine pulpwood plantation, approximately 8 years old, with a per-acre yield of 30 green tons at an assumed harvest moisture content of 50%. The biomass removal limit is assumed to be 95%. 90% of the land is assumed to be forest land, 90% of the producers are assumed to be pulpwood size trees, and 100% of the producers are assumed to be participating. Figure 3 outlines the 2012 Conventional woody design.

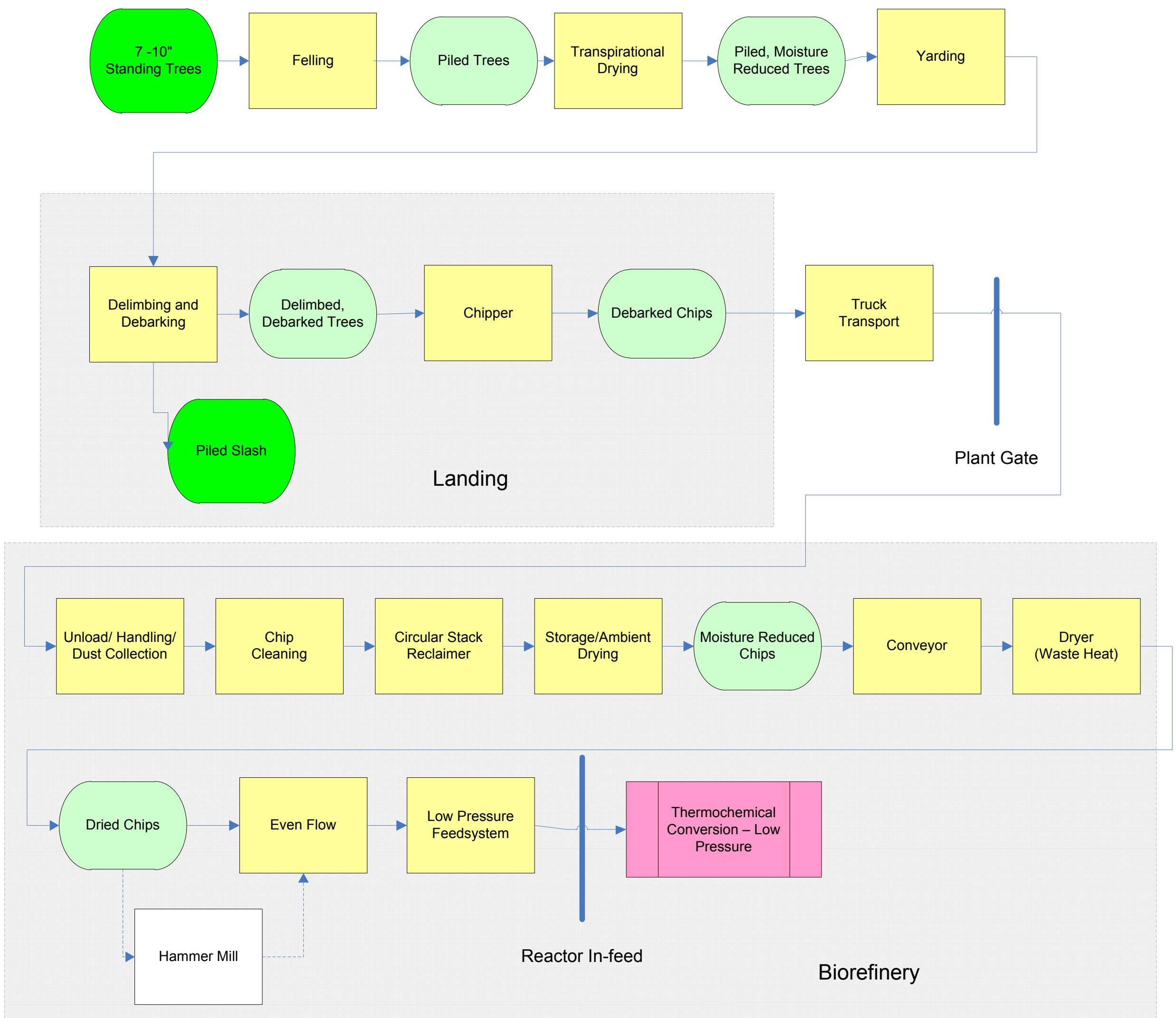

Figure 3. Feedstock logistics supply system for the 2012 Conventional woody for conversion via gasification. The trees are cut and brought to the landing where they are debarked and delimbed, then chipped and sent to the biorefinery for further preprocessing. Note that the ratio of the number of pieces of equipment shown is not 1:1 (i.e., there are, for example, more feller bunchers than chippers. The number of equipment is sized by the operation window and equipment operating capacity). Green boxes represent format intermediates, while yellow boxes represent equipment.

Standing southern pine trees are cut with an average diameter at breast height (DBH) of 7–10 inches using a feller buncher with an accumulator arm. Material is harvested 8 hours per day, 5 days per week, and 50 weeks per year. The cut trees are piled on the ground and transpirationally dried from 50% MC to 40% MC. A grapple skidder drags the piled trees to the landing, where a 3 chain flail equipped with a debris grapple on the end that loads material from the deck into the flail shredder. The debarked, delimbed logs are fed into the chipper which produces a 2 inch[a] chip, and has a rated capacity of 50 green tons per hour and an operating capacity of 21.25 green tons per hour. Chips are ejected from the chipper directly into a 45 foot Western Trailer flat floor chip trailer, and once the truck reaches capacity the material is taken an average of 50 miles to the biorefinery. The biorefinery operates 24 hours per day, 7 days per week. At the biorefinery, the truck is weighed and a truck dumper unloads the truck into a hopper. A dust collection system is present during unloading to prevent excessive dust accumulation. The chips are cleaned using an electromagnet, moisture is monitored, and material is conveyed into a pile using a circular stacker and overpile reclaimer, combined with an underpile. A five day supply of material is stored at the refinery[b]. The pile, which acts as a queue, is on an asphalt pad with a long grate running through it that allows material to flow out of the pile. A front end loader continuously pushes material onto the grate to maintain flow. A conveyor located at the bottom of the pit under the grate conveys the biomass into a waste heat, residence time drier, where the biomass is dried to 10% moisture content. From the drier, the biomass is conveyed into a metering bin where it is fed into the conversion process. Dry matter loss is assumed to be negligible during transport, receiving and handling, queuing, and drying.

Cost Modeling

The 2012 Conventional woody design is modeled in the Biomass Logistics Model (BLM) developed by INL, and supports the achievement of the $46.37/DM ton cost target. The calculated cost is a combination of ownership costs, operating costs, and dry matter losses. Installed Capital cost reflects the investment in equipment required for the supply system operation per dry ton of annual capacity. The BLM incorporates a combination of values and relationships obtained from other national laboratories, publications, consultation with academics and staff from the U.S. Department of Agriculture Forest Service, and published and unpublished INL data. Inputs into the model include:

Equipment and Building Costs

- Ownership costs
  - Annual depreciation
  - Interest on the value of the machinery and equipment
  - Property taxes on equipment
  - Insurance
  - Housing (e.g., equipment shed)
- Operating costs
  - Repair and maintenance
  - Fuel (diesel an electricity)

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a. The biomass is ground using a 2” screen to meet feed requirements for both gasification (Phillips *et al.* 2007) and feed requirements of the hammermill used to produce a 2 mm grind

b. Note that storage losses due to material degradation are assumed to be negligible due to the short queuing period of seven days. Chips are stored at 40-50% MC for longer periods will have a monthly dry matter loss of approximately 1-4 %, depending on the storage environment and local climate (for example, see Hamelinck *et al.* 2005, Suurs 2002, Pottie and Guimier 1985, Hall 2009), although figures of around 1-2 % per month are common (Hall 2009, Hamelinck *et al.* 2005).

- Other Materials
- Labor

Variables Examined

- Feedstock Variables
  - Biomass Yield
  - Biomass Removal Limit
- Harvest and Collection Variables
  - Harvest Window
  - Field Losses (Harvest Efficiency)
  - Machine Field Speed/Capacity
  - Machine Field Efficiency
  - Biomass Moisture at Harvest (e.g., standing tree moisture)
  - Biomass Bulk Density (e.g., tree pile or chip density)
  - Distance to Landing
- Storage Variables
  - Dry Matter Loss in Storage
  - Machine (e.g., loader) Capacity
- Preprocessing Variables
  - Machine Capacity
  - Biomass Moisture
- Handling and Transportation Variables
  - Transport Distance/Winding Factor
  - Transporter Speed
  - Loader/Unloader Capacity
- Plant Receiving Variables
  - Receiving Hours per Day
  - Feedstock Inventory
  - Feedstock Bulk Density.

INL has used the feedstock supply system model to run sensitivity analyses, examining the impact of changing equipment performance parameters and material properties throughout the woody biomass supply chain. These analyses helped identify areas in which to focus future research. Ongoing and future work will focus on equipment used in the supply chain, order of operations, and material properties in order to build off of baseline cost estimates, will identify potential cost reductions that can be achieved with supply-chain improvements, and will develop feedstock logistics cost targets for future years will also be developed. Table 2 shows a summary of the costs associated with the Conventional woody design modeled in the BLM.

Table 2. Achieving the $46.37/DM ton cost target for the 2012 Conventional woody design for conversion via gasification). Costs are in 2007 USD. Note that "Depot Preprocessing" occurs at the landing. In many cases, the performance of one supply system process is significantly impact.

	Gasification Cost ($/DM ton)
Total Feedstock Logistics (Harvest through insertion to conversion reactor inlet)	***$46.37***
Harvest and Collection	
Total Cost Contribution	$18.75
Capital Cost Contribution	$5.60
Operating Cost Contribution	$13.15
In-Field Preprocessing	
Total Cost Contribution	$11.42
Capital Cost Contribution	$4.20
Operating Cost Contribution	$7.22
Transportation and Handling	
Total Cost Contribution	$8.95
Capital Cost Contribution	$2.95
Operating Cost Contribution	$6.00
Plant Receiving, Storage and Queuing, and In-Feed Preprocessing	
Total Cost Contribution	$7.25
Capital Cost Contribution	$2.10
Operating Cost Contribution	$5.15

MEETING THE 2012 COST TARGET: $46.37/DRY TON

Harvest and Collection

The cost for the Harvest and Collection unit operation for the 2012 Conventional woody design is $18.75/DM ton. The design includes transpirational drying of the trees after felling from 50% moisture content to 40%. The lower moisture content decreases collection cost per dry matter ton, and improves the efficiency of equipment downstream. As is evident from the literature, the moisture reduction assumed from transpirational drying is a conservative assumption.

Effectiveness of Transpirational Drying

Transpirational drying is also known as sour felling leaf seasoning (which refers to the fact that much of the drying occurs in the leaves [Pottie and Guimier 1985]), leaf felling, biological drying, and delayed bucking (Stokes *et al.* 1993). Transpirational drying of trees has been shown to be effective at reducing moisture content prior to transportation from the landing.

In this process, felled trees are left for a period of time with the crowns intact. Trees naturally lose large amounts of water through their leaves through transpiration, which continues after a tree is felled if the branches and leaves are left on. This loss of water is known as transpirational drying and can significantly affect moisture concentration in most species of felled trees, depending mostly on the season of felling, species, and tree diameter (Johnson and Zingg 1969, Hubbard 2007). Tree tissues are designed to transport water longitudinally, but also contain specialized structures that transport water transversely. Bark is a barrier to water movement when present; consequently, debarked logs will air dry more quickly than logs covered in bark (Brackley 2009, Nurmi and Lehtimaki 2010). Also, in-field drying increases needle and leaf loss, which returns nutrients to the soil (NIC 2008, Hartsough *et al.* 2002). Transpirational drying is not commercially utilized in the southeast U.S. because it has not been desirable for southern pine lumber or pulp production (Taylor *et al.* 2009).

There is a variety of data on the effectiveness of transpirational drying, varying by region, species, age of tree, and duration of drying. INL conducted a study in the fall of 2010, transpirationally drying small diameter (4” DBH) pine trees outdoors in Mud Lake, Idaho. The trees dried from an average initial moisture content of 48.80 % down to an average final moisture content of 22.88 – 24.41%. A recent study by Klepac *et al.* (2008) showed significant moisture reduction via transpirationally drying in Alabama in plantation-grown 4.5 to 6.5 inch DBH Loblolly pine trees. The study showed significant drying both in the winter and summer months (Figure 4). The study looked at both whole trees and delimbed trees.

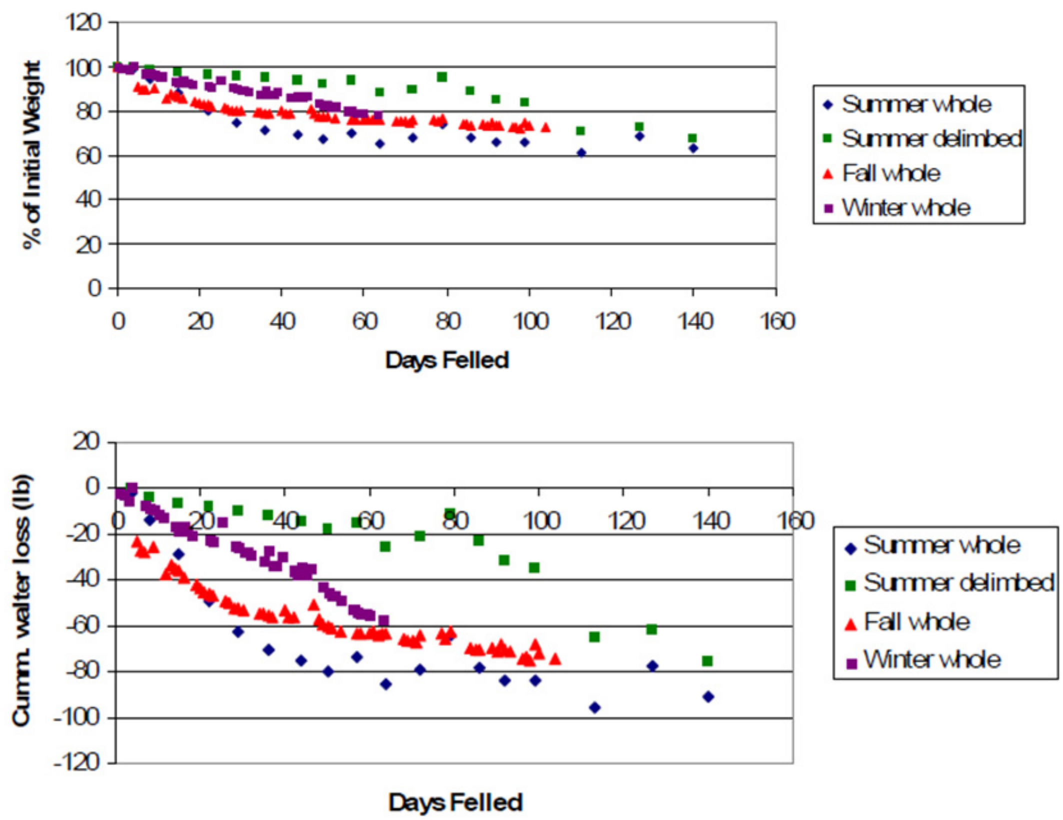

Figure 4. Drying trends observed in Loblolly pine in Alabama. The top graph shows tree weights as a percentage of initial weight by season, and the bottom graph shows cumulative water loss for total days felled for each season.

During summer drying, whole-trees lost a maximum of 37.2 % of their initial weight, compared to 33.2 % for the delimbed trees. Initial weight loss of whole-trees occurred at a higher rate compared to delimbed trees. For fall drying, trees averaged a 27.7 % loss in weight over a 104 day drying period. Winter trees (dried October to January 2007) lost 21.6 % of their total weight over a 63 day drying period (Klepac *et al.* 2008). Figure 5 shows an example of trees transpirationally dried in Alabama.

Figure 5 A bundle of transpirationally dried trees in Auburn, Alabama (photo credit: Christopher Wright, INL July 2010).

Patterson and Post (1980) found that paper birch trees have a significant moisture loss. Rogers (1981) found that in-field drying for three months after felling in the winter in eastern Texas decreased heartwood wood moisture content (OD basis) of loblolly pine, white oak, and sweetgum trees by 50.1, 7.0, and 11.5%, respectively. The sapwood moisture content for the same species decreased by 60.1, 23.8, and 28.5%, respectively. Lawrence (1981), studying transpirational drying in Virginia, also found the highest rates to be immediately after felling. Under optimum conditions, much higher drying rates have been found. For example, Scandinavian studies have shown moisture content reduction of 40-50% initial MC to 30-35% final MC for birch, and from 25-50% for spruce within the first two weeks (Pottie and Guimier 1985). Hall (2009) dried larger logging residues, stored as individual pieces with no ground contact, in the field from approximately 60% initial moisture to 30% in 24 weeks in the summer in New Zealand; stems in the same pile and of the same starting moisture dried to 40% final MC.

Sinclair *et al.* (1984) determined the approximate time frame for a strong and consistent drying trend in aspen tops remaining after traditional harvest (April) in Northern Minnesota. In this study, merchantable aspen tree tops were transpirational dried in Minnesota from April to November, and moisture content was sampled at monthly intervals. The average moisture content of the tops felled in April dropped from an initial moisture content of 99% to 42% (oven dry basis) at the end of July. However, trees felled in July only lost moisture in the first month, dropping from an average of 90% to 47% (oven dry basis), before settling at approximately 48% MC in the second month.

Drying is less effective if the trees are stored in piles or in the shade (Pottie and Guimier 1985). Storing trees in piles reduces convective moisture loss, and the shade reduces radiative moisture loss from warming. Thinner trees will dry more than thicker trees (Hall 2009). Excessive precipitation or low temperatures may hinder the efficiency of transpiration drying, if on-site storage is extended to late fall or even until winter in temperate countries (Hubbard 2007).

Cost Savings from Equipment Improvements

The 2012 Harvest and Collection cost incorporates equipment efficiency improvements achieved as a result of recent research studies. In earlier designs, harvest and collection efficiency were each assumed to be 65%, with trees at a moisture content of 50%. The modeled feller was a rubber-tired, four-wheeled, drive-to-tree feller buncher. Although these units have relatively low capital cost and are very productive, the ground pressure of the tires can produce unacceptable rutting when soil conditions become too soft, and therefore their use is weather-limited (Taylor *et al.* 2009). Improvements in the Harvest and Collection operation were drawn from hypotheses in the USDA funded research project "High Tonnage Forest Biomass Production Systems from Southern Pine Energy Plantations", with principal investigators Steve Taylor (Auburn University), Robert Rummer (US Forest Service), and Frank Corley (Corely Land Services), commenced in 2009. In the 2012 Conventional woody scenario, the harvest and collection efficiency were assumed to be 80% and 75%, respectively. The trees are harvested at a moisture of 50%, and then dragged to the landing at a moisture content of 40%. As described above, this lower collection moisture results in some efficiency gains during collection. Also, this design incorporates a track-type feller buncher. Compared to the feller used in an earlier design, track-type fellers exert very low ground pressure and therefore can operate in a wide range of soil and weather conditions (Taylor *et al.* 2009). Productivity is only marginally affected by weather, and they are rarely unable to work due to weather. Also, the track-type swing-boom carrier can reach a large circular area of trees from a single standing position, greatly reducing the amount of ground surface area contacted by the machine, and therefore greatly reducing environmental impacts of the felling operation. Finally, swing boom machines are more productive than drive to tree feller bunchers (Taylor *et al.* 2009).

The biomass delivery system proposed in the USDA-funded project mentioned above included felling of trees using track-type, swing-to-tree feller bunchers with new design features to enhance productivity, reduce energy consumption, and reduce operator fatigue. New geospatial tools were used to provide feedback on productivity and assist in product quality monitoring; as well as skidding of trees using wheeled skidders with high volume grapples normally installed on larger skidders (Taylor *et al.* 2009). Engineers with Tigercat completed the design of the track-type feller buncher and the wheeled skidder. New design features incorporated include (Taylor *et al.* 2009):

A. Automation of the tree accumulation process to increase machine productivity and reduce operator fatigue;

B. Further development of a small tree specific felling attachment to reduce the power consumption of the tree grabbing and accumulation arm functions;

C. Further development of the felling attachment to effectively cut and accumulate smaller hardwood and other volunteer woody species in conjunction with the intended pine harvest to increase site yield;

D. Implementation of an energy recovery type slew drive system on the excavator swing mechanism to significantly reduce fuel costs and increase net available engine power to boost productivity of other machine movements;

E. Use of a slightly smaller track-type machine than is used in short-rotation eucalyptus plantations (since pine plantations will have smaller trees) to help reduce the mass of the rotating structure and therefore reduce fuel consumption and fatigue loading on the machine;

F. Implementation of telemetric monitoring, recording, and analysis of machine performance data to provide information for the machine operator and manager so that they can implement practices to reduce fuel consumption, increase productivity, and reduce overall system costs; and

G. Implementation of additional energy storage techniques that capture energy as trees are deposited on the ground in bunches and then use this stored energy to help bring the felling attachment back to the upright position.

The skidder to be tested as part of the harvesting system will be a Tigercat wheeled skidder with high capacity grapples. New design features to be incorporated on the skidder include:

A. Implementation of high capacity grapples to accommodate the maximum number of small diameter stems;

B. Implementation of new seating systems that allow the operator to turn completely around and continue driving the machine in reverse with the same set of joystick controls;

C. Implementation of telemetric monitoring, recording, and analysis of machine performance data to provide information for the machine operator and manager so they can implement practices to reduce fuel consumption, increase productivity, and reduce overall system costs; and

D. Implementation of additional energy storage techniques that capture energy as the grapple is opened and then use this stored energy to help close the grapple more quickly to speed skidder operation.

Based on these improvements, an initial increase in harvesting productivity by 15 % was incorporated into the 2012 Conventional woody design (Taylor *et al.* 2009), and improvements in collection efficiency of smaller diameter trees through better piling techniques and different grapple heads to increase collection efficiency by 10% (Taylor *et al.* 2009)

Storage and Queuing

Cost savings incurred from operations relating to the storage and queuing of biomass are considered under Plant Receiving and In-Feed Preprocessing operation.

Depot Preprocessing

The Depot Preprocessing cost for the 2012 Conventional woody biomass scenario is $11.42/DM ton. This cost incorporates an increase in chipper efficiency due to the incorporation of pneumatics. This step also decreases the moisture content of the material, which results in cost savings later in the supply chain.

Pneumatic separation can enhance chipper performance by removing finer particles, while simultaneously drying the material. Comminuted material flowing through the chipper/grinder has a large amount of exposed surface area, and the chipper or grinder engine releases heat that is not captured in current designs. Using waste heat from the chipper engine to heat the air used in the pneumatic separation system, additional drying of the chips could be achieved. The resulting moisture reduction could assist in minimizing downstream costs, including transportation, handling, receiving, and finally storage, due to reductions in both moisture weight and dry matter losses. An additional benefit is that the fine particulates that is pulled off during pneumatic separation is known in many cases to have higher ash content than the larger particles, due to more dirt and bark in the smaller size fractions. Consequently, the separation is also potentially an ash reduction technique.

INL conducted a series of test to compare the performance of a HG200 comminution system with a chipper drum installed to compare performance with and without pneumatic assist. The effectiveness of ash removal, drying, and comminution performance was documented using woody biomass harvest in Utah. Whole tree, baled pinyon juniper was selected as a test feedstock due to its high ash content. Although limited effort was applied to optimize system performance by testing a variety of flow rates and comminution screen size, the test showed that pneumatics increased capacity for both the chipper and grinder (Figure 6, Figure 7) and increased drying in comminuted material (Figure 8).

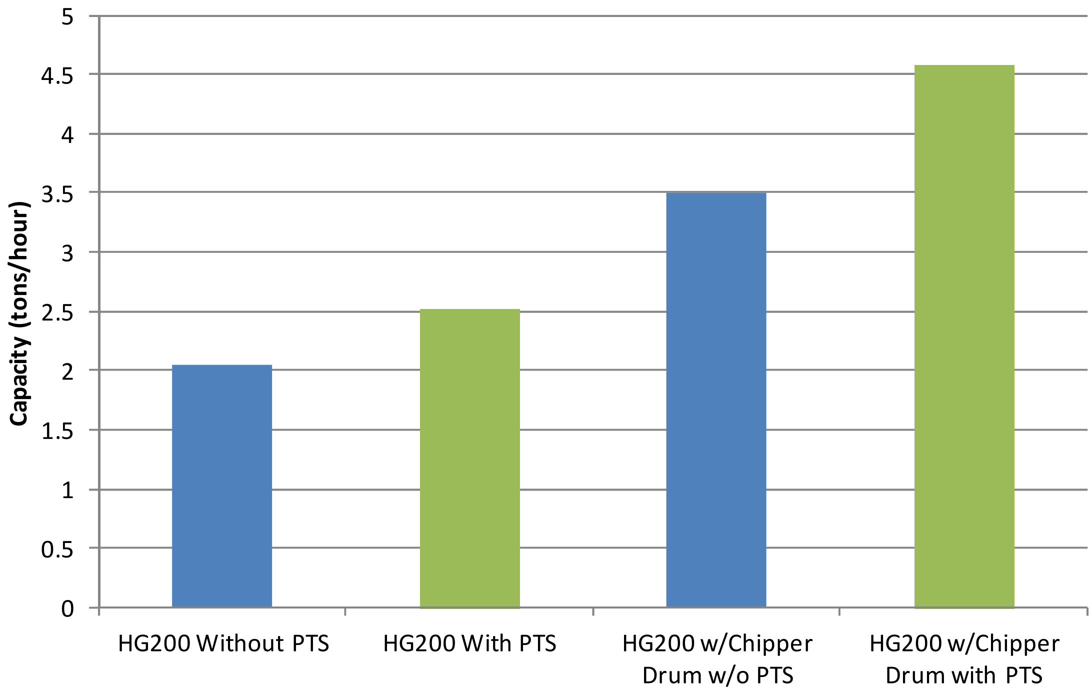

Figure 6. Improvement in grinder and chipper capacity (tons of through put per operating hour) for woody biomass as a result of adding pneumatic assist during comminution. "PTS" refers to the pneumatic transfer systems used.

From Figure 6, the capacity of both the chipper and grinder were increased by incorporating pneumatics in to the comminution operation. The increase in capacity was slightly higher for the chipper than the grinder (23% increase for the chipper, compared to a 20% increase from the grinder), however both systems displayed an increase beyond the 18% improvement assumed for the 2012 Conventional woody design. A possible reason that the biomass throughput was higher for the chipper than for the grinder both with and without pneumatics is that the drum of the chipper is much heavier and carries more momentum. Pneumatics had a larger impact on increasing biomass throughput in the chipper than on reducing energy consumption, however the pneumatics resulted in a similar proportional impact on increasing throughput and reducing energy consumption for the grinder (Figure 7).

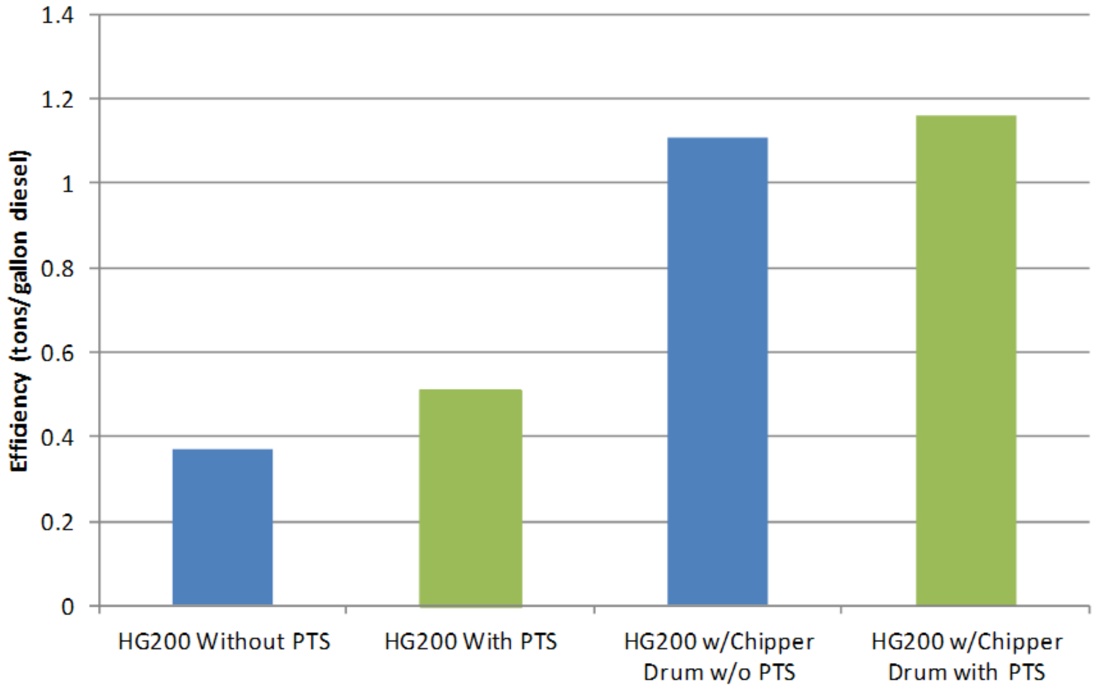

Figure 7. Improvement in grinder and chipper efficiency in tons of biomass throughput per gallon of diesel consumed for woody biomass as a result of adding pneumatic assist during comminution. "PTS" refers to the pneumatic transfer systems used.

Chippers have higher energy consumption than grinders per unit biomass throughput (see, for example, Pottie and Guimier 1985). The pneumatic assist reduced diesel consumption for both the chipper and the grinder (Figure 7). The reduction in diesel consumption was less for the chipper than for the grinder (approximately 4% as opposed to 24%).

Moisture content was reduced during comminution both with and without pneumatic assist (Figure 8). The initial moisture content of the pinyon juniper before comminution was approximately 22%. After comminution, the moisture content varied between 17% (chipping without pneumatic assist) and 11% (grinding with pneumatic assist). All scenarios demonstrated a moisture reduction of more than the 5% assumed in the 2012 Conventional woody biomass design scenario with the incorporation of the pneumatic assist.

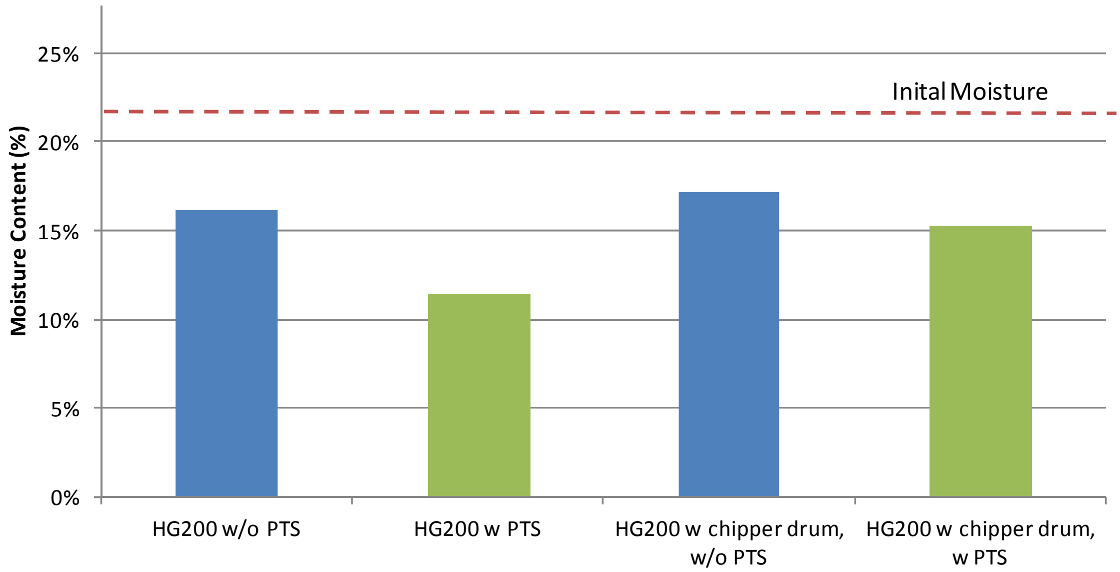

Figure 8. Change in moisture content during comminution using pneumatic assist. “PTS” refers to the pneumatic transfer systems used.

From the limited runs performed, the impact of pneumatics in reducing ash content during the comminution operation was unclear. The pinyon juniper tested was very heterogeneous, containing a mixture of needles, bark, large sticks, smaller pieces, etc., and therefore it was difficult to get a representative sample of ash content of the material. This heterogeneity is reflected in the high standard deviation, which in some cases was over 30%.

Ash reduction was higher for the grinder than the chipper, which is expected. Grinders operate using a high-speed impact to shatter material, which provides strong shock stresses that can dislodge fine ash particles. The high-speed impact operation of a hammer grinder also shatters brittle materials, resulting in wide particle size distributions with a high content of fines that can be extracted with the pneumatic assist. Conversely, the sheer forces present in chipping operations produces a more consistent particle size (i.e., pieces are cut semi-uniformly rather than shattered), which is a primary reason that chippers are more commonly used in pulpwood operations than grinders. There is a strong body of literature that supports that the fines, in general, have higher ash content (for example, Bakker and Elbersen 2005, Obernberger *et al.* 1997, Bridgeman *et al.* 2006). A reduction in ash content is desirable for both thermochemical and biochemical conversion processes.

Incorporating pneumatics into comminution was effective for reducing moisture content and increasing comminution performance. However, the system was not optimized to achieve the greatest benefit. Future optimization could be accomplished by testing a variety of pneumatic airflow rates, grind sizes, and air temperatures. To estimate the potential for reducing ash reduction by extracting the fine particles, the ash content was measured for a variety of size fractions (Figure 9).

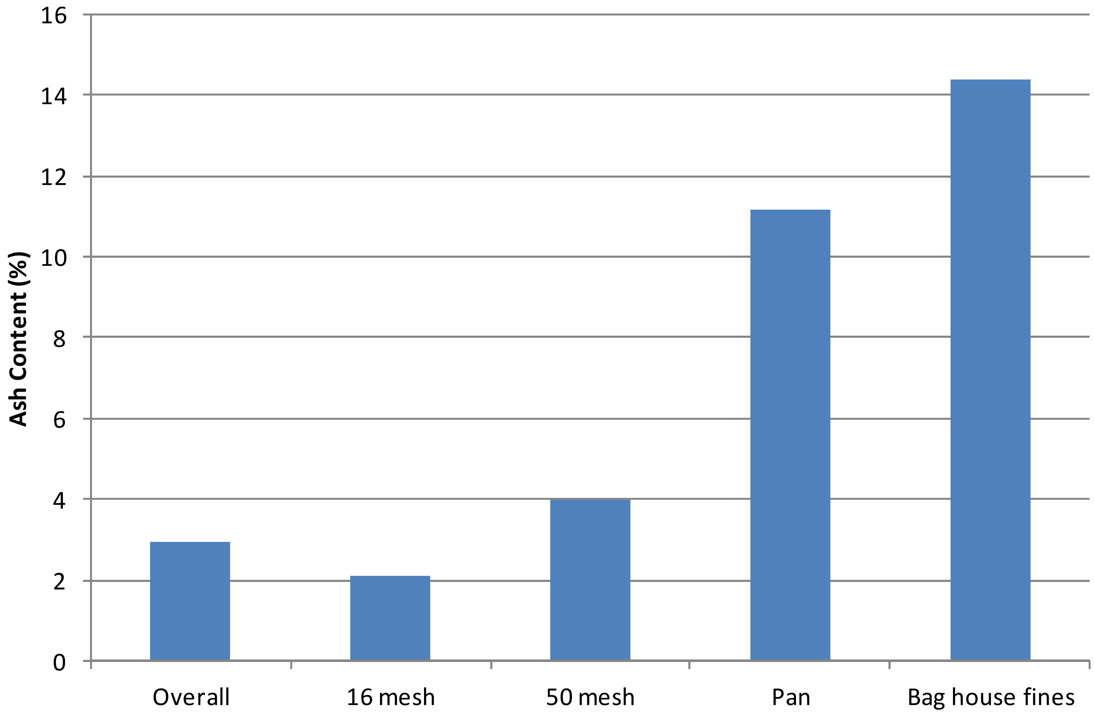

Figure 9. Ash content in various screen sizes for pinyon juniper biomass.

As expected, the highest ash content is found in the smallest size fractions, much of which is dirt entrained during the Harvest and Collection operation (Phanphanich and Mani 2009, Harkin and Rowe 1971). Because only a small portion of the total biomass weight is contained in the pan and bag house fractions, a significant portion of the ash that could be removed with the fine particles could compensate for the associated small loss of material.

Transportation and Handling

The Transportation and Handling cost for the 2012 Conventional woody biomass design is $8.95/DM ton. The decrease in moisture content of the transported material as a result of transpirational drying during the Harvest and Collection operation (from 50% to 40%), as well as pneumatic drying during comminution (from 40% down to 35%), increases the dry matter density transported, and therefore reduces cost. These cost reductions are consistent with those proposed in the USDA funded research project "High Tonnage Forest Biomass Production Systems from Southern Pine Energy Plantations", with principal investigators Steve Taylor (Auburn University), Robert Rummer (US Forest Service), and Frank Corley (Corely Land Services), a three year project commenced in 2009.

A reduced tree moisture content resulting from transpirational drying during Harvest and Collection, as well as from pneumatics during Depot Preprocessing carries through the supply chain. Notably, the Transportation and Handling costs are reduced because semi-trailer transportation for each truckload was previously weight limited. The new scenario with less moisture content allows more dry matter to be moved per truckload. Figure 10 shows an example of the relationship between moisture content and transportation costs at various dry matter densities, generated from the BLM.

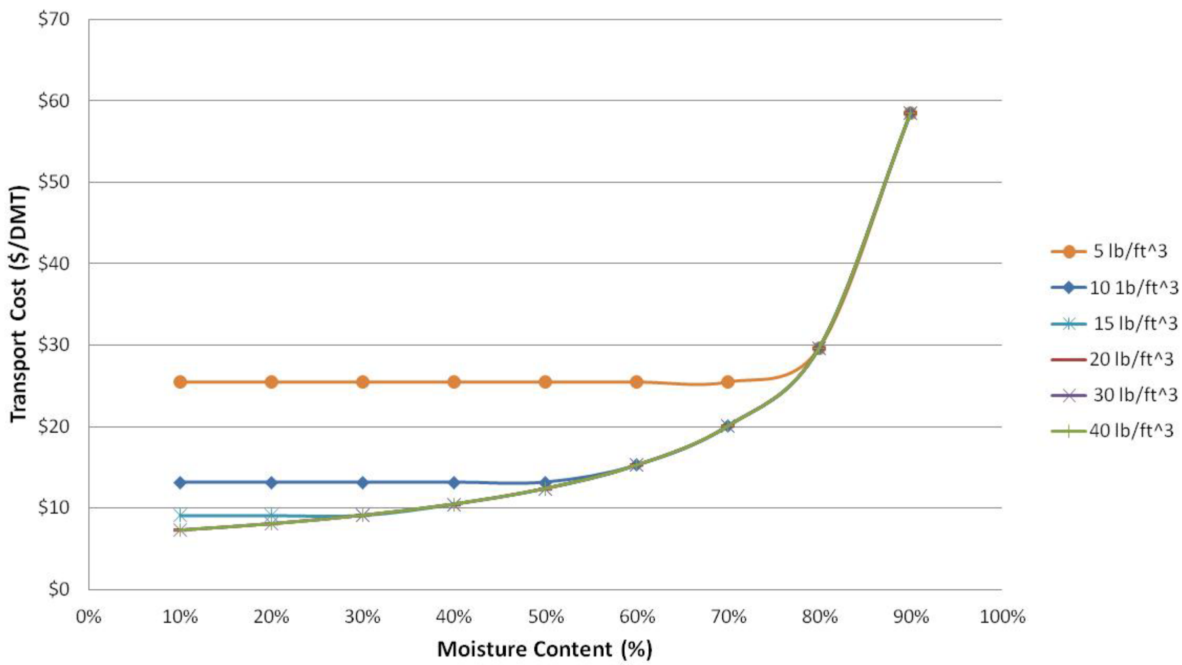

Figure 10. Example of the relationship between moisture content and transportation cost.

A higher dry matter density, the capital and operating cost of the truck is distributed over a larger mass, and therefore is a lower cost. Transpirationally drying the biomass reduces the amount of moisture being moved, and therefore the dry matter capacity of the truck increases with decreasing moisture, until the point that the truck becomes volume limited. Cost savings are realized until the truck reaches maximum weight capacity. Figure 11 illustrates the impact of material density on truck capacity.

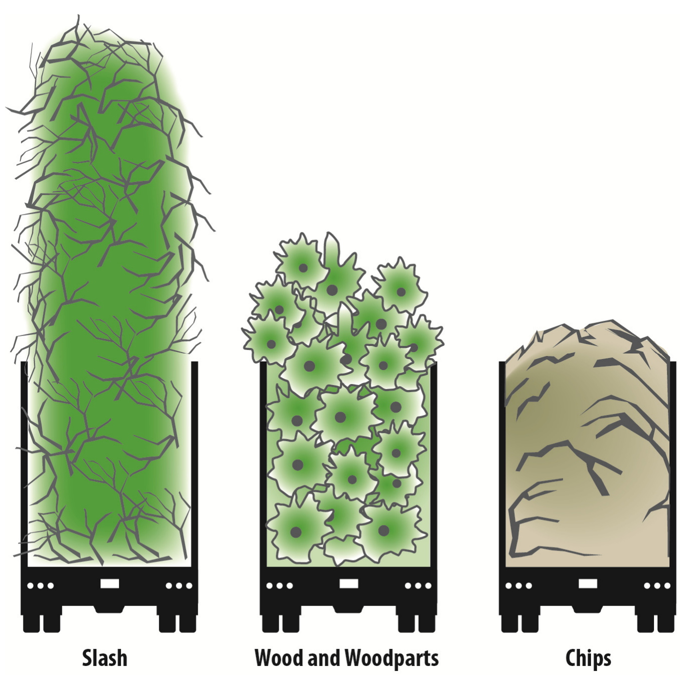

Figure 11. Volume differences of the same weight material by different product types (adapted from Schroeder 2007).

INL researchers are exploring high-capacity transportation options such as rail and to incorporate into advanced supply chains, which are required to meet longer term biofuels production goals. High-capacity systems could move densified, flowable biomass long distances without incurring the large incremental costs associated with truck transportation.

Plant Receiving and In-Feed Preprocessing

The 2012 Conventional woody biomass design has a cost of $7.25/DM ton for the Plant Receiving and In-Feed Preprocessing, which includes feed handling and drying. The dryer material (again, a carryover of the transpirational drying) can be handled more efficiently than wet material, and most significantly an efficient drying system substantially reduces drying costs. Earlier Conventional woody supply chain designs incorporated a rotary drum, natural gas-fired dryer, which is a very expensive drying option. The 2012 Conventional woody design incorporates a residence dryer that uses waste heat, and the dryer in-feed material has lower moisture content than the harvest moisture (30% MC in the 2012 Conventional woody design, as opposed to 50% harvest moisture). As well, an additional 5% moisture is lost via ambient drying during storage in the 2012 Conventional woody design. A study conducted by the INL during the summer of 2010 supports this assumption.

Biomass Ambient Drying during Storage

The INL conducted a field study over 6 weeks during the fall of 2010 to examine the effectiveness of ambient drying during storage in Idaho of various mixtures of same-source comminuted pine trees. Another purpose of the study was to monitor self-heating in the piles. This work, including additional data collected and details on methodology, has been submitted for publication in the Forest Products Journal (a peer-reviewed journal). Three mixtures of material were examined, including sifted ground chips (referred to in this study as overs), whole ground trees (herein referred to as unsorted), and the fines. The overs pile is closest to the 2012 Conventional woody design.

Small diameter Lodgepole pine trees from the Island Park area of Idaho in the Grand Targhee National Forest were felled, hauled[c], and comminuted the following day using a grinder with a 4" screen. The comminuted material was discharged directly into a trommel screen with a 3/8" screen. Initial sampling was performed for each material screen where it discharged onto the conveyors. Material was conveyed directly into walking floor trailers and again weighed at a grain elevator. The material was discharged onto the ground and stacked with an excavator. Three piles were built consisting of unsorted material, 3/8” minus material, and material greater that 3/8”, respectively, on September 15, 2010. Weather data was obtained from the Rexburg (KRXE) weather station. The average precipitation in Rexburg from 1977 to 2005 for September, October, and November were 0.82, 1.07, 1.09 inches, respectively (Western Regional Climate Center 2010), indicating that this is generally a dry climate.

After six weeks of storage (November 3, 2010), each pile was sampled and sensors retrieved. This was accomplished by carefully removing material from one side of the pile until a vertical face was formed in the center of the pile. Samples were obtained from the locations on this face and analyzed. Internal sensors were recovered and pile materials were again loaded in trucks and weighed to obtain a final mass. Analyses (before and after) performed include percent moisture content, ash content, bulk density, permeability, angle of repose, particle size distribution, and ultimate/proximate analysis. Monitored parameters were temperature and humidity. Samples were placed in 1 or 2 gallon zip-lock bags, sealed, and stored in coolers.

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c. Note that one of the interesting observations that came of this study was the effectiveness of modifying collection technique at decreasing ash content. Trees brought to the landing from the field were not dragged, but rather carried using a grapple. Samples of fines and unsorted material had a significantly lower ash content than samples dragged, which were taken as part of a previous study.

Sub-samples of the material used to build each pile was collected at the beginning of the study and were kept in storage simulators located at the INL, also the subject of a future publication. Shallow sensors were pulled from the pile. An excavator was used to carefully remove material from the north side and to create a vertical face through the center of the pile. Sampling occurred from this central area in each pile running east-west.

Initial moisture content of the piles was approximately 50% (Table 3). Each of the piles had zones of significantly decreased moisture, however there was a large range of moisture contents found in the samples taken.

Table 3 . Changes in moisture content. Data analyses performed by Hazen Research, Inc. (Golden, CO).

Parameter	Fines	Unsorted	Overs
Initial Moisture Content (%wb)	51.85	52.32	51.43
Final Moisture Content (%wb)			
Average*	35.73	39.81	28.54
Minimum	10.57	12.53	10.07
Maximum	47.28	50.57	36.82

*Average pile moisture determined geometrically from photos taken during deconstruction. Dry areas were visually distinct, allowing an approximation of volume for various moisture zones.

Although the overs pile most closely resembles the Conventional woody design scenario, all piles dried over 10%, which is well beyond the 5% assumed for this design scenario. Note that we are currently verifying the average pile moisture content (the nature of piles makes volumetric approximation challenging), however anecdotal evidence and initial calculations suggest that all three piles dried (Figure 12).

Figure 12. Distinct moisture zones were clearly visible in the piles during pile deconstruction. This picture is the fines pile (Photo credit: D. Brad Blackwelder, 2010).

There were visually distinct moisture zones in the piles (Figure 12). Self-heating is a significant contributor to moisture movement in the piles. During self-heating, the hot air rises from the pile center towards the surface, drying the pile center and pushing the water towards the outer pile layers where it condenses. If the hot air can exit the pile, the pile will dry to some extent. This was the case in this study, where moisture was carried to the top of the pile, forming a wet zone near the surface, and allowing moisture to evaporate. Pile height, ambient temperature, chip moisture, particle size, bulk density, and pile shape all influence the rate of drying and heating (NIC 2008, Hall 2009).

This study found that the pile with the most significant drying (the overs, and the pile similar to this SOT) had the lowest resistance to air flow. High permeability allows moisture-laden air to escape more easily from the pile. However, smaller particle sizes in the fines and unsorted piles restricts air flow and prevents heat dissipation (Fuller 1985). The unsorted pile had the most even distribution of particle sizes, ranging from 10% in the ½" fraction to 24% in the 1/16" fraction. As expected, the overs pile contained the highest proportion of larger particles sizes. The overs and unsorted pile had nearly the same proportion of ¾" pieces, however the overs pile had a much lower portion of smaller particle sizes than the unsorted pile. The fines did not contain any particles above ¼", with the majority of the fines being 1/16". In summary, the grinder was surprisingly effective at producing a good distribution of particle sizes, considering that grinders tend to be less effective at comminuting wetter material (for example Pottie and Guimier 1985, Arthur *et al.* 1982).

The results of this study show that comminuted material experiences some drying when stored in Idaho for 6 weeks. The extent of the drying observed in this study is well above the 5% assumed in the 2012 Conventional woody design. Although the effectiveness of ambient drying during storage varies (Afzal *et al.* 2010, Bedane *et al.* 2011, Brand *et al.* 2010, Casal *et al.* 2010, Gigler *et al.* 2004, Jirjis 2005), several studies in a variety of climates have found results that support the design assumption of 5% bulk moisture loss in storage (Afzal *et al.* 2010, Bedane *et al.* 2011, Brand *et al.* 2010, Gigler *et al.* 2004). Conditions that favor ambient drying during storage include storing piles on a well-drained pad, particle sizes greater than 22 mm or that 25 mm minus chips be partially covered to prevent atmospheric water input, that harvested materials enter storage in the spring, which provides the greatest opportunity for drying during the warmer months of summer, and that materials spend two to four months in storage to provide sufficient time for drying. Of course, dryer climates or periods of limited precipitation would be more conducive to drying than wetter climates and rainy seasons.

The Use of Waste Heat for Moisture Reduction

The 2012 Conventional design incorporates a residence dryer, which uses waste heat from the gasifier to reduce moisture from 30% down to 10% (the moisture required by the gasifier). The residence dryer is an active counter flow drying silo utilizing upward air flow while materials flows down thru the silo. Heated air is introduced to expedite the drying process, while the agitation mechanisms stir the material and prevent bridging and short-circuiting of gas flow.

Low Temperature Drying

Drying the biomass fuel improves the efficiency of thermochemical conversion systems (Table 4). In the 2012 Conventional woody design, the biomass needs to be drier than the 30% received moisture content before it is introduced to the gasifier.

Table 4. Relationship between the water content and heating value of wood (Omori 2006).

Moisture Content (%)	**Heating value (MJ/Dry-kg)**
0	1
20	2/3
40	1/3

If heat drying is from a waste heat source, the efficiency of the system increases significantly. To give an example the maximum efficiency of a boiler fired with wood chips of moisture content of 45% is about 74%. At moisture content of 10 to 15% the efficiency can be as high as about 80%, which significantly increases the steam production by 50 to 60 % (Bruce and Sinclair 1996). Also, lower moisture content assists in achieving a uniform flame and complete combustion. As noted previously, drying also has an impact on storage stability.

Drying requires a large energy input to produce the necessary heat, so design of a system should consider opportunities to recover process heat. Using waste heat for drying increases the total system efficiency, and the infrastructure required to use the waste heat for drying may be lower than that for using a conventional energy source. Low-temperature drying can prevent the loss of high-energy volatiles (Phanphanich and Mani 2009, Fagernas *et al.* 2007). The amount of volatile emissions is impacted by the type of material, type of drier, temperature, drying medium, and residence time (Fagernas *et al.* 2007). Emissions increase with increasing temperature. At around 150ºC, thermal degradation of woody materials starts by destruction of hemicelluloses, and alcohols, acids, and aldehydes are released (Fagernas *et al.* 2007). At lower temperatures (under 100 ºC), mainly terpenes are emitted (Fagernas *et al.* 2007). Fagernas *et al.* (2007) found that wood fuels could be dried to about 10% wt moisture without emitting large amounts of volatiles, provided the material is dried in a bed, the temperature of the inlet gas is below 180ºC, and the steam formed during drying is not condensed.

Bin Drying Systems

The dryer used in the 2012 Conventional woody design is a counter flow residence dryer that incorporates the use of waste process heat as an energy source. The dryer design is based on a modified flat bottom continuous flow silo (Figure 13). Material enters the silo from the top through an airlock and is removed from the bottom of the silo with a reclaimer which rotates around the bottom of the silo removing only the bottom layer. Below the reclaimer the material is collected in a hopper and control-fed out of the dryer with an auger through a discharge airlock. The flat floor of the silo is perforated and hot air introduced under the floor in the hopper area and is drawn up through the biomass bed with a blower which pulls air out the top of the silo. Material is continually flowing through the silo with a predetermined residence time controlled by the discharge auger. In the center of the silo is a rotating leveling arm which keeps the in-feed material level minimizing air channeling and providing even drying. The leveling arm also provides even flow of the material.

Figure 13.The low temperature residence dryer designed by INL will reuse excess heat from other operations to reduce moisture in biomass prior to additional pre-conversion technologies. Design of the system includes the primary vessel, inlet and output sections, internal augers to keep the material moving and evenly heated, and associated components. Bottom left is the bottom section from the front, right is the top section from the back.

The purpose of the residence dryer in the 2012 Conventional woody scenario is to dry the chipped woody biomass from a 30% MC down to 10% MC. However, to be conservative, we tested chipped pine with a higher starting moisture content (54%). A test run was executed for 7 hours, using inflowing air at 140°F to dry the biomass from 54% down to 9% moisture content after 5 h (the moisture after 7 h was approximately 3%) (Figure 14). The airflow rate was approximately 2000 cfm, although airflow through the material bed was controlled so that the air leaving the bed had a relative humidity of 90% or greater. At 90% relative humidity, the dew point is 65°F. The exit air temperature remained at approximately 68°F, which prevented water from re-condensing. The success of this run supports the design assumption in the 2012 Conventional design that we can dry chips from 30% moisture down to 10% using a residence dryer. The capital savings of a bin dryer in this design over a rotary-drum dryer in the 2009 design are significant.

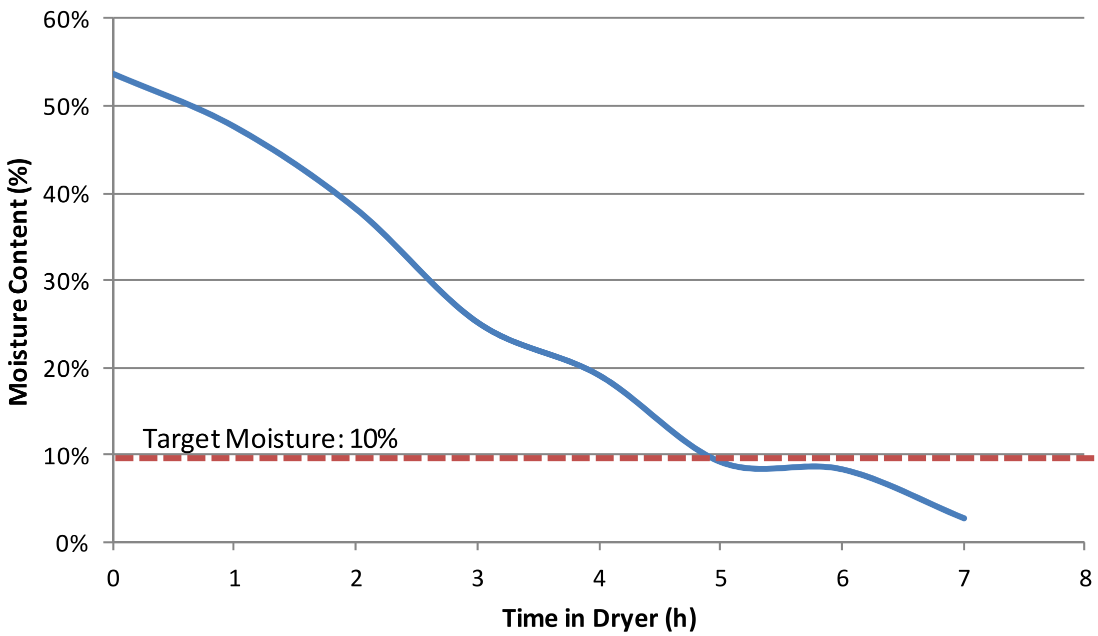

Figure 14. Moisture reduction observed in comminuted woody biomass dried in the residence dryer over seven hours. The moisture content of the biomass was reduced below the target moisture of 10% (Phillips et al. 2007).

MOVING BEYOND 2012

One of the principal challenges of establishing lignocellulosic biofuels as a self-sustaining enterprise is organizing the logistics of the woody biomass feedstock supply system such that it sustainably maintains the economic viability of supply system infrastructures while providing the needed quantities of resources. This requires a strategy of progression from a variety of conventional state-of-technology woody biomass supply systems to a commodity-scale, uniform-format supply system. The "Uniform-Format" Vision adapts supply systems incrementally as the industry launches and matures, providing progressive feedstock supply system designs that couple to and build from current systems and address science and engineering constraints that have been identified by rigorous sensitivity analyses as having the greatest impact on feedstock supply system efficiencies and costs.

Motivation for a Commodity-Driven System

The U.S. Department of Energy aims to displace 30% of the 2004 gasoline use with biofuels (60 billion gal/yr) by 2030. Of those 60 billion gallons, 15 billion are projected to come from grains, and the remaining 45 billion from lignocellulosic resources. This means that of the 700 million DM tons of biomass required annually, 530 million DM tons will come from a diverse variety of herbaceous and woody lignocellulosic biomass resources (also referred to as "cellulosic" biomass). For the biofuels industry to be a self-sustaining enterprise, the lignocellulosic feedstock supply system logistics (all processes involved in getting the biomass from the field to the conversion facility) cannot consume more than 25% of the total cost of the biofuel production.

While national assessments identify sufficient biomass resource to meet the production targets, much of that resource is inaccessible using current biomass supply systems because of unfavorable economics. Consequently, conventional biomass supply systems are incapable of meeting the quantity goals required to meet long-term biofuels production goals. Increasing demand for lignocellulosic biomass introduces many logistical challenges to providing an economic, efficient, sustainable, and reliable supply of quality feedstock to the biorefineries.

For woody resources, the gradual progression from a Conventional system to an Advanced Uniform system that meets all cost and quantity targets set by the U.S. DOE involves three increments, termed (1) "Conventional," which reflects current practice and was presented in this case study; (2) "Pioneer Uniform," which uses current or very near-term technologies and offers incremental improvements over the Conventional system; and (3) "Advanced Uniform," which meets all cost and supply targets and requires some conceptual equipment, such as a single-pass harvester, to provide a commodity-scale bulk liquid feedstock.

The Pioneer Uniform design enables the transition from the Conventional to the Advanced Uniform supply system by developing the supply chain infrastructure required for forward-deployed preprocessing. The Advanced Uniform system preprocesses biomass of various types (i.e., corn stover, woody) and physical characteristics (i.e., bulk densities, moisture content) into a standardized format early in the supply chain. This uniform material format allows biomass to be handled as a commodity that can be bought and sold in a market, vastly increasing its availability to the biorefinery and enabling large-scale facilities to operate with a continuous, consistent, and economic feedstock supply. The commodity-scale system also releases biorefineries from contracting directly with local farmers for biomass feedstocks. Figure 15 shows a schematic of the end-state commodity supply system for all types of lignocellulosic biomass resources.

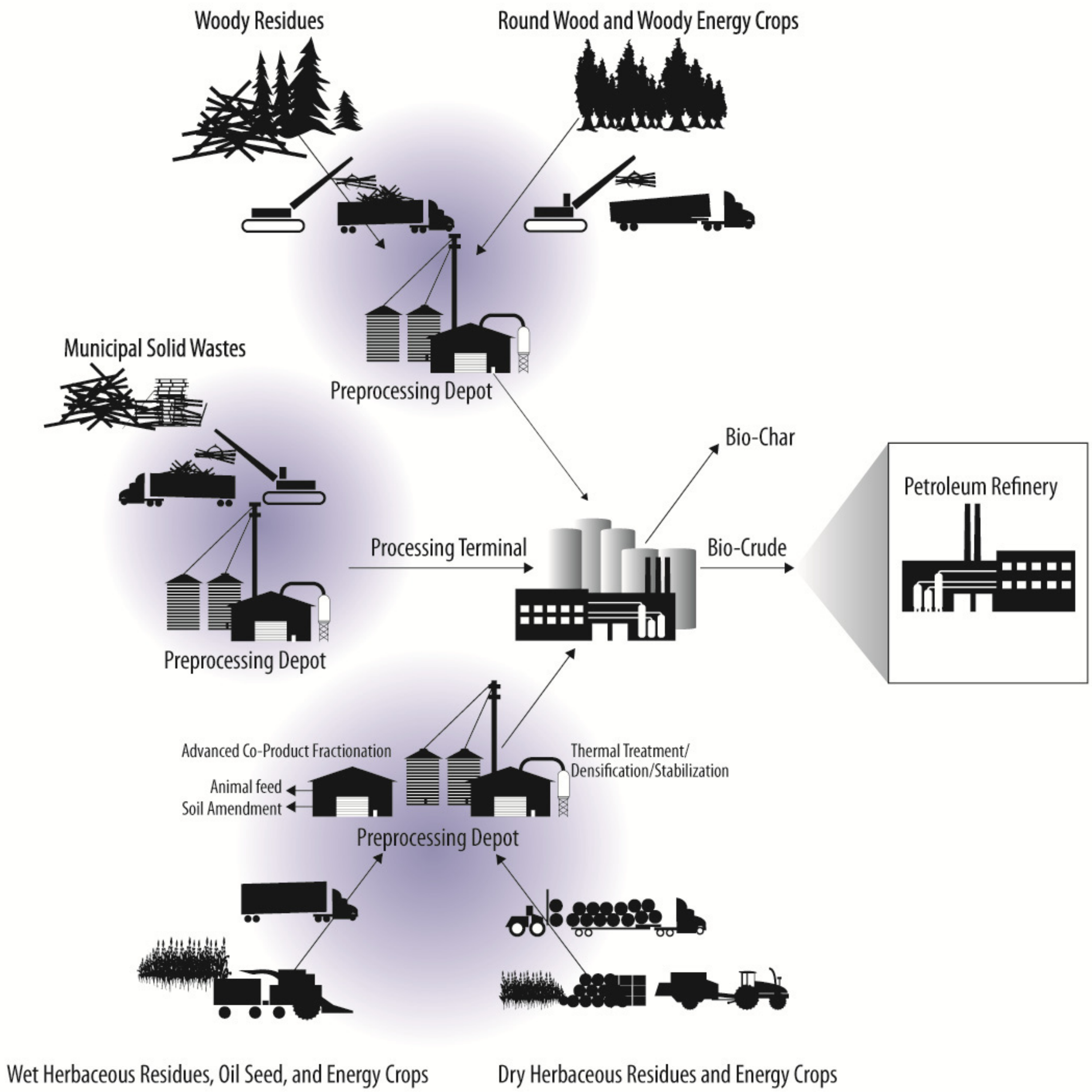

Figure 15. The Advanced Uniform-Format feedstock supply system resembles the grain commodity system, which manages crop diversity at the point of harvest and/or the storage elevator, allowing subsequent supply system infrastructure to be similar for all biomass resources.

Building a commodity market and trading system for lignocellulosic biomass is essential for creating a large-scale industry. As demonstrated through the current bulk-solid grain commodity system, with an aerobically stable and flowable product, replicable high-capacity equipment can be used to economically connect supplies with markets across large distances without spoiling. The ability to economically connect feedstock with markets 200 or more miles away ensures reliable supply by reducing production risks, and broadens accessibility by creating regional and national markets. Also, large commodity networks with organized and predictable commodity transfer between buyers and sellers and among markets limits spatial price differences, and therefore facilitates the entry of remote resources into the market (Schnepf 2006). Aerobic stability also allows for longer-term storage, if required, although the existing pulpwood industry moves woody biomass that is not aerobically stable. It is important to note that although woodchips are flowable, they cannot be handled in existing high-capacity petroleum infrastructure.

One inherent characteristic of a commodity system, including the grain commodity system, is that the material meets a definitive specification (a spec). The quality characteristics of new lignocellulosic feedstocks are less consistent than for grain, for example, which has known and highly consistent attributes developed over decades of seed development. Grain-fed biorefineries rely on consistent feedstock to achieve design production rates; however, new cellulosic crops have much higher variation (depending on age, storage time, growing conditions, etc). Meeting spec requirements ensures that biorefineries receive a consistent feedstock for their conversion process, and that the material has the appropriate properties to balance feedstock cost and conversion optimization. For example, thermochemical conversion processes are often sensitive to ash content, whereas biochemical conversion processes desire high sugar content. In some cases, feedstock properties can be achieved by mixing various biomass feedstocks at the terminal. A more controlled spec would come at a higher cost. An important consideration for the spec system is that biomass has certain inherent characteristics that would be cost prohibitive or impossible to change, such as the presence of oxygen. An example of the role of spec in the biomass commodity system is shown in Table 5.

Table 5. Role of feedstock specifications in a commodity-based biomass system. These specs impact feedstock cost, as well as conversion properties and other in-plant operations.

	Impacts		
Spec	Feedstock	Interface	Conversion
Moisture Content	Reduction of target (lower moisture) increases cost	Effects storage, grinding, and feed injection	Impacts pyrolysis chemistry and product quality
Particle size	Smaller particles/bulk handling increase cost	Handling (explosion) and injection challenges	Impact on pyrolysis rate and conversion efficiency
Ash content and composition	Reduction of target(s) increases cost	Minor impact	Impact on pyrolysis chemistry
C:H ratio, C:O ratio	Costs increase with severity of torrefaction	Improved feedstock storage, grinding, and injection	Potential improvement of pyrolysis rates and product quality
Trace species concentration	Removing chlorides, sulfur, and ash elements increase cost	Potential impact on handling and injection equipment	Impacts gas cleanup and product upgrading

Another benefit of a commodity-based feedstock supply system is increased cost competitiveness; more market participants are generally associated with a lower selling price (Schnepf 2006), which decreases the leveraging power of local producers and also provides flexibility to producers to sell to other customers. Also, inconsistency in the commodity (i.e., type, variety, quality, end-use characteristics) generally increases the price range and leads to undesirable instability in the market price. Having transparent price information, as opposed to private contracts commonly used for non-commodity crops, can prevent price manipulation (Schnepf 2006).

Providing a consistent, reliable feedstock to biorefineries is pivotal to creating a sustainable, growing biofuels industry. This requires a close coupling with the available resource, which includes understanding feedstock characteristics, location, and availability. There are four components of establishing this consistent supply relative to the feedstock supply system designs: (1) facilitating diversity in regional cropping options, (2) enabling access to remote resources, (3) allowing efficient transport of biomass beyond 200 miles; and (4) addressing supply risks associated with weather, competition, pests, and other local issues. All of these issues will be addressed in a later version of the report.

CONCLUSIONS

The goal of this Joule is to validate the woody cost of feedstock at $61.57/dry US ton for the production of ethanol via thermochemical conversion. The modeled feedstock is southern pine trees grown on a plantation. This goal was achieved using a number of technologies and processes, including transpirational drying, pneumatic assist during comminution, ambient drying during storage, and a residence dryer that uses waste heat from the gasification process. Meeting this cost target of $61.57/DM ton supports the DOE in meeting their 2012 cost target for biofuels production. Future designs will incorporate advanced design concepts which are required to make higher amounts of biomass available for biofuels production while meeting quality and cost targets.

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