INL/EXT-10-20372
Revision 0

Uniform-Format Feedstock Supply System:
A Commodity-Scale Design to Produce an Infrastructure-Compatible Biocrude from Lignocellulosic Biomass

September 2010

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Prepared for the
U.S. Department of Energy
Office of Biomass Program
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

ABSTRACT

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ACKNOWLEDGEMENTS

The Editors would like to gratefully acknowledge the support of the U.S. Department of Energy-Energy Efficiency and Renewable Energy Office of Biomass Program. Idaho National Laboratory's R&D Publications Support Services also made valuable contributions in the preparation of this report, and the authors would like to thank Caitlin Lanier and Leslie Ovard for publication management support; Kristine Burnham, David Combs, David Sharpe, and Allen Haroldsen for their graphics support; Quinn Grover, Gordon Holt, Lisa Plaster, Kim Jackson, Penny Simon, and Linda Coleman for editorial and text processing support. Others deserving of acknowledgement include summer research interns, the Bioenergy Group support staff, and the INL Research Library staff for research support.

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Uniform-Format Feedstock Supply System:
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1. EXPANDING THE "UNIFORM-FORMAT" VISION TO WOODY BIOMASS

U.S. interest is increasing regarding the use of lignocellulosic biomass as part of a portfolio of solutions to address climate change issues and improve energy security, in addition to other benefits that an invigorated agricultural industry can provide. One of the principal challenges of establishing lignocellulosic biofuels as a self-sustaining enterprise is organizing the logistics of the biomass feedstock supply system in a way that maintains the economic and ecological viability of supply system infrastructures while providing the needed quantities of resources. This report expands the Uniform-Format feedstock supply system design vision presented in Hess et al. (2009) to access woody biomass resources for energy feedstock production. Like Hess et al. (2009), this design document acknowledges the need for a progressive transition from present-day feedstock supply systems to a uniform-format supply system that accommodates a variety of resource types. Supportive design concepts are discussed that transition incrementally as the industry launches and matures. These designs couple to and build from current state of technology 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.

The purpose and objective of this woody biomass uniform-format feedstock supply system design document is threefold:

1. Provide a design basis for development of feedstock supply system designs using conventional technology and operations and provide sufficient supply system attribute and modeling data to evaluate the efficacy of those designs.
2. Set forth design concepts for a pioneer uniform-format feedstock supply system that will allow for simplified and highly replicable supply system infrastructure and biorefinery conversion facility designs that can be rapidly and universally deployed to achieve the 20-in-10 Plan (Bush 2007) and 30 × 30 Scenario (Foust et al. 2008) fuel displacement goals.
3. Present an advanced uniform-format feedstock supply system design that can
    a. Meet the feedstock specifications of both the biochemical (Aden et al. 2002) and thermochemical (Phillips et al. 2007) conversion platform designs
    b. Achieve the feedstock cost and quantity targets set forth in the Department of Energy (DOE), Office of Biomass Program (OBP) *Multi-Year Program Plan*, (U.S. DOE-OBP 2007).

1.1 Motivation for a Commodity-Driven Feedstock Supply System

When estimating biomass needs to reach the 20-in-10 goal (Bush 2007), up to 70 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]). Given current biorefinery designs (Aden et al. 2002; Phillips et al. 2007), the potential construction of more than 100 biorefinery facilities will be required within 10 years to process this quantity of lignocellulosic biomass. Under the most optimistic circumstances, and anticipating that currently planned commercial-scale biorefineries will be successful, the U.S. lignocellulosic ethanol capacity will likely be less than 1 billion gallons annually by 2012. Therefore, during the subsequent

5 years, 2012 to 2017, biorefineries will need to be replicated and scaled to produce between 4 and 6 billion gallons of ethanol.

Such a rapid replication and expansion of the industry cannot be accomplished with many diverse, custom-designed feedstock supply system infrastructures and conversion facilities. While the volume of lignocellulosic biomass feedstock that must be managed is of commodity scale, it comes from diverse resources for which there are few or no existing markets. The diversity of resources requires different preprocessing operations to make them suitable for conversion, and managing this diversity at the biorefinery requires front-end preprocessing systems that are capital intensive and custom designed for a limited variety of resources. The modular nature of feedstock supply system operations make it better suited to manage this diversity, as preprocessing can occur throughout the system while increasing efficiencies and reducing downstream logistics costs.

To accomplish the expansion of the industry necessary to meet interim milestones and ultimate targets for biofuels production, this design document operates under similar premises as the herbaceous bulk solid uniform-format feedstock supply system design report (Hess et al. 2009): lignocellulosic conversion facilities (biochemical and thermochemical alike) must be able to access feedstocks at commodity scales from standardized feedstock supply system infrastructures that have the following capabilities:

1. Tolerate wide variations in feedstock resources and moisture levels
2. Decouple capital-intensive, custom-designed preprocessing operations from conversion facilities and reduce capital investment and operational overhead
3. Produce uniform, aerobically stable, quality-controlled feedstocks for conversion infeed systems
4. Demonstrate compatibility with existing commodity supply system infrastructures.

1.1.1 Barriers in Conventional Woody Feedstock Supply Systems

There are no operations in proposed feedstock supply systems (Hess et al. 2009 and this design document) that are not already functioning today. Systems exist to supply virtually any lignocellulosic feedstock to a biorefinery facility, including agricultural and processing residues, dedicated energy crops, and woody resources. Even though we have a basic understanding of how current supply system technologies function within existing agricultural and forest operations, extending this knowledge to woody residues and woody energy crops quickly identifies gaps in the knowledge base. Many conceptual designs are available for moving biomass feedstocks from the forest to the biorefinery, and this variety poses a couple of considerable challenges for commodity-scale feedstock supply systems:

1. Developing a uniform-format feedstock supply system that connects the diversity of woody lignocellulosic feedstocks to a standardized feedstock supply system infrastructure and biorefinery conversion process
2. Improving feedstock logistics, specifically the efficiency and capacity of woody feedstock supply systems, to meet lignocellulosic biorefinery cost targets that are commensurate with other energy feedstock supply and conversion systems (i.e., corn grain to ethanol).

Even though the issues of feedstock supply system logistics are reasonably well understood, it is generally recognized that these logistics must be improved. However, improving logistics alone will not remove the most significant supply system barrier, which is economically managing the diversity and complexity of lignocellulosic feedstocks and feedstock supply system configurations needed to achieve both near- and long-term lignocellulosic biofuel goals (Fales et al. 2007).

1.1.2 Uniform-Format System Overcomes Feedstock Supply Barriers

The feedstock supply system encompasses all operations necessary to format and move biomass from the location of production (field or forest) to the biorefinery (Hess et al. 2003). The logistics of biomass collection, storage, preprocessing, handling, and transportation represent one of the largest challenges to this industry, and the supply system logistics associated with these activities can make up 40 to 60% of total ethanol production costs (Fales et al. 2007). For comparison, the feedstock logistics costs associated with corn-grain-based ethanol from a dry mill process range between 8% (2008$) and 27% (2002$), with increased energy costs likely being the primary factor in the range. While the actual percentage allocation for lignocellulosic biomass feedstock logistics will depend upon some factors that differ from those of corn grain, biomass feedstock logistics costs exceeding 30% of the total lignocellulosic ethanol production cost will leave little profit incentive for biomass producers and biorefinery operators.

For maximum efficiency in the feedstock supply system, handling and transportation must be minimized by reducing the variety of equipment types necessary to move lignocellulosic biomass from the forest to the biorefinery. For example, the woodchip-based feedstock supply system changes the biomass format at least three times from the forest to the biorefinery (e.g., standing trees $\rightarrow$ piled trees $\rightarrow$ chips). Each biomass format requires unique equipment that cannot be interchanged or used to handle other feedstock formats. To complicate the issue further, there are multiple formats (i.e., round wood, woodchips, and slash) with their own respective lines of harvesting and handling equipment. Thus, managing feedstock diversity by increasing feedstock bulk density and flowability as near to the feedstock source as practically possible can greatly improve the efficiencies of supply logistics. However, the cost and energy inputs required to reformat biomass and achieve the optimum densities must be improved, as demonstrated in the Advanced Uniform-Format design in Section 2.3.1.

Supply logistics costs vary substantially among regions, depending on weather, crop species, moisture content, feedstock types, and management practices, as well as transportation highway load limits and other regulations. Harvest systems and storage methods can also change supply logistics costs substantially. These inherent complexities and diverse feedstock types must be managed to optimize collection and handling activities and maximize revenue in the biomass biofuel production system. However, it is important to note that this design document discusses a “system,” or industry-wide set of feedstock supply chains; therefore, site-specific logistical solutions are not always preeminent. When considering the development of an entire industry that can be rapidly deployed, a uniform-format feedstock supply system design becomes a key consideration. Uniformity is necessary not only for the conversion plant owners, but also for equipment manufacturers, who require equipment to be broadly applicable across the industry. Conversion plant owners and equipment manufacturers must work together, not in a relationship of compromise, but rather through mutual optimization on a national scale.

One route towards achieving national biofuel goals is through the development of a uniform-format feedstock supply system consisting of modularized harvesting and preprocessing systems that can be adapted to the diversity of feedstocks, and yet connect to uniform-format receiving systems of standardized and highly replicable biorefinery designs. Additionally, the modularized feedstock supply system is better suited to handle feedstock diversity than the capital-intensive systems of the biorefineries.

1.2 Design Basis for Uniform-Format Woody Feedstock Supply System

The design basis considers that woody feedstock supply system deployment will demonstrate the following progression:

1. Conventional technology and operation systems that are uniquely designed to integrate with existing forest materials systems

2. Pioneer uniform-format systems wherein feedstock supply systems are standardized to a stable flowable format prior to delivery at the receiving gate of the biorefinery
3. Advanced uniform-format systems that standardize all feedstocks to one format prior to delivery at the receiving gate of the biorefinery and manage feedstock format diversity as early in the feedstock supply system as practically possible for each respective lignocellulosic feedstock.

1.2.1 Conventional Woody Feedstock Supply System 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 1-1).

Figure 1-1. 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 efficiency and capacities of these conventional supply systems within the constraints of existing local feedstock supplies, equipment, and permitting requirements. In reality, the 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 1-2).

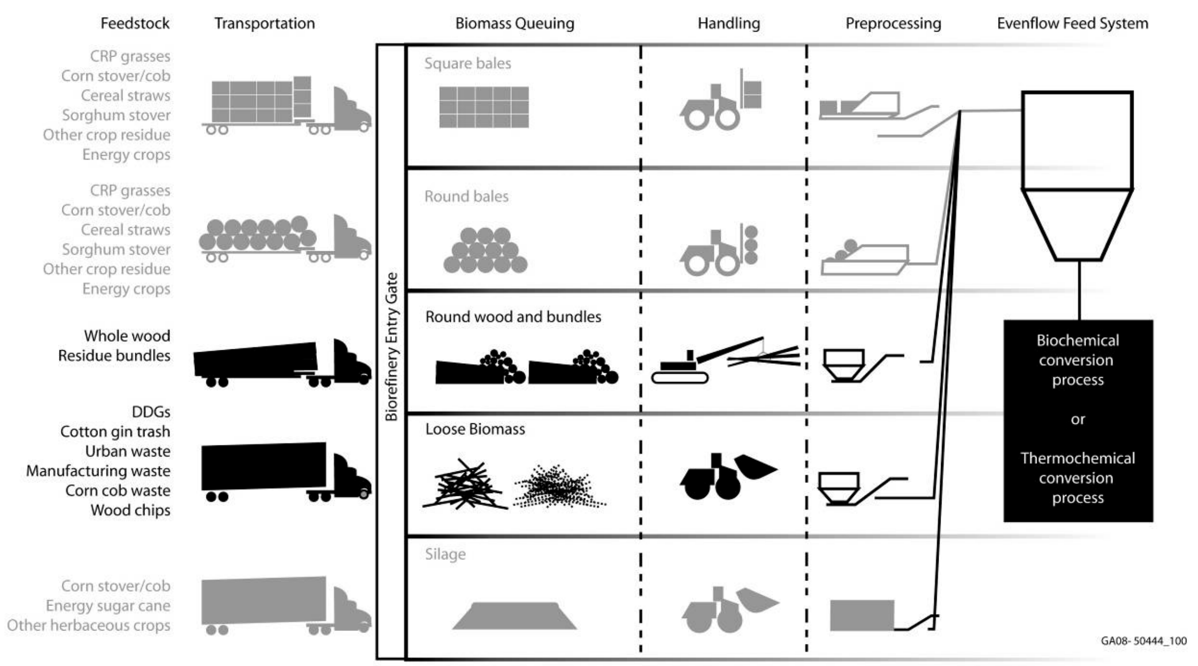

Figure 1-2. Conventional feedstock supply system designs are tailored for each facility and respective feedstock resource. No two are alike, and components are only replicable to the extent that feedstock

sources and local conditions are similar. Conventional woodchip systems (in bold) are the focus of Section 2 of this design report.

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 will accept. 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.

1.2.2 Pioneer Uniform-Format Feedstock Supply Systems

As Pioneer Uniform-Format feedstock supply system (Pioneer Uniform) designs emerge, all feedstocks will arrive at the biorefinery gate in a quality-assured and quality-controlled, uniform format. The diversity of biomass formats (not biomass composition) will be largely managed by the feedstock supply system infrastructure rather than the biorefinery feedstock receiving and processing systems. This will be accomplished by advancing the preprocessing operation in the supply system (Figure 1-3).

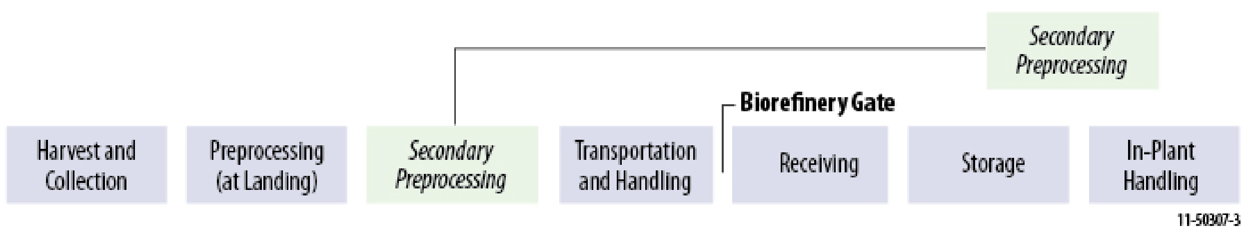

Figure 1-3. Pioneer Uniform-Format feedstock supply system designs move preprocessing from inside the biorefinery gate to earlier in the supply chain.

While the biorefinery feedstock receiving and conversion systems will still be tailored to multiple biomass formats, the Pioneer Uniform design reduces those formats to one consistent format. Wet biomass has a moisture concentration that is aerobically unstable, which is typically greater than 15 to 20% w.b. Because of the entrained moisture, this biomass requires stabilization techniques to be implemented if the biomass is not consumed immediately. These include reducing the biomass moisture to the point it becomes aerobically stable (e.g., field dry, aerated storage/queuing, preprocessing) or stabilizing the biomass material in the presence of water. Green harvest, coupled with timely delivery and conversion, could also be an option in some areas for handling aerobically unstable biomass, which is often the case for woodchips. The aerobically stable, dry feedstock supply system is described in Hess et al. (2009).

A key feature of the Pioneer Uniform design is the flexibility of the system to interface with the multiplicity of existing feedstock resource supplies and deliver a standardized format material to the biorefinery (Figure 1-4). This system will also demonstrate improvements in overall supply system efficiencies and capacities for biomass harvesting and collection formats (e.g., round bales, loose stacks, chips, slash piles, processing waste, rubbish piles) that are not optimized for downstream transportation. Pioneer Uniform designs will also overcome the local specialized design approach of pioneer biorefinery and feedstock supply system infrastructures, which will facilitate the more rapid deployment of biorefining facilities across the United States.

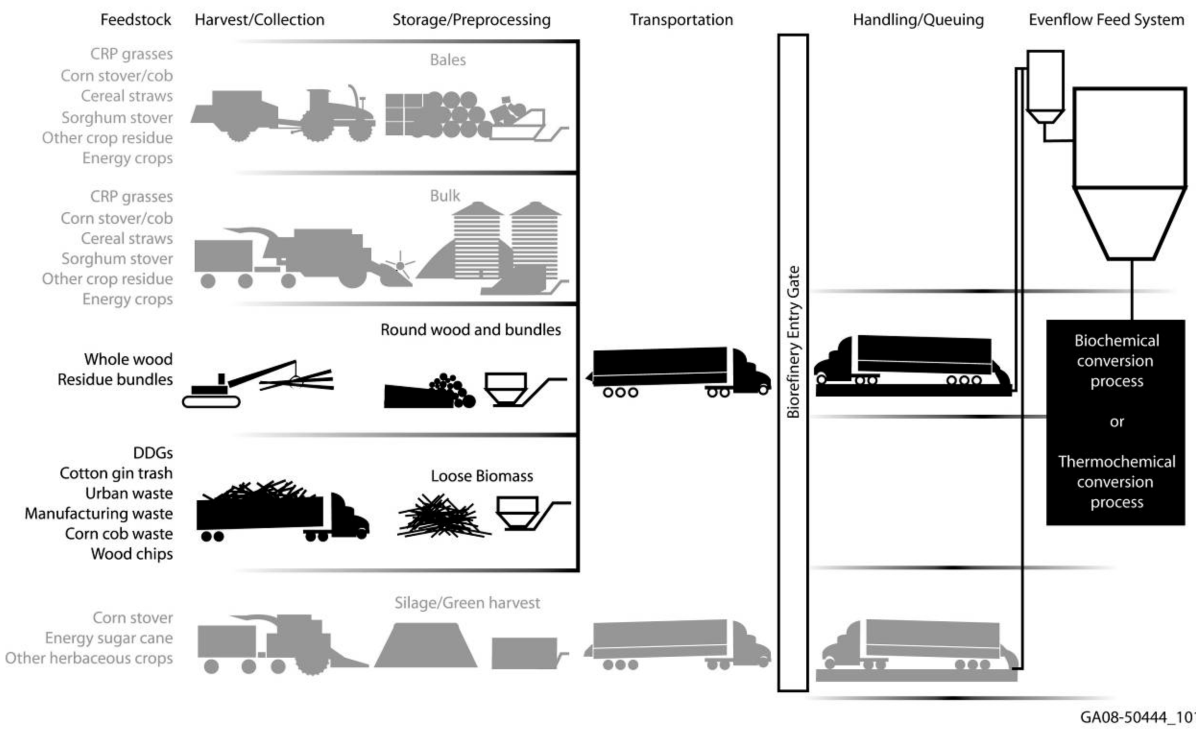

Figure 1-4. Pioneer Uniform-Format feedstock supply system (Pioneer Uniform) designs will allow lignocellulosic biomass to arrive at the biorefinery gate as a uniform-format, flowable material.

Woody resources (in bold) are discussed in detail in later sections of this design report.

1.2.3 Advanced Uniform-Format Feedstock Supply System Design

The fundamental premise of the Advanced Uniform-Format feedstock supply system (Advanced Uniform) design concept is that the high-capacity and high-efficiency supply systems already exist (e.g., grain and petroleum crude) and that handling low-density/aerobically unstable material is inherently inefficient. As such, the Advanced Uniform concept employs preprocessing technology to remedy the density and stability issues that prevent woody lignocellulosic biomass from being handled in high-efficiency bulk dry solid or liquid logistic systems. The design results in a single-format feedstock supply system in which the diversity of biomass formats is eliminated as early in the supply system as practically possible through some type of preprocessing (Figure 1-5).

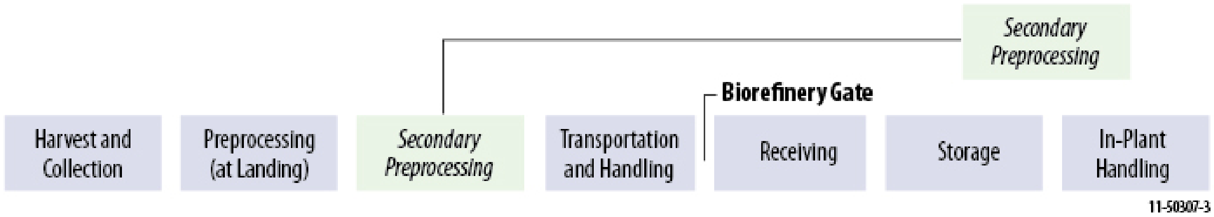

Figure 1-5. Overview of the advanced woody biomass feedstock supply system.

The preprocessing may occur during Harvest and Collection and/or at centralized preprocessing sites (depots), which are envisioned to resemble existing depot-type systems like the grain elevator or beet dump. From the depot, downstream feedstock supply systems and infrastructure will become uniform commodity-scale equipment and handling systems (Figure 1-6).

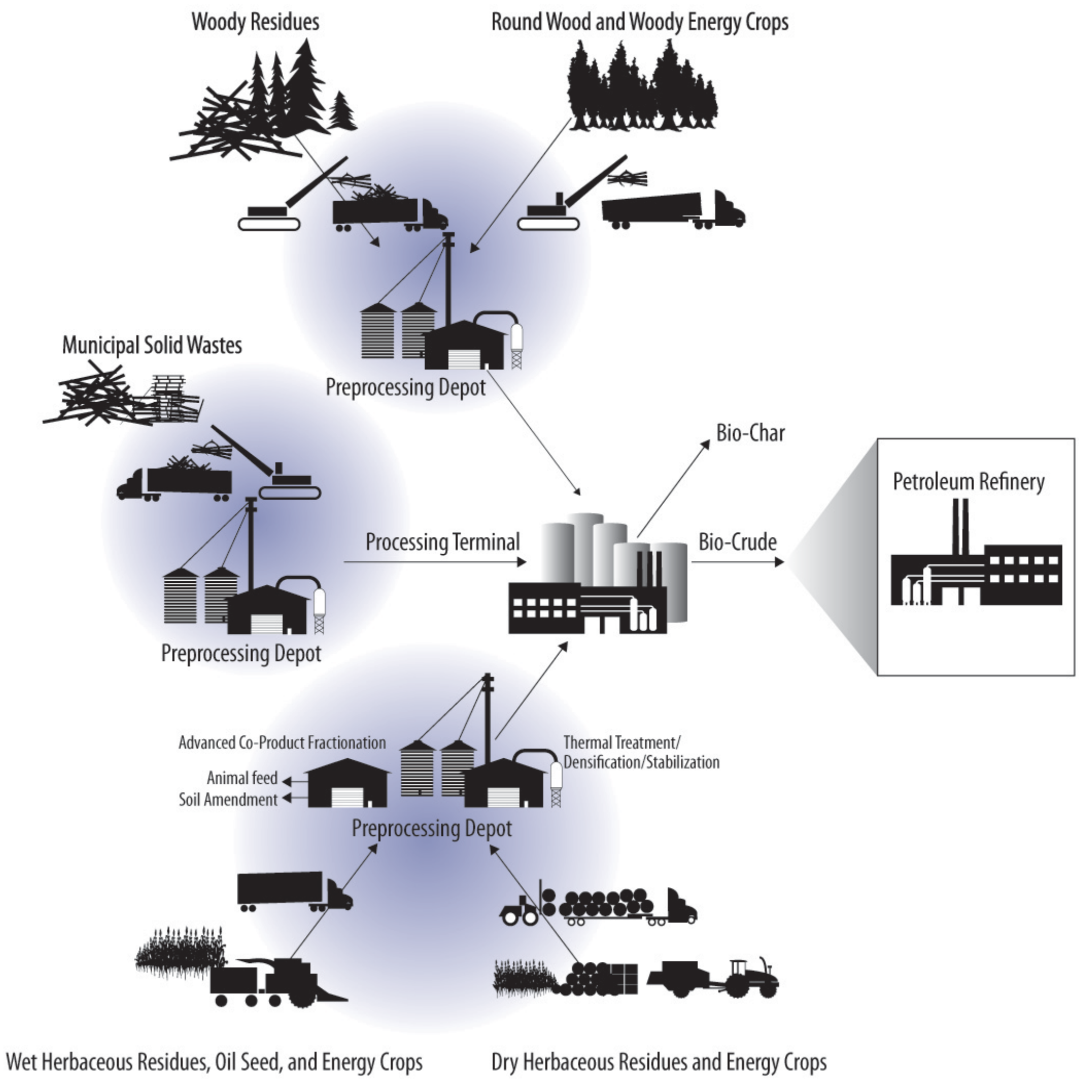

Figure 1-6. Advanced Uniform-Format feedstock supply system designs (Advanced Uniform) follow the model of the current commodity grain supply system, which manages crop diversity at the point of harvest and/or the storage elevator, allowing all subsequent feedstock supply system infrastructure to be similar for all biomass resources.

The Advanced Uniform design transitions lignocellulosic biomass from a local bought-and-sold product to a large-scale commodity, thereby allowing for long-distance transportation (50+ miles), bulk-flowable handling, and feedstock blending to achieve standardized feedstock compositional targets and/or other target properties beneficial to the conversion process(es). All biomass will be preprocessed into one flowable, aerobically stable format: either a high-density dry-solid product (i.e., flour, granules, select pellet concepts) or a high-density liquid product (i.e., pyrolysis oil). While it is not known at this time whether the mature lignocellulosic biomass industry will implement a bulk solid or liquid feedstock supply system (or a combination of both), the high-density liquid product design concept will be the model system presented in this report. A bulk format is presented in Hess et al. (2009).

The biomass blending design feature of the Advanced Uniform concept precludes the use of high-density handling systems (i.e., bales, modules, containers, bundles) beyond the preprocessing unit operation. However, such a unitized handling system may continue to be the system of choice for the field/forest harvesting and collection operations. Nevertheless, bulk density and material stability requirements will be the same for both bulk and unitized systems.

The design goal for the Advanced Uniform system for a high-density liquid format is to increase bulk and energy density of the biomass, and increase material stability, while decreasing the variability in format to produce a high-density, uniform product that can be handled in the existing petroleum infrastructure. The bulk solid system is analogous to the grain industry. Grain harvesting systems (i.e., a combine) adapt to the diversity of grain crops by threshing adjustments and/or header attachments, and once the grain reaches the clean grain elevator, all subsequent grain handling systems from the field to the point of use are uniform. Driving the feedstock uniformity to the point of harvest is highly dependent upon major advances in harvesting and preprocessing systems; however, if this can be accomplished, all lignocellulosic biomass material (energy crops, residues, wood, and manufacturing wastes) will be in standardized, common-physical-properties formats that can be handled by common supply system infrastructures.

A standardized feedstock format system should appeal to feedstock producers and processors alike by allowing both parties more flexibility in contracting and marketing feedstocks (i.e., single processor and producer relationships are no longer inseparably linked). Additionally, the Advanced Uniform design will establish lignocellulosic biomass as a true commodity that is not limited to local markets, thus setting the stage for development of larger-scale and more efficient conversion facilities.

1.3 Design Scope for Uniform-Format Woody Feedstock Supply System

The scope of the feedstock designs described in this report replaces Area 100, the “feedstock handling” design sections of the biochemical (Aden et al. 2002) and thermochemical (Phillips et al. 2007) conversion platforms. It is also important to note that the “plant gate” (point of transition when product is transferred to biorefinery) boundary is not a supply system design boundary in this report (Figure 1-1, Figure 1-3, and Figure 1-5). Rather, this design report considers all supply system elements, from the standing biomass, to the point of insertion into the biorefinery conversion process reactors. It is also important to note that woody biomass supply systems have no financial transaction when the material leaves the landing; however, in herbaceous systems, a financial transaction does occur when the biomass leaves on-farm storage (i.e., the farm gate).

The content boundaries of this design report are as follows:

- The designs are modeled as woody feedstock supply systems.
- The wood product feedstock supply infrastructure is a mature and well-proven industry. The bioenergy woody supply system will likely evolve from the current wood supply systems and will include some of the nontraditional woody resources, such as forest thinnings, logging residues, new

woody energy crops, urban wood residues, and other woody resources that are currently not handled in traditional wood-product industry supply systems. Harvesting and preprocessing systems to make these resources available and adaptable to the current supply chain and/or future advanced-uniform bioenergy supply chains will be required.

- While this design encompasses all feedstock logistics activities, from harvest to insertion into the conversion process, the feedstock production costs and quantity issues (i.e., resource production) are not addressed in this report. The models in this report focus on improving feedstock logistics efficiencies/cost and use a baseline feedstock production quantity/cost input.
- This report assumes that all feedstock passing through the supply system meets conversion process quality specifications, and supply system quality control measures are assumed to be inherently acceptable for all designs. This is a recognized over-simplification, and these design elements must be more fully addressed in future studies.

While this design report focuses solely on the feedstock-supply logistic elements from harvest to conversion reactor handling and queuing systems, it is recognized that no part of the system is truly independent. As such, the designs presented herein include a high degree of coordination with feedstock production systems and conversion processes. In fact, this coordinated approach forms the basis for the uniform-format feedstock supply system design concepts. Cost and technology barriers within the feedstock supply system are identified by evaluating each unit operation with respect to four established metrics:

- *Stumpage Fee (also called Grower Payment)*. A fee paid to the landowner for the rights to harvest woody biomass, or the cost value assigned to access a given quantity of biomass in the forest. (This is not a forest landing value.)
- *Inputs*. The operational costs – as influenced by materials, supplies, labor, logistical issues, and material losses – associated with particular equipment configurations. (May also represent direct energy consumption.)
- *Outputs*. The material throughput of particular equipment or sets of equipment.
- *Quality*. The product specifications, value, and functional end-product yields of the biomass passing through the supply system. Quality is intrinsically linked to capacity and efficiency.

These metrics constitute the core criteria for comparing and optimizing the logistics of different feedstock supply systems. Equation 1-1 is a simplified but accurate representation of the overall feedstock supply logistics design model.

$$FeedstockCost\ (\$/ton) = \underbrace{StumpageFee\,(\$/ton)}_{a} + \underbrace{\left[\frac{Inputs\ (\$/hr)}{Outputs\ (ton/hr)}\right]}_{b} \pm \underbrace{Quality\ (\$/ton)}_{c} \tag{1-1}$$

The *inputs by outputs* element (b) represents the engineered logistics systems from the field to the conversion process and forms the basis of this design document. Though not represented in the equation, the design scenarios modeled in this report also include direct energy consumption per ton for determining the overall delivered feedstock cost (in total dollars or direct logistics energy consumed) to the biorefinery.

The feedstock logistic design models presented herein do not include the *stumpage fee* (a) or the biomass *quality* (c) elements.

The *stumpage fee* (also called grower payment) element (a) is an input into the design models; however, calculations of *stumpage fee*, which represent resource cost and availability, are purposely omitted from the scope of this design document because they do not describe or directly constrain the engineering operations or the logistics of the supply system. The *stumpage fee* is a model input parameter meant to represent a variety of non-engineering costs, such as production, nutrient replacement, grower participation, market demands, etc. A host of resource assessment, forestry, and production management models may be used to quantify *stumpage fee* input parameters. The resource assessment tools include POLYSYS as a policy and grower decision modeling framework, and the suite of U.S. Department of Agriculture (USDA) Forest Service productivity databases. *Stumpage fee* element input modeling is not described in this report.

The biomass *quality* element (c) represents the interface with the biorefinery conversion processes. Like *stumpage fee*, this is a credit or debit input into the feedstock design logistics models. The respective credit or debit can be calculated using process models representing the respective conversion processes, such as those described in Aden et al. (2002) and Phillips et al. (2007), which were modeled using Aspen Plus. Biomass *quality* input modeling is not described in this report.

Because this report is focused on supply logistics and a subset of biomass resources, interface input assumptions have been simplified and/or assumed constant, and extensive analysis and discussion of these elements are not within the bounds of this design document. However, the reader should not conclude that these interface externalities (i.e., resource production and delivered quality) and other resources (i.e., dry herbaceous) are of lesser importance or have little or no impact on supply system performance. The reality is that both feedstock resource and conversion interface assumptions can greatly impact supply system design and performance, and all of the analysis models used for these designs require resource input and quality output data to function properly.

1.3.1 Feedstock Supply System Processes

The feedstock supply system processes encompass all the activities necessary to move lignocellulosic biomass feedstock from the place where it is produced to the point of insertion into the conversion process ("reactor throat") of the biorefinery. These feedstock supply system processes can be generally grouped into five unit operations (Figure 1-7) (Hess et al. 2003):

- *Biomass Production* is the beginning of the feedstock supply chain and involves producing biomass feedstocks to the point of harvest. Production addresses important factors, such as selection of feedstock type, land-use issues, policy issues, and agronomic practices that drive biomass yield rates and directly affect Harvest and Collection operations.
- *Harvest and Collection* encompasses all operations associated with getting the biomass from its production source to the queuing location, which is usually the landing. For woody biomass this includes felling and forwarding/yarding.
- *Storage and Queuing* are essential operations in the feedstock supply system and are used to accommodate seasonal harvest times, limited operational windows, variable yields, and delivery schedules. The objective of a storage system is to provide the lowest-cost method (including cost incurred from losses) of holding the biomass material in a stable form until it is called for by the biorefinery.
- *Preprocessing* must occur prior to conversion to physically transform the feedstock into the format required by the biorefinery. Preprocessing can be as simple as grinding and formatting the biomass for increased bulk density or improved conversion efficiency, or it can be as complex as improving feedstock quality through fractionation, tissue separation, drying, and blending. In many conventional woody designs, an initial preprocessing operation occurs at the landing (comminution), and there may be further preprocessing operations at the conversion site.

- *Transportation, Receiving and Handling* consists of moving the biomass from one point to another, and occurs throughout the supply system. Transportation options are generally fixed and well-defined for respective locations throughout the country and can include truck, rail, barge, or pipeline. The system used will directly affect how the feedstock is handled and fed into the conversion process. Transportation, receiving and handling methods are highly dependent on the format and bulk density of the material, which makes them tightly coupled to each other and all other operations in the feedstock supply chain. Feed handling includes unloading the biomass from the trucks (or other transport medium) at the plant-receiving yard, transporting it into short-term storage (queuing), and transferring it from storage to the plant for the pretreatment process. Feed handling systems are also integral parts of harvesting, collection, and preprocessing.

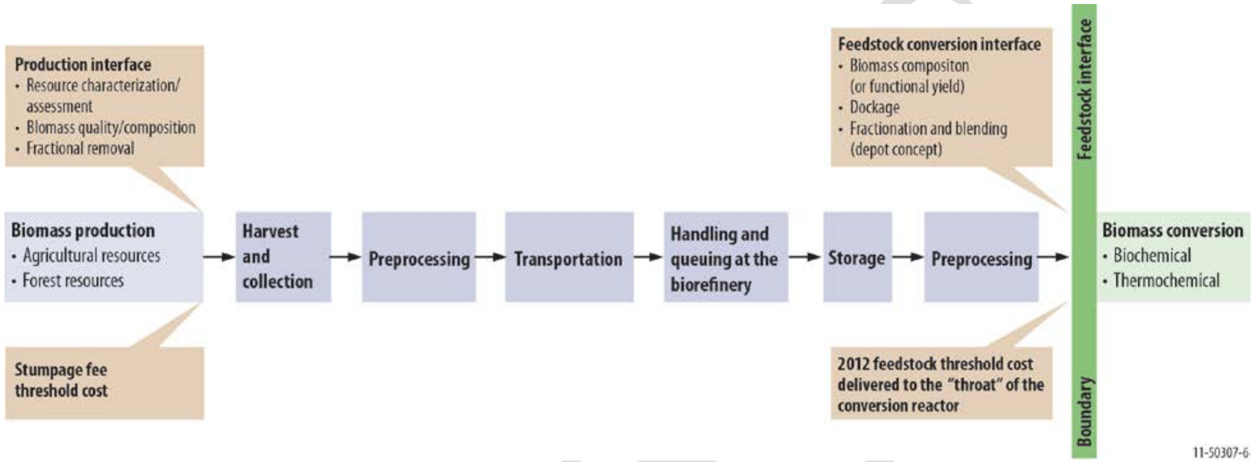

Figure 1-7. Schematic and boundaries for a lignocellulosic feedstock supply system design that allows unit operations to be reordered to achieve optimum supply system performance. Note that the order of operations may change, depending on the supply-chain arrangement.

As this design report will demonstrate, these processing operations can be rearranged and even implemented at various stages to optimize not only the supply system efficiencies, but also the external processes, like conversion facilities. Recognizably, transportation and handling happen throughout the supply system.

While various business units may be involved in or control these unit operations, the system in this design report is defined by the technical unit operations of the feedstock supply system, rather than the business and/or transaction boundaries. In technology selection and design, however, recognition of these business units and transaction boundaries throughout the supply system is very important.

Of the feedstock supply system unit operations, producers are responsible for harvest, collection, delivery to storage or the landing, and, in the case of woody biomass, delivery to the biorefinery. These assembly functions are integral to production and, thus, remain under the producer's control[a] (even if the producer chooses to have them performed by others). Often, the biorefinery transaction is based on feedstock value in addition to these operations at the point of production.

Each of the business elements of the feedstock supply chain must work seamlessly with the others to provide biomass to the biorefinery. However, the seamless integration of business elements does not mean the entire biomass production, supply, and conversion system must employ common technologies and decision criteria. In fact, it will not use common technologies nor decision criteria, and as a result, production costs will vary across feedstocks and regions. Thus, supply system designs and technology

a. Note that this is assuming private land ownership for woody biomass.

selections are not constrained by landing or plant-gate boundaries, but they do consider technologies and costs in terms of landing and plant-gate interfaces.

1.3.2 Design Cost Targets for the Feedstock Supply System

A state of technology (SOT) of the Advanced Uniform design has also been established and contains currently available technologies capable of meeting the feedstock material performance targets. The various types of SOT equipment used in this design are not currently cost effective due to high energy inputs, interface inefficiencies, and the need for advanced technologies. Nevertheless, the basic unit operations of the Advanced Uniform design have clearly definable performance targets that will improve equipment efficiencies and capacities while enhancing feedstock quality. A discussion of the unit operations that make up this design is found in Section 1.3.1. Fundamentally, this design would add to, or at least maintain, the value of the biomass feedstock as it passes through each unit operation.

Initially, the Advanced Uniform design will require a feedstock format change to bulk dry or liquid-based material, which will increase the cost of the feedstock supply system. However, when considering that the Advanced Uniform design is targeted to overcome the challenges associated with feedstock diversity, this transition puts the supply system on an appropriate path to meet both cost and tonnage targets for all types of biomass feedstocks.

1.4 Analysis Approach

A primary objective that drives the feedstock supply system designs is the selection of technologies that are adaptable to existing local feedstock resources and infrastructures. Conventional and Pioneer designs represent feedstock supply system technologies, costs, and logistics that are achievable today for supplying lignocellulosic feedstocks to pioneer biorefineries. Efforts are made to optimize the efficiency and capacities of these supply systems within the constraints of adapting to existing local feedstock supplies, equipment, and permitting requirements.

For any supply system design (Conventional, Pioneer Uniform, or Advanced Uniform) to be truly functional, it must demonstrate the ability and flexibility to physically and logistically couple to the resource. The analyses of Conventional and Pioneer Uniform designs are accomplished through the coupling of existing technologies with existing available biomass resources, where the diversity of the resource is managed by the selection of appropriate equipment and supply system logistics. The analyses of Conventional and Pioneer Uniform feedstock supply systems are also highly location dependent—location determines the feedstock type, the quantity of available feedstock, the timeframe for harvesting and collecting the feedstock, weather considerations relating to storage options, and the infrastructure restrictions that govern the quantities of biomass that can be transported on the roadways. The analysis of the Advanced Uniform design, like the Conventional and Pioneer Uniform designs, demonstrates flexibility in coupling to the resource but diverges from the Conventional and Uniform-Format designs in that all resources are preprocessed into a standardized commodity format as early in the supply chain as possible for the respective resource.

1.4.1 Resource Coupling Analysis

For the purposes of the analyses within this report, the resource coupling analysis is simplified. However, the key elements of resource coupling that impact technology selections within the logistic designs are important design considerations.

In addition to the biomass resource cost, quantity (i.e., yield/acre and quantity/square mile), and physical characteristics, other issues come into play, including merchandizing biomass to multiple markets (i.e., food, feed, lumber, or fiber versus fuel), sustainability, and local environmental and/or production system constraints. This report groups these issues into five key resource-supply factors that impact the functional connection of the feedstock supply system to the biomass resource:

- Unique physical and compositional diversity of the various biomass crops

- Sustainable biomass removal
- Harvest and Collection access priority relative to other biomass uses
- Typing or grouping according to critical feedstock characteristics
- Contracting interface to feedstock resources.

1.4.1.1 Unique Physical and Compositional Diversity of Various Biomass Crops

This resource supply factor refers to variables in the diversity of feedstock resources that the supply logistic designs must accommodate, which include (1) identification of the resources and the associated characteristics of each, and (2) assessment of the volume of resource that exists or could potentially exist (that is, total quantity, yield/acre)

The Billion Ton Study (Perlack et al. 2005) identified more than 1.3 billion tons of biomass feedstock resource potential in the United States (Figure 1-8). Unlike other major commodity crops, the billion-ton resource for biofuels is comprised of many underused or unused resources that collectively comprise the major biomass resource for the biofuels market (Figure 1-9). In some cases, such as the removal of residues that may pose a fire threat, there are other added benefits to diverting the material to bioenergy uses. Specific to woody resources, the amount of wood materials harvested from timberlands in the United States is less than the annual forest growth and considerably less than the total inventory. This difference offers the opportunity for expanding use as a biofuels resource, and significant quantities have been identified by the U.S. Forest Service as needing to be removed to improve forest health and reduce the risk of fires (Perlack et al. 2005).

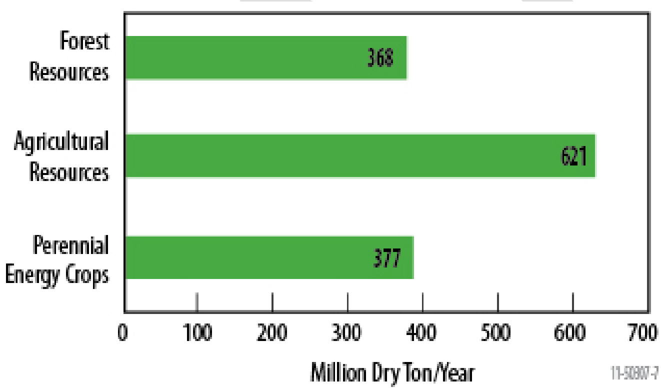

Figure 1-8. The U.S. agricultural and forest lands resource potential as projected by the Billion Ton Study (Perlack et al. 2005).

While the design objective of the Uniform-Format concept is to accept and manage this resource diversity and create a commodity-scale biomass feedstock for biorefining, the actual design scenario analyses rely on a subset of model feedstock resources. The analyses for the Conventional system are limited to woodchips produced from comminuting delimbed, debarked, small-diameter trees, which have become available due to the recent decline in the pulpwood industry (Johnson and Steppleton 2005). Many of the 368 million dry tons of forest resources available per year are currently unexploited (Figure 1-9), and the Pioneer Uniform and Advanced Uniform systems are modeled using a combination of these resources, including thinnings (also termed fuel treatments). The costs of using forest thinnings in the advanced systems may be compared to the use of slash (the tops and limbs that accumulate when trees are delimbed to produce logs). Note that as short-rotation forestry production would likely occur on agricultural lands (Perlack et al. 2005), this production is considered part of the herbaceous analysis (available at www.inl.gov/bioenergy/uniform-feedstock).

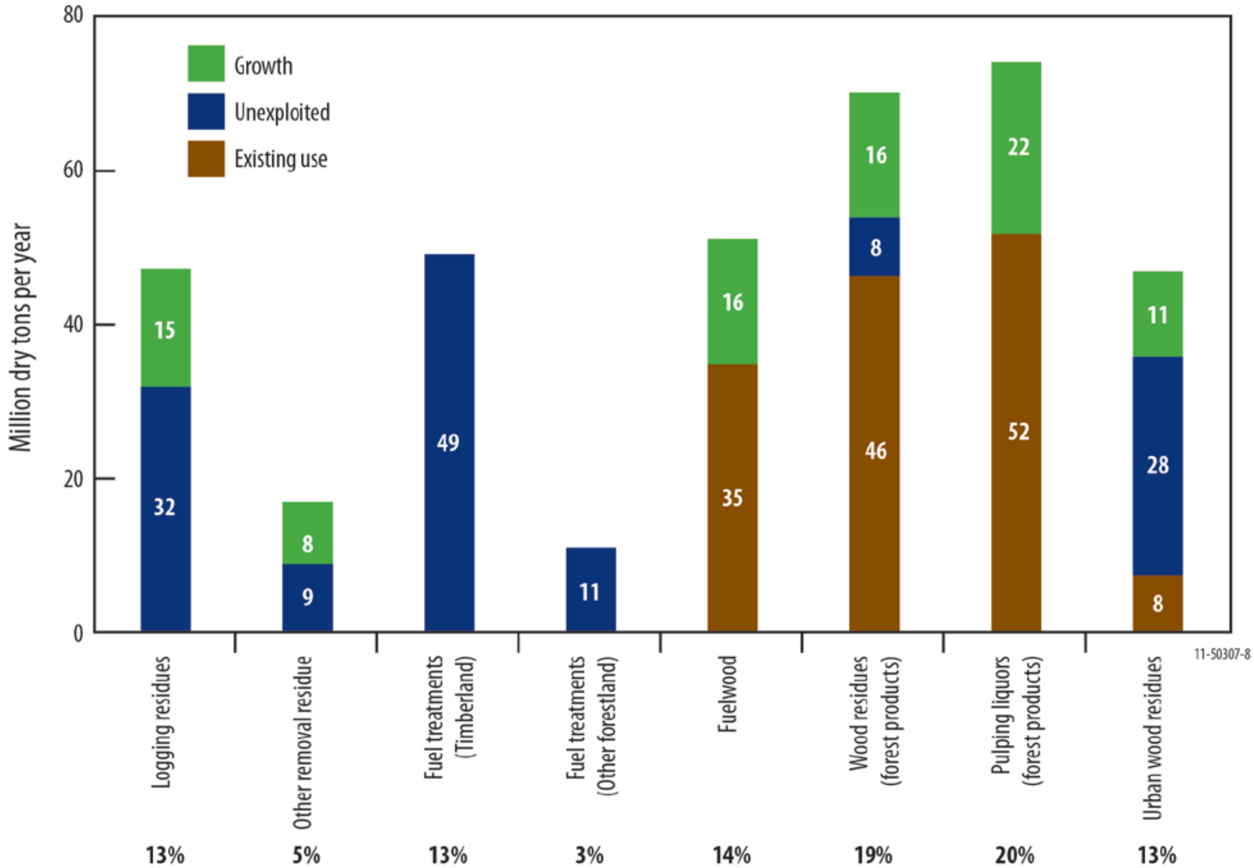

Figure 1-9. Estimate of available forest-derived biomass resources, including materials under existing use, those that presently exist, but are unexploited, and materials projected to become available in the future (Perlack et al. 2005).

Finally, supply logistics are highly dependent on biomass quantity per area, distribution of biomass (for example, stand distribution for woody resources), and biomass yield per acre. For woody resources, the yield is also highly dependent on the frequency of harvest. The modeled yields are estimated from values reported by the U.S. Forestry Service and cited in literature (e.g., Stokes and Watson 1991, Hartsough et al. 2002). Residue-to-wood ratios vary depending on tree variety, physiological factors such as plant maturity and stress, and planting density (Kemanian et al. 2007). The residue-to-wood ratio used for the designs and analyses in this report are the same as those used in the biomass yield estimates in the Billion Ton Study (Perlack et al. 2005).

1.4.1.2 Sustainable Biomass Removal

Although certain areas will have a gross annual yield of biomass, not all of the biomass can be collected and used for bioenergy. The net yield must be discounted according to two factors: (1) the collection efficiency (field losses) of the equipment used to collect the residue and (2) the amount that must be left in the forest to satisfy agronomic issues, such as erosion control, soil carbon management, and soil nutrient replacement.

Field losses are generally represented in terms of harvest efficiency, which is defined as the ratio of the residue mass harvested to the mass available in the forest. Although there are large variations in these values, depending on such factors as terrain, tree type and age/size, climate, and operator experience, the materials that generally fall off and are not collected are the nutrient-rich components (needles and leaves) that promote forest soil health. Harvest efficiency is affected by many variables, including moisture content, weather during harvesting, size of material (whole trees vs. residues), ability of machinery to collect biomass from the ground, stand distribution, and terrain.

The amount of biomass that must be left on the ground following biomass removal to maintain soil health and biomass sustainability is an important consideration of feedstock supply system design. Sustainable residue-removal limits depend on soil types, rainfall conditions, tree types and varieties, yields, and harvesting methods; thus, residue maintenance requirements (RMRs) are highly variable and site-specific (Perlack et al. 2005), and establishing national-level RMRs is a challenge. National RMR estimates for minimizing wind and rainfall erosion to soil erosion tolerance (T) levels were presented in the Billion Ton Study (Perlack et al. 2005) based on analytical studies conducted by Graham et al. (2004) and Walsh (2004). Soil carbon and nutrient replacement are additional considerations affecting residue removal rates, and in some locations, the residue removal limits for these may be even more conservative than the removal limits to maintain T levels. As shown in Figure 1-11, significant amounts of material remain on the field after harvest.

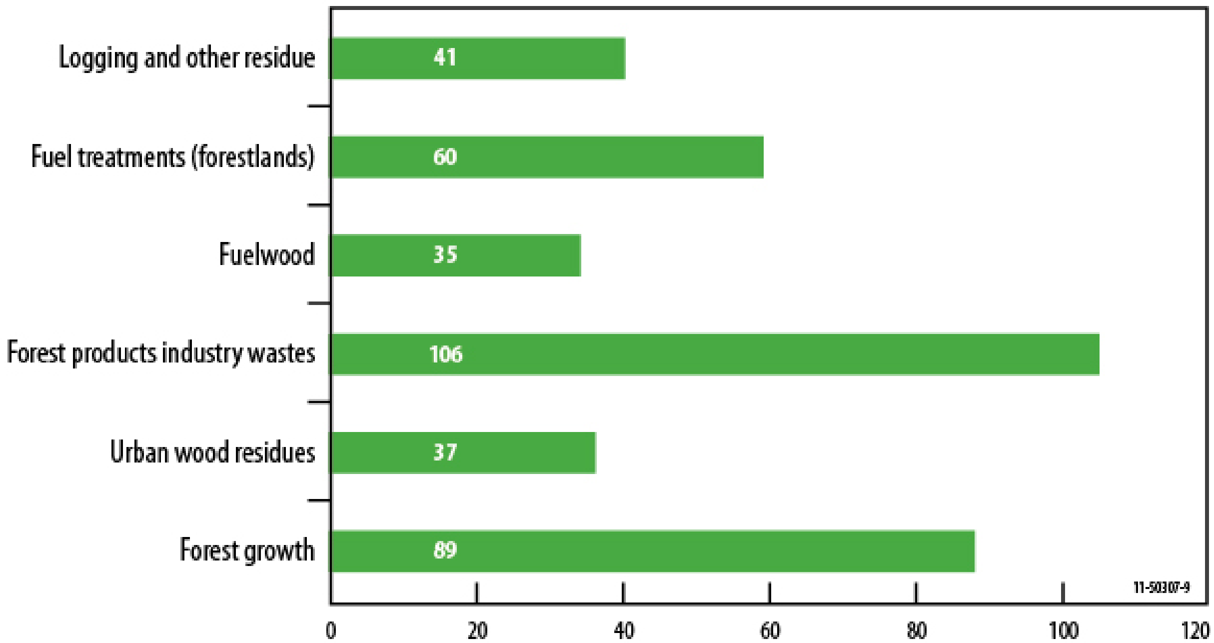

Figure 1-10. Estimated sustainable material recoverable from forest biomass (Perlack et al. 2005).

Figure 1-11. After the merchantable timber was harvested, slash and small trees were harvested and ground for hog-fuel. The remaining material is shown above (Photo credit: D. Brad Blackwelder, INL).

The objective of this report and the feedstock designs herein is to represent the capabilities of the engineering system. Thus, we set the removal rate in the feedstock model (used in developing the feedstock designs presented in this report) to 100% to prohibit the impact of sustainability factors on the engineering design.

The Billion Ton Study (Perlack et al. 2005) projects that biomass removal rates will increase with equipment improvements, better organized and more extensive collection programs, and increased collection incentive; however, some residue will always need to be left in the field to maintain soil tilth (a soil's ability to support root growth). Fortunately, in the case of woody biomass, the parts of the tree more inclined to fall off and be left in the field (i.e., needles and leaves) contain the highest nutrient content and are best suited for soil health, while fractions best suited for biofuels production are collected. Therefore, sustainable residue removal rates may be even higher than the Billion Ton Study projections.

1.4.1.3 Harvest and Collection Access Priority Relative to Other Biomass Uses

Access priority is a feedstock logistic perspective of the more commonly referenced issues of food, feed, and fiber versus fuel and land-use allocation. In other words, it is the availability of that resource for the biomass-for-biofuels market relative to other potential uses or markets. The larger issue is how to sustainably and equitably balance these competing demands, but from a feedstock supply perspective, it is the ability of the biomass-for-biofuels market to bring a particular resource into the supply system relative to that resource being diverted to other uses or market.

These issues have two major impacts on supply system designs: (1) to define the minimum land area (i.e., square miles or acres) needed to produce the quantity of biomass required for the biorefinery and (2) to assess the available resource mix (i.e., primary, secondary, or tertiary [Perlack et al. 2005]) within that land area. It should be noted that yield can impact availability and access to a resource, but it is not the primary factor considered here. Access priority involves competition for the resource and the land to produce the resource, producer socioeconomic participation basis, and/or, in the case of residues, agronomic cropping practices (i.e., sustainability removal limits) that allow for the biomass residue to be accessed and removed. Defining the required land area establishes transportation distances and storage/preprocessing depot locations, and even characterizes the level of grower participation.

These design analyses operate under the simplified assumptions that sufficient biomass quantities can be accessed within a cost-effective transportation radius of the final biorefinery delivery point and that grower participation in lignocellulosic biomass production (including grower's decisions on land-use allocations) is equally distributed throughout that radius. Because the resource mix can significantly impact supply system designs, these design analyses focus on woody biomass, which represents primary resources. Secondary (i.e., manures, processing residues) and tertiary (i.e., MSW and post-consumer residues) feedstocks can be accommodated in these designs, but are not included as part of the detailed cost and logistics analyses.

1.4.1.4 Typing or Grouping According to Critical Feedstock Characteristics

For the purposes of developing supply system technologies and designs, all feedstocks can be categorized into either dry or wet feedstock types. This classification is representative of major differences in supply system technologies, equipment, and methods that must be employed to handle each respective biomass. The feedstock types, particularly herbaceous biomass, are segregated with respect to moisture content because feedstock moisture content, in many cases, dictates the processes that must be employed to manage these biomass feedstocks.

While all supply system design concepts presented herein accommodate both resource types, detailed design analyses and modeling are limited to wet feedstock resources.

1.4.1.5 Contracting Interface to Feedstock Resources

Feedstock resources are accessed through contracts with the biomass producers. The assumed contracting mechanisms include the following:

- Biorefinery or some other entity contracts directly with the producer for a multiyear access agreement
- Producer sells to the biorefinery or other biomass purchasing entity on the “spot market” (purchases from the open market at the time of need) but does not have a multiyear agreement
- Producer sells into a commodity lignocellulosic market that does not currently exist, but is assumed to have the same characteristics and features of the existing major crude oil markets
- For the conventional and pioneer-uniform designs, it is assumed that 100% of the projected biomass resource needs of the biorefinery are directly contracted with the producer, and that any shortfalls caused by annual yield variations could be filled with “spot market” purchases.

The impact of this assumption on the supply system design is this: harvesting, collection, and storage capacities do not exceed the annual quantity of biomass required by the biorefinery, nor is any portion of the biomass material stored beyond one year. The Advanced Uniform design assumes that the future commodity marketing strategy for lignocellulosic biomass (as it relates to biomass receiving, preprocessing, and storage systems) will functionally resemble grain elevators/depots or petroleum terminals that deliver a standardized product to the biorefinery as it is needed.

Regardless of the contracting mechanism, feedstock value for the biomass (the price that must be paid to the producer) must be determined. Different feedstocks have different median and average values (Foust et al. 2008), and their price ranges vary from less than $10 per DM ton to $40 per DM ton, or more (Perlack and Hess 2006). Feedstock values are difficult to assess because there are no major markets for crop residues, energy crops, or many varieties of woody biomass. Also, values are affected by limited, regional-scale markets, such as fiber, feed, and animal bedding.

The design analyses include feedstock cost as a total stumpage fee (or in the case of herbaceous residues, a grower payment) that is added to the summed logistics costs. This stumpage fee represents all of the complexities of the feedstock interface, and realized costs will be subject to contract arrangements and producer enterprise variables, such as management decisions on species, harvest frequency, soil organic matter, and field-operations impacts and offsets (Turhollow et al. 2008). It is important to note that stumpage fee *does not* represent a farm-gate or forest-landing pricing structure. For these design analyses, stumpage fee represents the price paid for the biomass in the field or on the stump, and there are *no* logistic cost assumptions included in the stumpage fee cost input.

1.4.2 Biorefinery Coupling Analysis

The biorefinery coupling analysis, like the resource coupling analysis, is generally oversimplified. This report assumes that the biomass that is supplied through the logistics system will meet biorefinery quality assurance and quality control specifications without requiring additional treatment or amendments that would add additional costs to or otherwise perturb the supply system. As such, quality credits or debits (dockage) are assumed to cause no logistical impact and to have no impact on feedstock costs. In reality, this is not the case, especially when considering that a fundamental design concept of the Uniform-Format supply system is to control and mitigate quality perturbations through significant advances in preprocessing and feedstock blending.

1.4.3 Economic Analysis

Two widely accepted engineering-economic costing methodologies for agricultural equipment have been developed by the American Society of Agricultural and Biological Engineers (ASABE) and the American Agricultural Economics Association (AAEA). The two methodologies largely use the same equations and machinery data, but the AAEA method incorporates several additional cost factors that the ASABE method does not. The two methodologies were reviewed and compared by Turhollow and Sokansanj (2007), who compiled a recommended standard costing methodology for biomass. While the ASABE and AAEA methods apply specifically to machinery, Turhollow and Sokansanj (2007) extended the methodology to include buildings, shelters, and transportation and handling equipment associated with biomass supply and logistics.

The cost methodology described by Turhollow and Sokansanj (2007) was used to develop the feedstock cost model. The two-step process for biomass costing includes (1) the calculation of machinery cost (represented in $/hr or $/DM ton), and (2) the calculation of machinery performance (generally represented in $/ton). An overview of the methods and considerations for calculating these two cost parameters is presented in the following two sections.

1.4.3.1 Equipment and Buildings Costs

The cost calculations for equipment, buildings, and other handling and processing equipment generally follow the methodology described by Turhollow and Sokansanj (2007). These costs are categorized as ownership costs and operating costs. Ownership costs are generally represented in $/yr and operating costs in $/hr. For the machinery cost calculations in our analyses, the annual usage (in hours) was calculated based on the operational window, machine capacity, and number of machines, and the ownership costs in $/yr was divided by the annual use in hours, to provide an hourly ownership cost. The ownership cost ($/hr) and operating cost ($/hr) was summed to provide a total hourly machinery cost. For these designs ownership and operating costs included in the economic analyses are as follows:

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

- Labor.

All costs are based on values obtained for a particular year. For example, the cost of a harvesting machine may be based on a vendor quote obtained in the year 2005, while the cost of diesel fuel for this equipment may be based on fuel prices in 2008. To normalize costs to a common cost basis, so that analyses can be performed for years other than those in which the costs were obtained, and to avoid the need to update costs annually, a method was developed to allow backcasting to previous years and forecasting to future years. For cost items in which a cost database exists with current and historical costs recorded on at least an annual basis, this database is integrated with the feedstock cost model. For current year and backcasting analysis, the database is simply indexed to the appropriate cost year. For forecasting, the values in the database are regressed to a simple equation for extrapolating to future years. Cost databases are included for estimating fuel prices, labor rates, and land rent values. These databases are generated from data provided by the Energy Information Administration, the U.S. Department of Labor – Bureau of Labor Statistics; and USDA-NASS.

For other cost items (e.g., capital costs or repair and maintenance costs) for which historical cost records do not exist, a representative cost index is used to estimate the backcasted and forecasted costs. The USDA-NASS publishes monthly Prices Paid by Farmers indexes that represent the average costs of inputs purchased by farmers and ranchers to produce agricultural commodities and a relative measure of historical costs. For machinery list prices, the Machinery Index is used, and for machinery repair and maintenance costs, the ASABE R&M factors are used, and for machinery salvage values, the ASABE Salvage factors are used. These USDA-NASS indexes are used for all equipment used in the feedstock supply system analysis, including Harvest and Collection equipment (fellers, skidders, balers, tractors, etc.), loaders and transportation-related vehicles, grinders, and storage-related equipment and structures. For the plant handling, queuing, and storage equipment, such as conveyors and storage bins, the Chemical Engineering Plant Cost Index is used.

1.4.3.2 Equipment Performance

Biomass costs are calculated after the machine has performed a function on the product or on the land; these costs are a function of machinery performance and are expressed in \$/ton, \$/item (e.g., tree or ft^3), or \$/acre (e.g., harvesting a stand in \$/acre, grinding the biomass in \$/ton). For calculating these costs, the operating characteristics of the machines are needed, such as speed, efficiency, width of operation, moisture content, and/or throughput. Machine speed, capacity, or throughput are rarely provided by the manufacturer because of the variability attributed to factors like operator skill level, field conditions, feedstock type and conditions, and equipment conditions (e.g., how well it has been maintained). Consequently, equipment performance can be quite difficult to identify.

Several sources of equipment performance data are used in the cost analyses described in this report. In some cases, the capacity is determined from time-in-motion studies, and in other cases, it is determined from typical machinery speeds published in ASAE D497.5 (ASABE 2006) or from data provided by expert operators (e.g., custom harvest operators). The source of machinery performance data is noted in the cost analyses presented in this report.

1.4.3.3 Biomass Cost

As described in Section 1.4.3.1, ownership and operating costs are calculated for all processing machinery, handling and transportation equipment, and storage and queuing infrastructure throughout the supply chain. These costs are summed to provide an hourly usage cost (\$/hr) machinery and a yearly usage cost (\$/yr) for infrastructure. The hourly costs (\$/hr) are then divided by the machine capacity (ton/hr), and the yearly costs are divided by the annual tons processed to give a \$/ton for each operation. Finally, the feedstock cost (FC) is determined by summing the machine cost per ton for each piece of equipment used in the supply system analysis as shown in the following equation:

$$FC(\$/ton) = \sum_{i=1}^{i=n} \frac{\$/hr}{ton/hr} \qquad (1\text{-}2)$$

where

n = number of unit operations within the supply system.

Additionally, the number of machines or equipment required in particular unit operation is determined by using the following equation:

(1-3)

where

Q_{eq} = the quantity of equipment

$D_{tons/acres}$ = the processing demand for the equipment, given in acres or tons

C = the equipment capacity, given in acres/hr or ton/hr

t = the amount of time (hr) available for the operation.

Finally, the total annual costs are determined by summing the operating costs ($/ton) for each piece of equipment and multiplying the sum by the total annual tonnage (800,000 tons) processed by this equipment. The total capital investment is determined by multiplying the number of equipment units by the equipment purchase price for each piece of equipment used in the supply system analysis.

1.4.4 Energy Use Analysis

Energy consumption is of particular importance in analyzing feedstock supply system designs. Energy consumption throughout the supply chain unit operations is calculated based on each piece of equipment's estimate of fuel or electricity consumption.

When available, diesel fuel consumption estimates are based on actual consumption estimates from either equipment specifications or manufacturer or dealer quotes. For equipment where specific fuel consumption is not available, the following equation is used to estimate the average annual diesel consumption (ASABE EP496.2, 2003):

(1-4)

where

Q_{avg} = average diesel consumption, (gal/hr)

P = maximum power take-off (PTO) power, (hp)

Equation (1-4) was approximated from the Nebraska Tractor Test Data, but for the analyses in this report, the rated engine horsepower was substituted for the maximum PTO power in the above equation. Further, dividing the annual fuel consumption by the annual hours of use gives the hourly fuel consumption. The energy consumption values given for diesel-powered equipment are calculated by simply converting gallons of diesel to BTUs using the following conversion factor (ORNL 2009):

- 1 U.S. gallon diesel = 130,500 BTU

Thus, the following equation represents the energy consumption of diesel-powered machinery.

- (Gallons/hr) * (130,500 BTU/gallon)/(ton/hr) = BTU/ton.

Likewise, for electrically powered equipment (e.g., conveyors), energy consumption is based on the rated horsepower of the electric motor, according to the following conversion factor (ORNL 2009):

- Horsepower (hp) = 2545 Btu/hour.

The energy consumption in BTU/ton for electric-powered equipment is then calculated by

- (Horsepower) * (2,545 BTU/hr)/(ton/hr) = BTU/ton.

Thus, the energy consumption values presented in this report represent direct BTU calculations (that is, fuel consumed) and do not include indirect BTU calculations associated with the production of the supply system equipment, replacement parts, etc.

1.4.5 Sensitivity Analysis: Implementing the Feedstock Supply Model

Sensitivity analyses were conducted for each of the design scenario using the PowerSim sensitivity analysis feature. PowerSim takes a systems approach to modeling based on positive and negative feedback, and accumulations and flows. Variables within the model are assigned probability distributions and ranges determined from research and documentation. For each sensitivity run, a value is randomly selected for each variable from each probability distribution and computed as one scenario of the model. This process is repeated thousands of times and the results are collected. A statistical analysis provides the confidence interval, mean, and standard deviation for the overall sensitivity analysis.

The parameters that are included in the sensitivity analysis vary between design scenarios because the model input is different for each of the scenarios. The parameters generally include the following:

- 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 hr/day
  - Feedstock inventory

- Feedstock bulk density.

For each of the selected input variables, a range (including a minimum and maximum value), most likely value and probability distribution were identified. A triangular distribution was used to describe the probability distribution of most input variables and is appropriate due to the small amount of data available.

We chose a Latin Hypercube analysis for a variable selection criterion for each sensitivity run.

2. CONVENTIONAL WOODY BIOMASS SUPPLY SYSTEMS

As outlined above, the primary objective of the conventional biomass feedstock supply system designs is that they are constructed using technologies that are adaptable to existing local feedstock resources and biomass infrastructures. Conventional designs represent feedstock supply system technologies, costs, and logistics that are achievable today for supplying biomass feedstocks to pioneer biorefineries. This report outlines two conventional woody biomass design scenarios, one that delivers a woody biomass feedstock to the biorefinery that does not meet a material specification (the "Base Case Conventional" scenario), and another that meets DOE cost targets and delivers an on-spec material to the throat of the gasification conversion reactor (the "Low-Ash/Low-Moisture Conventional" scenario). The two designs reflect examples of the range of material quality that exists even within the modeled niche feedstock. The impact of material quality on conversion is briefly outlined in Section 2.3, "The Conversion Interface."

Both the Base Case and Low-Ash/Low-Moisture Conventional designs are based on a specific feedstock, southern pine pulpwood. The assumption of a niche feedstock allows conventional systems to meet DOE cost targets. However, an expanding bioenergy industry will require a broader biomass feedstock source, and therefore advanced designs presented in this report include more resources and a modified design to accommodate these resources.

2.1 Base Case Conventional Woody Feedstock Supply System

The scope of the Base Case Conventional Woody feedstock supply systems 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 whole-cut southern pine trees on private commercial lands. The trees are chipped whole at the landing. Figure 2-1 shows the process flow for the Base Case Conventional system.

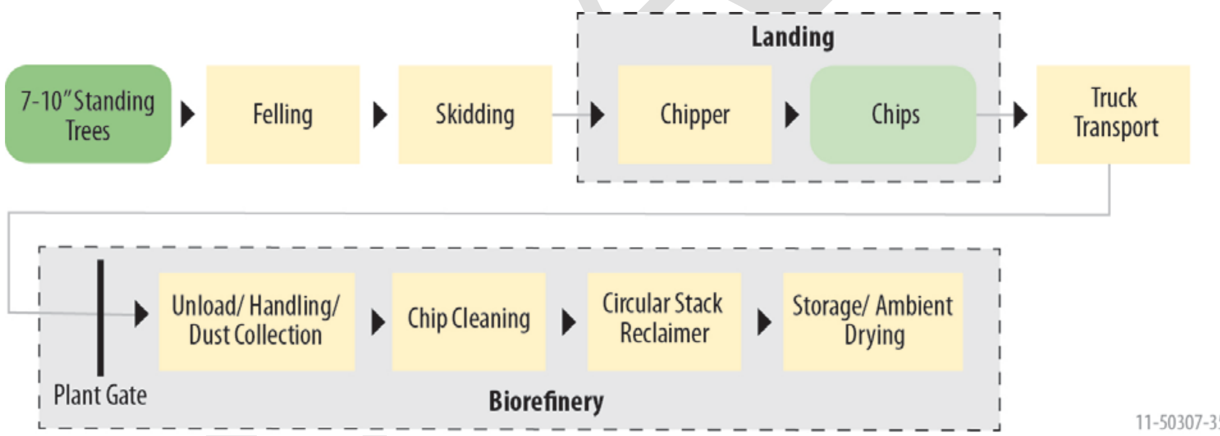

Figure 2-1. Order of unit operations in the Base Case Conventional Woody feedstock supply system design. Operations occurring at the landing are shown in the upper gray square, while operations occurring at the biorefinery are shown in the lower gray square. *Note: Yellow rectangles represent individual modeled processes, while green ovals represent changes in format intermediates.)*

In the Base Case Conventional design, whole trees are cut, skidded to the landing, and chipped whole. These chips are blown into a truck and transported to the biorefinery. (Note that the Base Case Conventional Woody design is not designed to meet a particular material specification and is instead based on common currently used supply systems designed for other industries.)

The Base Case Conventional system is presented by discussing each major supply system unit operation in the respective order of appearance in the design. The units of operation in the conventional system are as follows:

- Harvest and Collection
- Preprocessing
- Transportation
- Receiving and Handling
- Storage.

The backbone of the modeled supply system design is the flow and format changes of biomass material as it passes through the individual supply system processes, from the production location to the biorefinery conversion processes (Figure 2-1).

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. Within each unit operation section of this report, the modeled attributes of all biomass material intermediates (hereafter referred to as “format intermediates”) are identified, and variances in those attributes are discussed to provide a better understanding of how supply system performance is, or may be, affected by feedstock format intermediate attributes. Additionally, the specific machinery modeled for the processes of each unit operation is described in terms of its respective purpose and function.

The modeled feedstock system is designed to supply a biorefining facility with 800,000 DM tons of biomass annually (Table 2-1). The supply system design does not meet any specific material quality specification.

Table 2-1. Base Case Conventional supply system design annual capacity assumptions for woodchips.

	Woodchips
Plant Operation Size (delivered tons[a])	800,000 DM tons per year
Acres Harvested Annually	32,640 acres per year
Participating Acres	100%
Acres Available for Contract	90%
Cultivated Acres	90%
Feedstock Draw Radius[b]	4 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.

2.1.1 Base Case Conventional Harvest and Collection

Harvest and Collection encompasses all processes associated with moving the biomass from the location of production, in this case the tree stand, to the queuing location (Table 2-2). In forestry operations, queuing usually occurs at a landing. Harvest and Collection processes generally consist of tree felling, gathering, and moving from the field to the landing. The yellow boxes in Figure 2-2 identify the specific processes being performed. However, depending on a number of variables, the specific processes, equipment, and associated costs may vary significantly from one feedstock to another. Many of the variables that impact the selection of processes and equipment are based on the feedstock, location, and the biomass material format changes between process operations. The dark and light green ovals in Figure 2-2 identify the feedstock and its format as it moves from one process to the next within the supply system. Although the modeled feedstock is southern pine pulpwood, the same harvesting and collection equipment may be used for various whole tree harvesting.

Figure 2-2. Base Case Conventional Harvest and Collection supply logistics processes and format intermediates. *(Note: Green ovals represent format intermediate, and yellow rectangles represent individual modeled processes.)*

In the Base Case Conventional Harvest and Collection operation, pulpwood trees are cut using a feller buncher, then piled in the forest. Piled trees are yarded using a skidder, and then moved to the landing near the chipper.

2.1.1.1 Base Case Conventional Harvest and Collection Format Intermediates

The size, distribution, and type of woody biomass significantly affect Harvest and Collection operations, and many systems and operations are used to harvest and collect woody biomass. A typical operation for harvesting and collecting pulpwood sized trees (i.e., approximately 7 to 10 in. DBH, Figure 2-3) involves removing the woody biomass from the field and forwarding the material to the landing. In the scenario modeled for this design— southern pine trees at a commercial plantation—trees are cut and piled near the point of harvest, and then the piles are forwarded to the landing. The intermediate formats of the feedstock play critical roles in determining both the type and size of equipment to be used and the timeliness of the operation necessary to control the feedstock properties as the feedstock moves through the supply system. Table 2-2 identifies the woody biomass attributes of the feedstock format intermediates used as inputs and outputs of the Harvest and Collection equipment.

Table 2-2. Attributes of Harvest and Collection format intermediates for the modeled Base Case Conventional scenario.

	Standing Trees	Cut Trees	Skidded Trees
Biomass Anatomical Output	Standing whole trees	Cut whole trees	Cut whole trees
Yield (DM ton/acre)	20	20	20
Format Output	Standing tree	Pile	Pile
Bulk DM Density Output	—	8 lb/ft^3	8 lb/ft^3
Output Moisture (% w.b.)	50	50	50

Figure 2-3. Lodgepole pine tree stand in Island Park, Idaho (Photo credit: D. Brad Blackwelder, INL).

An alternate scenario is to remove the tree limbs (i.e., delimb) immediately after cutting with a combination feller/processor. Although this could increase the amount of nutrients that are returned to the soil, it also increases the risk of fire and the cost of collecting the residues, should that be desired at a later point.

Loblolly pine is the most widely planted tree in the United States (Dickmann 2006). Southern pine plantations in the southeast United States typically plant Loblolly or Shortleaf pines at a density of 300 to 1100 seedlings per acre and average 700 trees per acre (tpa) (Caulfield et al.1992). When planted with pulpwood sales as the primary goal, higher numbers of 700 to 800 tpa are often planted. These trees can then be harvested for pulpwood in 12 to 15 years. Yields average12.6 m^3 per acre per year (Moorehead et al. 1987), resulting in production of between 15.6 and 32.5 dry tons of merchantable wood (University of Georgia 1998, McMahon and Bush 1998).

Tree species has an impact on the Harvest and Collection operation. Different tree species exhibit considerable variation in hardness and friability, which can impact the efficiency of harvest. Some examples of tree hardness are shown in Table 2-3. Even among trees of the same species, size differences and varying environmental conditions during growth can cause noticeably different comminution (i.e., size reduction) characteristics. For example, a young tree may have a higher moisture content due to a higher proportion of sapwood. Trees of higher moisture chip more efficiently but grind less efficiently (see Section 2.2).

Table 2-3. Hardness of select wood (Alden 1997, Alden 1999).

		Janka Test, at 12% Moisture Content	
Common Name	Scientific Name	Kilonewtons	Pounds-force
Ash, white	*Fraxinus americana*	5.9	1320
Aspen, quaking	*Populus tremuloides*	1.6	350
Birch, yellow	*Betula alleghaniensis*	5.6	1260
Cottonwood, black	*Populus trichocarpa*	1.6	350
Cottonwood, eastern	*Populus deltoides*	1.9	430
Douglas-fir, coast	*Pseudotsuga menziesii*	3.2	710
Hemlock, western	*Tsuga heterophylla*	2.4	540
Locust, black	*Robinia pseudoacacia*	7.6	1700
Maple, sugar	*Acer saccharum*	6.4	1450
Oak, white	*Quercus alba*	6.0	1360
Pine, ponderosa	*Pinus ponderosa*	2.0	460
Pine, Monterey	*Pinus radiata*	3.3	750
Redcedar, Eastern	*Juniperus virginiana*	4.0	900
Sweetgum	*Liquidambar styraciflua*	3.8	850
Sycamore, American	Platanus occidentalis	3.4	770
Tupelo, water	*Nyssa aquatica*	3.9	880
Yellow poplar	*Liriodendron tulipifera*	2.4	540

Wood hardness is compared using the ASTM D 143, Janka hardness test, which measures the force required to embed a 0.444-in. steel ball into the wood to half the ball's diameter. Often used to compare the ability of wood flooring to withstand denting and wear, the Janka hardness test it is also a good indicator of energy required to “work” (i.e., hammer, saw, or grind) the wood.

Format and Bulk Density Impact on Supply System Processes

Costs associated with the Harvest and Collection operation are influenced by many factors, including those associated with tree stand density. The layout of the stand has a large impact on harvesting cost and speed. For example, increased stand density can potentially decrease equipment performance by constricting the maneuvers of the equipment, while bigger trees increase mass harvest rate. Plantation-grown trees, planted in straight rows and of consistent size, can be harvested at reduced costs as compared to natural stands of trees. Small diameter trees have a higher branch-to-stemwood ratio, making them bulkier. Thus, piles of small trees have a lower bulk density than piles of larger trees, which decreases skidding efficiency, although this can be overcome somewhat by using an oversized grapple.

Material losses in the form of broken branches occur during felling and skidding. Typically 10–30% of the material is lost between the stump and the landing, depending on size and species of trees being harvested and the skidding distance.

The felling operation also introduces contaminants into the bark. When trees are dragged to the landing, ash-rich dirt is picked up by the tree, substantially increasing the ash content of the pile (Phanphanich and Mani 2009, Harkin and Rowe 1971, Figure 2-4). Thermochemical conversion processes such as gasification, the modeled conversion process for this design, are very sensitive to the presence of ash, as it can damage conversion equipment and decrease yield (Dhutta et al. 2011).

Additional impurities such as rocks and metal pieces may be picked up as well. Grit contamination of biomass can cause problems during handling, comminution, and conversion into final products. Although not completely avoidable, grit contamination can be reduced by forwarding rather than skidding biomass, using chippers with grit separators, minimizing handling, and storing material on grit-free surfaces (Hubbard et al. 2007).

Figure 2-4. Ash-rich dirt is dragged into trees during yarding in Greenville, Alabama. (Photo credit: Christopher Wright, INL, July 2010).

Biomass Moisture Impact on Supply System Processes and Material Stability

Moisture content varies between species and throughout different parts of the tree (Table 2-4). The moisture content in stem wood is highest in the sapwood. Sapwood is the living, outer section of the wood that conducts water and nutrients between the leaves and the roots (Figure 2-5). The moisture content is lowest in the heartwood, which is the dead, inner section of the wood that is more naturally chemically resistant to decay. Therefore, the moisture content is higher in the upper part of the tree compared to the lower part because of the high ratio of sapwood to heartwood. The moisture content in the branches is greater than in the stem wood because of higher ratio of sapwood to heartwood. The sapwood-to-heartwood ratio is also what tends to make the moisture content higher in young trees than older trees. The needles and leaves have the highest moisture contents of any tree tissues. The moisture content in stem wood and branches is higher in the wintertime and lower in the summertime. This is caused by the variation in the moisture content of the sapwood. The prevailing climate also affects the moisture content in fresh trees (Suadicani et al. 1999).

Table 2-4. Examples of moisture content of various tree species (Erickson 1972).

Moisture content for woodchips and bark of six northern species (%)		
Species	Bolewood	Topwood
Aspen	50.3	47.9
Maple	36.3	36.7
Jack Pine	48.9	54.9
Red Pine	50.9	59.6
Balsam Fir	57.7	56.5
White Spruce	47.5	55.2

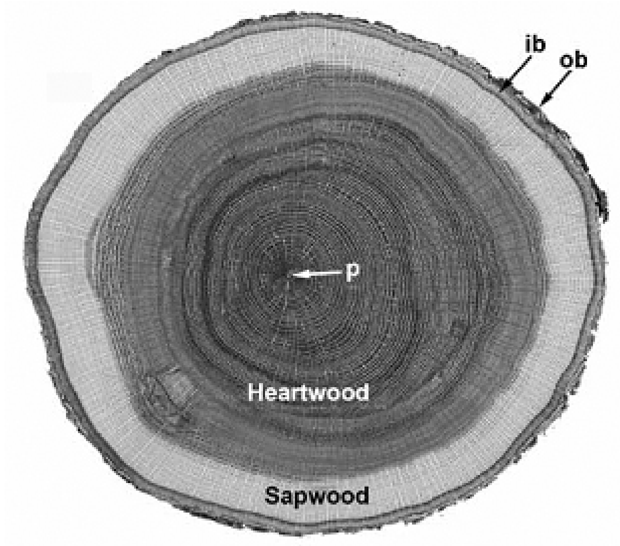

Figure 2-5. Macroscopic cross section of a white oak trunk. Beginning at the outside of the tree, the outer and inner bark (ob, ib) cover the outside of the tree, followed by the sapwood, which is easily differentiated from the heartwood that lies toward the interior. At the center of the trunk is the pith (p), which is barely discernible in the center of the heartwood (Wiemann 2010).

Note that younger trees have a higher sapwood content, and therefore they tend to have a higher moisture than older trees of the same location and species.

2.1.1.2 Base Case Conventional Harvest and Collection Equipment

Tree harvest involves many variables such as terrain, soil type, timber species, and tree diameter. This range of variables has resulted in establishment of literally dozens of tree harvest techniques, although the more expensive methods are generally reserved for higher value merchantable timber. These range from skidding with horses to helicopter logging (Sims 2002, Browers and Parker 2006). Depending on the terrain, many options are available for the Harvest and Collection of woody biomass. For example, harvest techniques on high sloped or sensitive lands may incorporate cable yarding systems (Tiernan et al. 2002) or helicopter collection (Sims 2002, Browers and Parker 2006). For the modeled scenario, the trees are assumed to be on private lands used for commercial tree operations, which are typically of low grade, and the trees are regularly distributed to facilitate harvesting. Therefore, more extreme extraction techniques are not required for the modeled scenario (Table 2-5).

The Base Case Conventional Harvest and Collection operation starts with the felling of trees using tracked drive-to-tree feller bunchers. This style of feller buncher is common in the pulp and paper industry. Smaller, less expensive, and more maneuverable three-wheeled feller bunchers are often used when harvesting smaller trees (such as in precommercial thinning operations), but the productivity of these machines is lower. Tracked, swing-boom feller bunchers are not commonly used to harvest plantation wood due to their high cost and lower productivity; however, they may have an advantage when used to clear-cut small diameter trees and may be necessary on steeper slopes.

Table 2-5. Harvest and Collection equipment specifications for the Base Case Conventional design.

Operation	Felling	Skidding
Equipment	Tracked carrier with a rotary head feller buncher	Wheeled grapple skidder
Haul Distance	N/A	400 m
Rated Capacity	20 ton/hr/machine	15 ton/hr/machine
Field Efficiency (%)	65%	65%
Operational Window		
Frequency	Every 6 years	N/A
Hr/day	8	8
Day/year	220	220

Skidding is done with a wheeled grapple skidder for this design scenario. This felling and skidding system is one of the most common and cost effective when harvesting plantation-grown southern pine (Cubbage and Greene 1989). Larger skidders are more productive than smaller ones and are more commonly used. Cable skidders of all sizes are often used on steeper slopes, but little plantation wood is grown on steep slopes. It is possible to move small-diameter trees to the landing using a front-end loader equipped with a grapple. This reduces dirt contamination and may be more efficient (Stokes 1990, Spinelli and Hartsough 2001).

Equipment Used in Conventional Design Model

Felling

Felling is normally the first operation in tree harvest. There are two general methods of felling, manual felling with chainsaws and mechanized felling with feller bunchers or harvesters (Figure 2-6). The former is generally reserved for harvesting higher value merchantable timber and, therefore, won't be described herein. Feller bunchers are one of several options available for felling standing trees on low-sloped land. They cut trees with a felling head, which may be a shear head or a rotary/disc saw cutting head (shown in Figure 2-7). After felling, the trees are collected in an accumulator, located in the felling head (Figure 2-8), which can hold multiple smaller diameter trees. After a few trees are accumulated, the buncher lays a pile of trees down to be collected by a skidder. Some fellers do not have an accumulator pocket and lay the trees on the ground individually after felling.

Figure 2-6. An accumulating head feller buncher mounted on a tracked excavator for a small diameter harvest study. Using smaller, less expensive, and more maneuverable equipment may improve efficiency when harvesting small trees (Photo credit: D. Brad Blackwelder, INL).

Figure 2-7. Rotary-head feller buncher cutting blade. The upper metal disc is stationary, while the lower toothed disc rotates and cuts the tree. Teeth are bolted on individually and replaced as needed (Photo credit: D. Brad Blackwelder, INL).

Figure 2-8. Rotary-head feller buncher. The upper arm holds the tree during felling, and the lower arm collects the tree after felling, forming a bunch (Photo credit: D. Brad Blackwelder, INL).

The predominant feller buncher type used in the United States is the four-wheeled, drive-to-tree feller buncher, which is often used for clearcut harvesting. Smaller, three-wheeled machines are often used for thinning operations. Feller bunchers are relatively inexpensive, but have high productivity. Drive-to-tree feller bunchers have a fixed felling head, and they, therefore, must be driven to each tree that will be cut. Tired feller bunchers are generally faster than track feller bunchers (Leinonen 2004); however, swing boom machines are more productive than drive-to-tree feller bunchers in dense stands because they can harvest multiple trees from one position and, when they reposition, they usually are not carrying any trees. Rubber-tired feller bunchers are more productive in open stands, but their use may be limited due to ground pressure of the tires producing rutting and erosion when on soils that are soft or wet. Tracked feller bunchers, due to the large foot prints of the tracks, exert low ground pressures and can operate in a wide range of soil and weather conditions. Their productivity is only slightly affected by weather. Tracked swing-boom feller bunchers can reach a large circular area of trees from a single standing position. This reduces the amount of ground surface area contacted by the machine and therefore greatly reduces environmental impacts of the felling operation. In a plantation environment, a tracked, swing-to-tree feller buncher may outperform a drive-to-tree, as a tracked model could potentially harvest three rows while traveling in a straight line.

Figure 2-9. An example of a wheeled feller buncher, John Deere 643J (John Deer 2011).

Tracked swing-to-tree feller bunchers are the most common choice for mechanical felling of trees on slopes steeper than ~15%, but not exceeding about 50% (Figure 2-10). Machines used on steep slopes often have self-leveling cabs to improve operator performance and machine stability. These operations will often use tracked skidders, which minimize damage to the land by traveling on designated trails. Instead of a grapple, they have multiple cables with chockers that are attached to the logs individually. The logs are then winched to the back of the skidder and collectively skidded to the landing.

Figure 2-10. Typical tracked, swing-to-tree feller buncher (Cat 521) (Photo by Caterpillar 2010). Swing-to-tree tracked feller bunchers are often the only mechanized choice for felling operations on steep, erodible slopes. These machines often have self-leveling cabs that provide stability and reduce operator fatigue.

In Europe and some areas of the United States, cut-to-length (CTL) harvesting systems are commonly used. In these operations, specialized harvesters fell, delimb, and cut logs to length (for example, Figure 2-11 and Figure 2-12). The biomass accumulates at the stump and can be left in the forest to dry or removed soon after harvest while logs are extracted. Whole-tree skidding, in which slash is transported to the landing in the same operation as the wood, has been shown to be more efficient. However, leaving residue in the forest to dry reduces moisture content, which improves grinder performance, reduces dry matter loss during storage, and does not promote colonization of fungi that produce harmful spores.

Figure 2-11. Processing head mounted on a tracked, swing-to-tree, primary mover for delimbing and bucking at the stump in a CTL harvest system. This type of head can also be used at the landing to process trees (Photo credit: D. Brad Blackwelder).

Figure 2-12. Tigercat LH830C harvester suitable for CTL operations on steep terrain (photo from Tigercat (2010)).

Skidding

Yarding is the act of moving the tree to the landing after felling. This is done either by skidding (part of the tree is in contact with the ground) or forwarding. Forwarding is usually associated with CTL logging, where a harvester delimbs and bucks the trees at the stump, and then a forwarder comes later to transport the logs to the landing. Timber harvesters may be purpose-built machines or excavator-type machines equipped with a harvesting head.

After felling, trees are skidded or forwarded to the landing. The central piling location at the landing, known as the log deck, is located to optimize both skidding distance and haul road construction (Heinimann 1998). As a rule of thumb, landings are located so that skidding distance is kept to 1500–2000 ft or less for flat and typical terrain (Greulich et al. 1996); however, maximum yarding distance depends on the shape and land condition of the area harvested. The distance from the tree to roadside significantly impacts costs of harvesting (Table 2-25). In the case of the skidder, haulage distance is the most important factor impacting productivity (Leinonen 2004).

Table 2-6. Maximum yarding distance for various equipment, terrain, and weather scenarios (Virginia Department of Forestry 2011).

Logging System	Weather Sensitivity	Terrain Slope (%)	Yarding Distance (ft)	Average Tree Size	Volume per Acre	Volume per Track	Cost of Road	Terrain Shape and Length
Animal	Moderate	<20	<500	Small	Low	Small	Low	Flat Short
Tracks	Moderate	<40	<800	Large	Common	Small	Low	Moderate Short
Skidder	High	<35	<1500	Medium	Common	Medium	Med	Flat + common
Shovel	Low	<45	<400	Medium	Common + clear cut	Small	Low	Moderate broken
Forwarder	High	<30	<2500	Medium	Low	Large	High	Gentle long
Cable	Low	Any	<1500	Medium	Common	Medium	High	Steep Concave long
Helicopter	Low	Any	<6000	Large	High Sawtimber	Large	High	Any

In parts of the western United States, cable skidding and manual felling using a chainsaw are still common on steep slopes. Trees may be skidded whole or bucked at the stump. This type of harvest operation is expensive and not suited to extraction of low-value trees for energy wood, although whole tree operations may accumulate large slash piles that could be used for energy purposes at a relatively low cost. It should be pointed out that this type of felling is much more dangerous than mechanized methods. Many loggers do not allow any operations to occur when personnel are outside of their machine because of insurance requirements.

Where minimizing site disturbance is a priority or on highly sloped lands, more sophisticated collection technologies, such as cable yarding systems or helicopters, may be used to remove trees. However, for the low-slope scenario modeled, ground-based skidding is appropriate. Grapple skidders grasp a group of trees piled by the feller buncher with a hydraulically actuated grapple (see Figure 2-13) and pull the material to the landing. Other machines may out-perform skidders when moving small trees on flat terrain. In studies by Spinelli and Hartsough (2001), a Caterpillar 950F front-end loader and a Caterpillar 528 grapple skidder were used to extract bunched whole trees to a landing in a short-rotation Eucalyptus plantation. The data collected suggested that the loader was 40–60% more productive than the grapple skidder. On relatively flat ground, the loader performed better than the skidder. The loader was useful at the landing and, due to its large capacity, it yarded wood more efficiently. It also resulted in cleaner wood because it transports wood without dragging it on the ground (Spinelli and Hartsough 2001). Forwarding by front end loaders is only feasible in clear-cut operations.

Figure 2-13. Grapple for skidding trees (Photo credit: D. Brad Blackwelder, INL).

The grapple skidders can be equipped with rubber tires (Figure 2-14) or tracks (Figure 2-15); the former are faster and cheaper than track skidders (Leinonen 2004). However, track skidders can haul heavier loads, cause less soil disturbance and site damage, and are suitable for sloped terrain (Leinonen 2004).

Figure 2-14. Wheeled grapple skidder with grapple head in Greenville, Alabama (Photo credit: Christopher Wright, INL, July 2010).

Figure 2-15. Caterpillar 527 tracked grapple skidder. This type of skidder is usually used on slopes from 15–30% grade (Photo credit: D. Brad Blackwelder, INL).

Equipment Capacity and Operational Efficiency (Field Efficiency)

Unlike agricultural harvesting equipment, field speed and field efficiency are not often used when assessing performance of woody biomass harvesting equipment. The characteristics of the forest being harvested have a large affect on the efficiency of the operations. Timber harvests use production per scheduled machine hours (SMH) as an efficiency metric. SMH is the time in which a machine is intended to be operated and has an operator scheduled to run it. Production per productive machine hours (PMH), the time during scheduled operating hours when a machine performs its designated function (time exclusive of such things as machine transport, operational or mechanical delays, and servicing or repair), is also used to measure efficiency. The system may be balanced around the most productive process, which is usually the chipper that is located at the landing. Felling and bunching operations are balanced to optimize chipper usage and ensure a continuous supply of feedstock. In the hot-loading operation, the number of trucks delivering material will also be matched to the chipper or grinder.

Equipment capacity and operational efficiency for tree-based harvesting operations are highly dependent on the stand density, tree size, haul distance to the landing, season, tire/track characteristics, and terrain conditions (Leinonen 2004, Beardsell 1983). Sparse stand density, small tree size, highly sloped land, and very wet conditions will all decrease machine harvest and collection productivity, and therefore, machine performance is, by comparison, regionally specific.

Field efficiency and capacity should not be confused with “harvest efficiency,” which is a measure of field loss that is related to the machine’s ability to gather or collect the biomass. Field efficiency is a factor used to account for conditions that cause a machine to operate at less than theoretical rated capacity. Time spent unloading, refueling, and in unproductive travel (for example, turning around and maneuvering) are all events contributing to a reduction of field efficiency.

A key factor for improving the field capacity (amount of material being moved while the machine is doing productive work) and field efficiency (percent of the time that the machine is being used for productive work) of a given machine is reducing unproductive operational time, which is particularly important in sparsely wooded areas or challenging terrain. Equipment service crews working at night can reduce equipment downtime for service and maintenance during hours when machinery should be operating. Solutions to improved field capacities and efficiencies are a combination of new technologies, additional pieces of equipment, and management.

Operational Dry-matter Losses

There are a number of potential Harvest and Collection design concepts for pulpwood plantation systems. The impact of equipment configuration choices on the specification of the material leaving the landing is potentially significant. This creates a need for a robust methodology accounting for cost and performance assessments across the wide range of system designs. One flexible approach that can facilitate a range of landing preprocessing options is attributing incurred costs to the marketable mass of material that leaves the landing. Through this methodology an equipment configuration which harvests and collects material will be evaluated to determine the percentage mass of the previously standing tree that leaves the landing. This will be the “marketable” portion of the biomass. All costs incurred to get the material to that spec at the landing exit will then be attributed to that mass of material. An example of the application of this approach is material lost during collection, as described above. The material that breaks off during yarding is not part of the marketable portion of the biomass. Rather than treating this as a dry matter loss, the accounting of all costs getting material to the landing exit are simply attributed to mass of material that leaves the landing on spec. However, as a sustainability consideration, the material lost during Harvest and Collection is described below.

Dry matter losses of woody biomass during harvest are due to breakage of limbs and tops during felling and yarding. Foresters and loggers have estimated these losses, but with the traditional focus of harvest on bolewood (which rarely experiences losses during Harvest and Collection), precise estimates of losses during felling, yarding, comminution, and handling of biomass are unavailable. Traditional estimates of biomass loss from the stump to the landing are 25 to 40%, with considerable variation based on tree species, size, and equipment used. Losses during felling have been cited around 5% (Hartsough et al.2002), while dry matter losses of approximately 15% have been cited while dragging with grapple skidders.[b] (Stokes et al.1991. and Watson et al. 1991).

Stokes and Watson (1991) performed a study that looked at losses per unit operation on a weight basis for three different harvesting operations. The work was done in a 21-year-old slash pine plantation in the Southeastern U.S. Felling resulted in losses of 9.1%, and skidding lost another 6.5%. Delimbing lost 8.5%, for a total loss of 24.1%. The felling and skidding losses for all scenarios resulted in losses of 15.6%. This material is scattered in the forest and is uneconomical to recover. The flail delimbing/ debarking system used a flail and in-woods chipping. The combined processes produced three different products: flail residues (limbs, tops, needles, and bark), chipper rejects, and chips. Percent of the whole-tree biomass was 12.4%, 2.7%, and 69.3% respectively. Whole-tree harvesting skidded trees to the loader, which loaded the trees onto trailers with screens to prevent losses. The total biomass that made it onto the trucks in this scenario was 84.4%. Tree-length harvesting lost 8.5% during delimbing with 75.9% of total biomass loaded on the truck.

The least amount of loss occurs when harvesting small, softwood species. Smaller trees, being lighter and having higher moisture content, have more flexible limbs and tend to hold their branches during felling and yarding operations. Larger trees tend to lose more and larger branches during felling than smaller trees, as larger trees tend to fall with more force. Species-dependent variation occurs also as some trees are inherently more brittle and prone to breakage during harvest than others. Hardwood trees tend to be more brittle and often have larger biomass losses during Harvest and Collection. Dead, dry trees also are more brittle and prone to loss. Ground skidding will result in losses not incurred when using a highlead skyline cable yarding system. Skidding distance may also affect limb breakage as longer skidding distances are associated with greater loss.

Operational Window

For pulpwood-size trees, the rotation age is assumed to be 12 years, although this period may vary. Seasonal harvesting limitations also exist, including soggy, wet lands or excessive snow that inhibits access. Typical timber harvesting operations use heavy logging equipment, such as rubber-tired feller bunchers and skidders. When dry soil conditions prevail, these machines cause only minor soil disturbance. However, moist or saturated soils are prone to rutting and compaction (Reisinger et al. 1988; Aust et al. 2004). Sensitive areas should be logged when the ground is dry or in winter when it is frozen (Turcotte et al. 1991). Other factors of influence include worker and equipment availability, as well as relevant permitting.

For the South/Southeast U.S., harvesting can normally be performed most of the year, with the exception of the regular holiday shutdown periods.[c] In the Northwest U.S., such as in western Oregon, some large private ownership lands (for example, those owned by Weyerhaeuser) are thinned essentially all year, although there is the possibility of a month of downtime due to weather conditions that are conducive to fires. During winter, operations shift from higher elevation to lower sites when snow prevents access to the harder-to-reach zones.[d]

In the Pacific Northwest, such as British Columbia, Canada, pulp mills generally have a maximum of 3 months storage because it gets too slushy in the spring to harvest. They generally store the chips uncovered.[e]

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b. Personal communication with Leonard Johnston, 2009.

c. Personal communication Tom Gallagher, Auburn University.

d. Personal communication Bruce Hartsough, UC Davis, July 2009.

e. Personal communication with Amit Kumar, University of Alberta, Edmonton, AB, Canada.

Harvesting on public lands accounts for about half the timberland, but much less of the harvest in recent years due to a shift in land management objectives. There are more constraints and definite shutdown windows when using these lands,[f] and loggers will typically try to arrange alternate work, possibly on small private holdings, during the slack season on public lands.[g]

For both private and public land harvests, operating hours per day and number of operating days per week are generally greater during the warmer part of the year, so wood flow to the biorefinery would be higher in warmer months than the cooler, stormy portion of the year.

2.1.1.3 Base Case Conventional Harvest and Collection Cost Analysis

Cost Summary

A breakdown of the costs associated with each piece of equipment used in the Harvest and Collection operation identifies significant cost components that are valuable for making individual comparisons and recognizing areas of research potential (Table 2-7 and Table 2-8). These costs are reported in terms of DM tons entering each process, respectively.

Table 2-7. Static model costs for major Harvest and Collection equipment in the Base Case Conventional scenario. Costs are expressed in 2010 $/DM ton unless otherwise noted. Total operation cost is the sum of ownership, operating, and DM loss cost.

	Felling	Skidding	
Equipment	Tracked carrier with a rotary-head feller buncher	Medium grapple skidder (wheeled)	Total Costs per DM ton for Harvest and Collection
Installed Equipment Quantities (# of machines)	38	77	---
Installed Capital	11.76	15.77	27.53
Ownership Costs	*5.8*	*2.36*	*8.16*
Operating Costs	*3.69*	*15.92*	*19.61*
Labor	1.16	2.38	3.54
Non-Labor[a]	2.53	13.54	16.07
Dry-matter loss Costs	--	--	---
Energy Use (MBTU/DM ton)	62.8	92.0	154.8

From Table 2-7, the total Harvest and Collection cost for pulpwood sized trees is $27.77/DM ton, which is the sum of ownership, operating, and dry matter loss costs. A large portion of the costs are operating costs, which include labor, fuel, and material costs. Because each tree has to be harvested individually, harvesting is less productive than mass harvesting operations, such as for wheat or corn.

Hartsough and Stokes (1990) identified key parameters for any harvesting system, including material type (trees vs. residues), piece size, and amount removed in green tons/acre. They observed that for practically all analyzed systems, cost increased as the piece size was reduced, and cost decreased as the total volume removed per acre was increased. Additional studies (Holtzscher and Lanford 1997, Kluender et al. 1997) showed that stand treatment and tree diameter were two of the primary factors in determining harvesting costs.

f. Personal communication from John Zeni.

g. Personal communication Bruce Hartsough, UC Davis, July 2009.

2.1.2 Base Case Conventional Preprocessing

The transport and handling costs of moving whole trees are greatly reduced by comminution at the landing and prior to transport, as the packing density is greatly increased. The chipped trees are loaded into trucks and then taken to the biorefinery for further processing (Figure 2-16).

Figure 2-16. Preprocessing supply logistic processes and format intermediates for the Base Case Conventional design. *(Note: Green ovals represent format intermediates and yellow rectangles represent processes modeled in this report).*

Whole trees that were piled at the landing during Harvest and Collection are loaded into the chipper to densify the material for transport. The chipped material is ejected into a chip van for transport to the biorefinery.

2.1.2.1 Base Case Conventional Preprocessing Format Intermediates

After the biomass is brought to the landing and piled by a skidder, the grapple attached to the chipper loads the trees into the chipper. Chipped trees are ejected into the back of a chip van. The chips are high-moisture (approximately 50% wet basis); therefore, much of the transported mass is water (Table 2-8).

Table 2-8. Attributes of Preprocessing format intermediates for the Base Case Conventional design.

Operation	Chipped Trees	Transported Chipped Trees
Yield (DM tons/day)	2330	2330
Format Output	Chipped trees	Chipped Trees
Bulk DM Density Output (lb/ft^3)	20	20
Output Moisture (% w.b.)	50	50

Biomass Deconstruction, Fractionation and Physical Property Changes

Different tree species exhibit considerable variation in hardness and friability. Trees of the same species, but of different sizes or grown under different environmental conditions, can have noticeably different comminution characteristics. Different trees will produce chips with varying particle-size distributions, depending on the tree species, age, moisture content, and weather conditions, among other factors. The Base Case Conventional design scenario assumes chipping of southern pine pulpwood pine trees with a moisture content of 50%.

The whole tree is comminuted in the Base Case Conventional design, and therefore the chips will be a mixture of needles, bark, wood, and contaminants such as bark (Figure 2-17).

Figure 2-17. Example of whole tree chips. There is a noticeable portion of bark and leaves present (Photo credit: D. Brad Blackwelder, INL).

Format and Bulk Density Impact on Supply System Processes

Comminution results in a density increase of pulpwood sized trees, which increases the efficiency of transportation and handling processes (Table 2-9).

Table 2-9. Woody biomass wet bulk density at a moisture content of 50% (McDonald et al. 1995). Note that whole tree chips have a higher bulk density due to a larger portion of fines.

Format	Dry Matter Density (lb/ft^3)
Roundwood[a]	15.5–17
Tree Section[a]	6–7.5
Small Trees[a]	5–6
Logging Slash[a]	6
Whole Tree Chips[b]	15.5–25
Cleaned Chips[b]	19–22

a. McDonald et al. 1995
b. Alakangas et al. 1999

The properties of the chips are dependent on the source of the chipped material (Table 2-10), and key considerations include species, tree age, parts of the tree included in the mixture, presence of contaminants such as dirt, and moisture content of the chipped material.

Table 2-10. Properties of various types of comminuted woody biomass (Alakangas et al. 1999, unless otherwise noted).

Property	Slash Chips, Pine	Whole Tree Chips, Pine	Log Chips, Pine	Stump Chips	Small Whole Douglas Fir[a] Chips[b]	Small Whole Chips, pine
Moisture Content, w.b.% (fresh chips)	50–60	45–55	40–55	30–50	45–55	10.0–50.0
Net Calorific value in dry matter, MJ/kg	18.5–20	18.5–20	18.5–20	18.5–20	19–21	18.5–20
Net Calorific value as received, MJ/kg	6.0–9.0	6.0–9.0	6.0–10	6.0–11	10@50%	6.0–15.0
Bulk Density as received, kg/loose m^3	250–400	250–350	250–350	200–300	260–320	150–300
Energy density, MWh/m^3 of bulk volume	0.7–0.9	0.7–0.9	0.7–0.9	0.8–1.0	N/A	0.7–.9
Ash content in dry matter, w.b.%	1.0–3.0	1.0–2.0	0.5–2.0	1.0–3.0	0.1	0.4–1.0
Hydrogen content in dry matter (H), w.b.%	6.0–6.2	5.4–6.0	5.4–6.0	5.4–6.0	6.2	5.4–6.4
Sulfur content in dry matter (S), w.b.%	<0.05	<0.05	<0.05	<0.05	0.02	<.05
Nitrogen content in dry matter (N), w.b.%	0.3–0.5	0.3–0.5	0.3–0.5	0.3–0.5	0.1	0.1–.5
	Softwood Bark	Pine Bark[a]	Birch Bark	Grinding Dust	Sawdust	
Moisture Content, w.b.%	50–65	30–60	45–55	5.0–15	45–60	
Net Calorific value in dry matter, ML/kg	18.5–20	19–25 GJ/odt	21–23	19–19.2	19–19.2	
Net Calorific value as received, ML/kg	6.0–9	11 GJ/odt @ 11%	7.0–11	15–17	6.0–10	
Bulk Density as received, kg/loose m^3	250–350	290–380	300–400	100–150	250–350	
Energy density, MWh/m^3 of bulk volume	0.5–0.7	N/A	0.6–0.8	0.5–0.65	0.45–0.7	
Ash content in dry matter, w.b.%	1.0–3.0	3.0	1.0–3.0	0.4–0.8	0.4–0.5	
Hydrogen content in dry matter (H), w.b.%	5.7–5.9	5.8	6.2–6.8	6.2–6.4	6.2–6.4	
Sulfur content in dry matter (S), w.b.%	<0.05	0.1	<0.05	<0.05	<0.05	
Nitrogen content in dry matter (N), w.b.%	0.3–0.5	0.1	0.5–0.8	0.1–0.5	0.1–0.5	

a. Source: Bruce and Sinclair 1996
b. Small diameter tree chips

From Table 2-10, it can be seen that different tree components result in different chip composition. For example, grinding dust from stump chips has a low density due to its fine particle size and low moisture content. It is also low in ash. The low moisture content also results in a high heating value of the material. However slash chips have a high bulk density because of the large range of particle sizes and impacts from the moisture in the material. Bark has a high ash content, and a large range of potential moisture content.

Biomass Moisture Impact on Supply System Processes and Material Stability

Comminution [h]

Green wood has not been dried and often has a moisture content of 50% or more (wb). Dry wood typically has a moisture content of between 10 and 25% (wb). Moisture content will affect the energy required to comminute woody biomass, and the level of impact varies depending on the comminution method (Table 2-11). For chipping, the energy required to chip to a given length increases with decreasing moisture content; however, the opposite is true for hogging (Himmel et al. 1985). Dry wood is more difficult to cut, and since chippers comminute primarily by a cutting action, it requires more energy to chip dry wood. Dry wood is more brittle than wet wood. Machines that rely primarily upon impact for comminution, such as hogs, will therefore require less energy to comminute dry wood (Pottie and Guimier 1985) because the wood effectively shatters or breaks when struck by the hammer.

Table 2-11. Mean shear strengths and cutting energy for dry/fresh hickory wood (Womac et al. 2005).

Blade Angle (º)	Hickory (fresh, 35% MC)		Hickory (dry, 13% MC)	
	30 (º)	45 (º)	30 (º)	45 (º)
Mean Shear Strength (Mpa)	10.94 ± 1.06	13.41 ± 1.13	16.77 ± 1.13	24.92 ± 2.91
Mean Cutting Energy (KN/m)	91.60 ± 9.42	114.31 ± 19.07	121.99 ± 11.69	160.07 ± 12.73

2.1.2.2 Base Case Conventional Preprocessing Equipment

The chipper is the only preprocessing equipment used in the Base Case Conventional scenario (Table 2-12).

Table 2-12. Preprocessing equipment specifications for the Base Case Conventional design.

	Chipper
Rated Capacity	50 ton/hr
Operational Efficiency (%) [b]	65%
Operational Window	50 wk/yr
Hr/day	8
Day/yr	5

h. Note that alternative preprocessing options are included in Appendix B.

Comminution

Comminution is a generic term meaning size reduction, and generally refers to either chipping or grinding with respect to woody biomass. The choice and location of a comminution device in the woody biomass supply chain are among the most critical components of a processing supply system for woody biomass. Factors affecting comminution choices include customer requirements for the raw material, total woody biomass volume, forest stand characteristics and nature of the road network, accessibility and equipment at the end-user reception facility, and feasibility of creating terminals for efficient handling and storage without incurring excessive additional haul distances (Hubbard et al. 2007). In the modeled Base Case Conventional scenario, there is whole-tree skidding to roadside, with assumed good road access for chip vans and chippers/grinders, and sufficient biomass volume per acre (Hartsough et al. 1997, Rummer et al. 2004).

Chippers and grinders loaded with either a grapple arm attached to the comminution machine, or a separate loader. Figure 2-18 shows a chipper equipped with a boom and grapple. The Base Case Conventional incorporates a chipper with a grapple arm. The feed rate of material into the grinder or chipper should be kept as constant as possible to optimize efficiency by avoiding peak stresses. Using a long feeding table facilitates even loading. Also, the comminuter should have a force-feed feature and be resistant to clogging (Alakangas 1999).

Figure 2-18. Chipper equipped with a boom and grapple (Photo credit: Wood Chippers & More 2011). The Base Case Conventional scenario uses a similar chipper design.

Chipping[i]

Currently, the most economical method of recovering woody biomass is chipping prior to transport (for example, Hartsough et al. 1997 and Rummer et al. 2004). Chippers reduce particle size using sharp blades and are either disc or drum chippers. Disc chippers (Figure 2-19, Figure 2-20) have blades inserted in a heavy rotating disc that generally rotates at speeds between 400 and 600 rpm (Leinonen 1985, Pottie and Guimier 1985, Alakangas et al. 1999). They are commonly used to chip debarked logs or mill trimmings to produce pulp chips. Whole trees or residues are fed endwise, and pieces are sheared off at about a 30-degree angle as the woody biomass contacts the knife blades. The cut material passes through slots, at which point a fan may blow them into a container (for example, chip van). They may be ejected via momentum coming off of the disc, or they may fall via gravity onto a conveyor (Pottie and Guimier 1985). Disc chippers are usually not used for logging residues as they produce splinters and, therefore, lead to inconsistent chip size (Alakangas 1999).

i. Note that additional comminution options are presented in Appendix B.

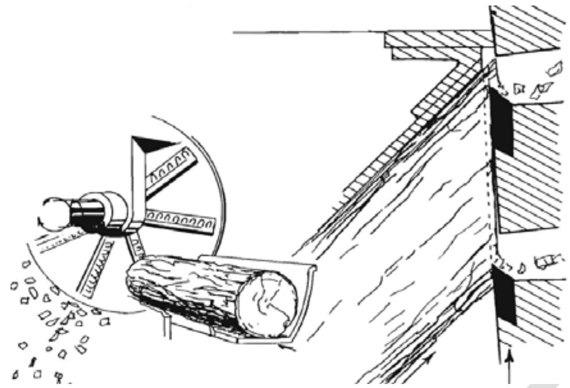

Figure 2-19. Schematic of a disc chipper, similar to that used in the Base Case Conventional design (Pottie and Guimier 1985).

Figure 2-20. Disc chipper used to comminute whole trees (Photo credit: Christopher Wright, INL, July 2010).

A drum chipper (Figure 2-21) consists of a rotating drum with knives on the surface. The knives shear off pieces of wood. The woody biomass is loaded onto a horizontal feeding table that feeds the material into an opening with rollers that push the material into the chipper. The disc chipper is suitable for chipping whole trees or logs because of the small feeding opening, while a drum chipper, with bigger feeding opening, is suitable for chipping of both whole trees and forest residues (Leinonen 2004). The drum chipper is less sensitive to impurities and produces fewer splinters from whole trees, but it also produces a less consistent chip (Alakangas 1999).

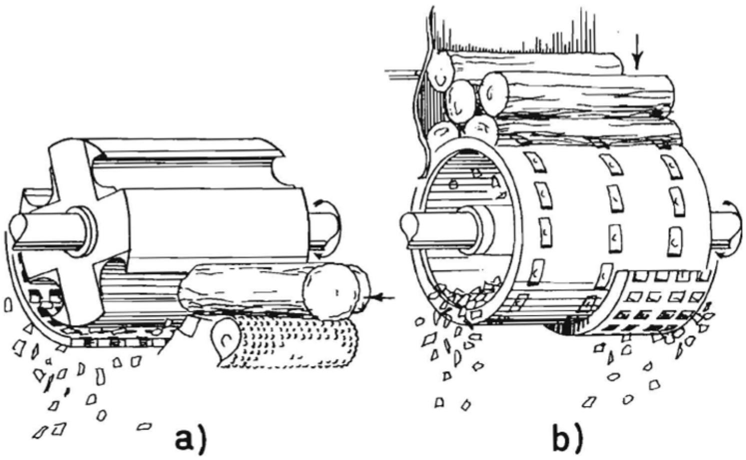

Figure 2-21. Schematic of a drum chipper (Pottie and Guimier 1985). Large knives may be mounted to the drum (a), or smaller knives may be mounted in a spiral pattern around the drum (b).

Loading Chip Van

Chippers and grinders blow comminuted material out of the machine, often directly into the back of a chip van. Some vans are loaded from the rear (Figure 2-22), and others have a top load configuration (Figure 2-23). Generally, top loading vans are used with grinders, and the material is conveyed rather than blown. Top loaded configurations are also common in cold loading operations, where front end loaders are used, and in hot loading DDC operations. Rear loading vans are often used in hot chipping operations for any material.

Figure 2-22. Mechanism of throwing material from chipper into back of chip van in Greenville, Alabama (Photo credit: Christopher Wright, INL, July 2010).

Figure 2-23. Vermeer HG6000 horizontal grinder conveys material into the top of a chip van. This is a "hot" loading operation with the system designed to keep the grinder operating at maximum efficiency.

Top loading a van requires the driver to periodically move the van forward as it loads in order to distribute the material evenly. Rear loading vans can remain stationary while they are loaded and can be left at the landing and hauled away when full.

Equipment Capacity and Operational Efficiency

Communition[j]

The maximum theoretical productivity of any chipper is calculated as the product of (Pottie and Guimier 1985):

$$P = RPM \times K \times L \times A \tag{2-1}$$

where

P	=	production capacity (volume per unit time)
RPM	=	rotation speed of chipper disc or drum (revolutions per unit time)
K	=	number of knives or number of cuts made per revolution
L	=	length of cut parallel to wood infeed direction (length units)
A	=	maximum surface area of material perpendicular to the wood infeed direction (area), and is generally the area of a log cross section (that is, a circle)

The actual operating capacity of a chipper is a fraction of the maximum theoretical productivity, and depends upon many factors. The power supplied to the chipper must be sufficient; otherwise, operation is below full capacity. Changing the cutting angle, average chip length, knife sharpness, wood density, temperature (for example, when chips are frozen), and moisture content all impact chipper power requirement (Figure 2-24, Pottier and Guimier 1985). The power requirement for drum chippers generally ranges between 215 hp (160kW) and 860 hp (640 kW), although there are other sizes available, while for disc chippers, the power range is generally about 425 hp (320 kW) to 1000 hp (750 kW) (Leinonen 2004). The power demand for grinders with horizontal feed systems is between 250 hp (190 kW) and 1000 hp (750 kW) (Leinonen 2004, Morbark 2002). Changing and sharpening chipper knives is a major source of downtime, especially for disc chippers. and the time between knife changes will depend on many factors, including machine utilization and production rate, presence of foreign material (such as rocks and metal), and tree species. The frequency for changing knives on a particular chipper can range from twice per day for extremely dirty material to once per week or less for very clean material (Pottie and Guimier 1985). One Finnish company estimated that only 57% of actual working hours for a chipper were spent chipping,

j. Note that additional comminution options are presented in Appendix B.

and most of the idle chipper time was attributable to waiting for trucks at the landing (46% of idle time) and changing knife blades (23%) (Alakangas et al.1999).

Disk chippers are self-feeding once the wood is in contact with the disk, because the knives pull the trunk towards the disk with each cut. Linear feed rate is determined by (1) the rpm of the disk (fixed within a narrow range; chippers don't work well if the speed is reduced much); (2) the number of knives (usually fixed, although sometimes can be reduced from four to two); and (3) the thickness of the cut (set by the width of the knife blade and can be adjusted by changing the amount of Babbitt metal poured behind the blades after grinding).

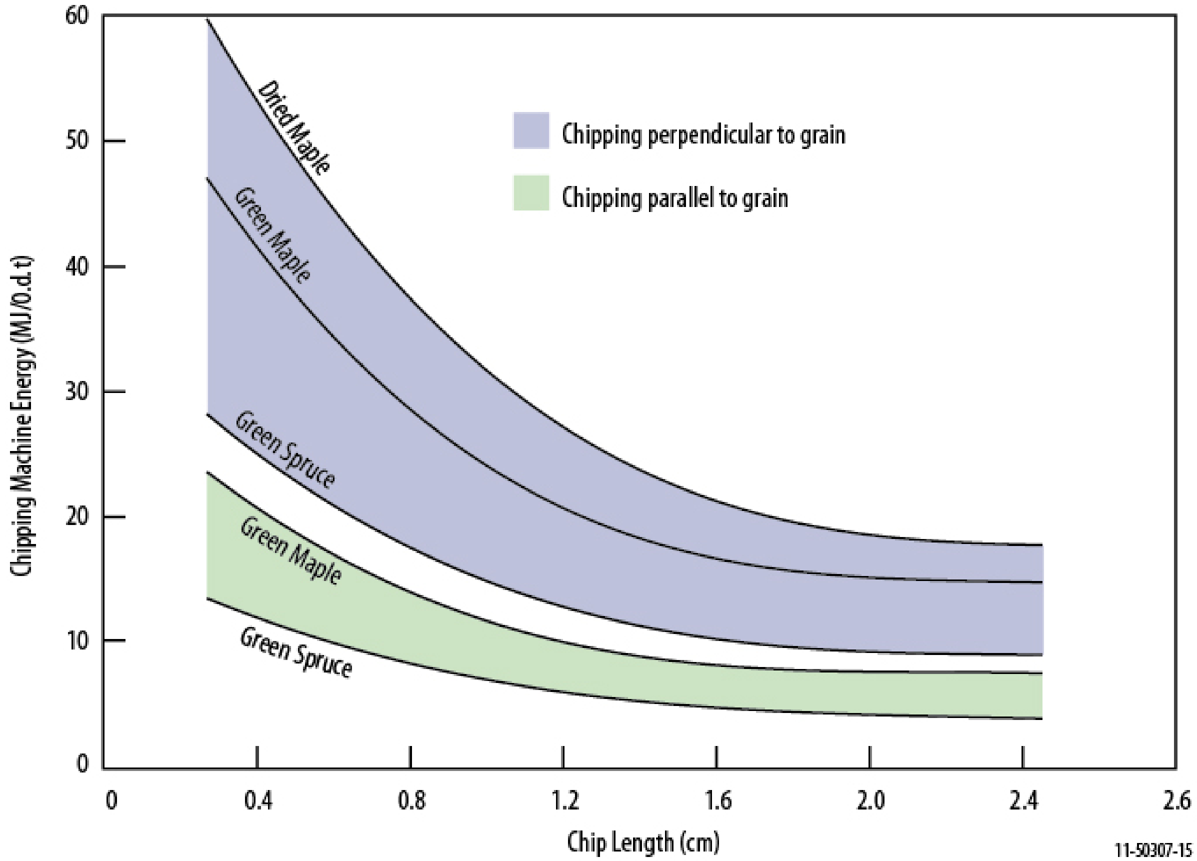

Figure 2-24. The relationship between chip length, cutting angle, and moisture content on energy required for chipping (Pottie and Guimier 1985).

Figure 2-24 shows that chipping perpendicular to the grain reduces the energy required to size-reduce the wood, and the higher density wood, maple, has a higher energy requirement than lower density wood, spruce (also shown in Figure 2-25). More energy is required to produce a finer chip, and the difference is more significant with a higher density wood. More energy is required to chip a drier wood (note that the opposite is true for grinding, see Appendix B) and, therefore, fresh logging residues or logs are usually faster to chip than dried residue (Alakangas et al.1999). One possible reason for this is that the moisture in the wood lubricates the knives and facilitates cutting.

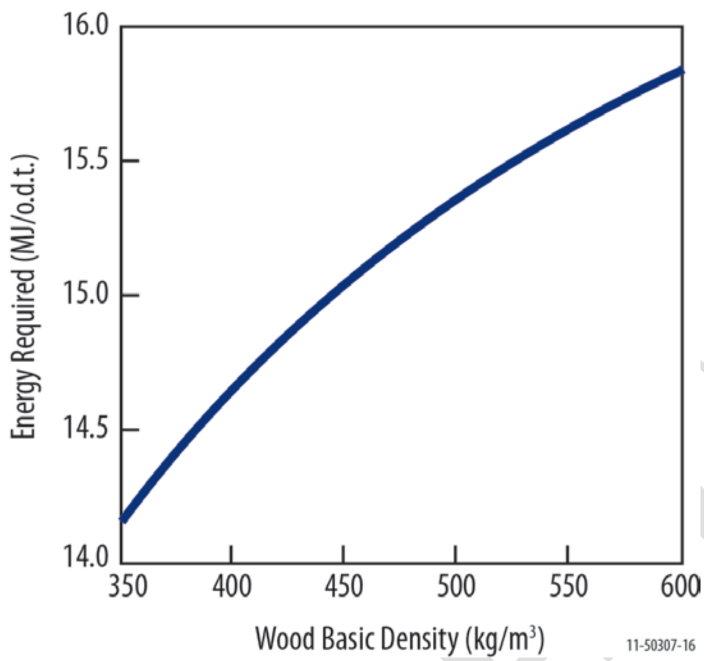

Figure 2-25. Impact of wood density on chipping energy per ton. Chipping energy requirement increases with increasing wood density (Pottie and Guimier 1985).

Other factors that influence chipping energy requirements are tree diameter and size of the chipper. Figure 2-13 shows a trend towards increased power consumption with increasing tree size and a larger chipper. Also, the larger chipper displayed a larger range of energy consumption values. Table 2-13 again shows that harder, higher density tree species require more power to chip.

The productivity of chipping is also influenced by the storage and working arrangements (for example, ensuring continuous feeding of the machine in sufficient quantities that the loader is fully used) (Leinonen 2004).

Table 2-13. Impact of tree species group, tree diameter, and chipper size on chipper power consumption (Stokes and Watson 1987).

Species	DBH Class (in)	Small Chipper Mean, (hp)	Large Chipper Mean, (hp)
Pine	1		280 ±61
	3	156 ± 32	255 ± 149
	5	225 ± 19	470 ± 48
Average		196 ± 43	358 ± 142
Soft Hardwood	1	144 ± 37	178 ± 116
	3	231 ± 21	338 ± 134
	5	210 ± 67	423 ± 121
	7	189 ± 62	413 ± 130
	9	235 ± 55	295 ± 135
	13	301	363 ± 50
Average		208 ± 62	324 ± 147
Hard Hardwood	1	156 ± 61	215 ± 204
	3	188 ± 53	414 ± 125
	5	221 ± 61	401 ± 151
	7	185 ± 46	328 ± 137
	9	269 ± 29	395 ± 94
	11	291 ± 12	495 ± 6
	13	316 ± 10	493
Average		220 ± 67	358 ± 142

Dry Matter Losses

During comminution in the field, it is not common to have a dust collection system. Therefore, there are some material losses through dust, in addition to those from material falling out of the chipper/grinder, or being propelled beyond the truck after comminution. Although not a lot of information is available on dry matter losses during comminution at the landing, Hamelinck et al.(2005) estimate dry matter losses to be around 2% for both chipping and grinding. The reason for the lack of literature is the difficulty in obtaining accurate measurements of initial dry matter content and final dry matter content.

However, as described in Section 2.1.1.2, this report takes the approach of attributing incurred costs to the marketable mass of material that leaves the landing. Using this methodology, an equipment configuration that harvests, collects, and preprocesses (i.e., chips in this case) material will be evaluated to determine the percentage mass of the previously standing tree that leaves the landing as a chip. This will be the "marketable" portion of the biomass. All costs incurred to get the material to that spec at the landing exit will then be attributed to that mass of chipped material. Therefore, material entering the chipper that does not end up in the chip van will not be considered a loss.

Operational Window

The comminution process must be carefully monitored so as to maximize chipper/grinder use and ensure that the chipper/grinder does not become a bottleneck for chip delivery to the biorefinery. One approach to maximizing chipper/grinder use is moving to a “cold chain” system, which accumulates material at different stages in the supply chain to optimize system operation (Figure 2-26). This system is opposed to a “hot chain” system, where the goal is to keep the material continuously moving through the supply chain. There may be additional costs associated with the cold chain operation, such as moving the material from the cold deck to the chipper.

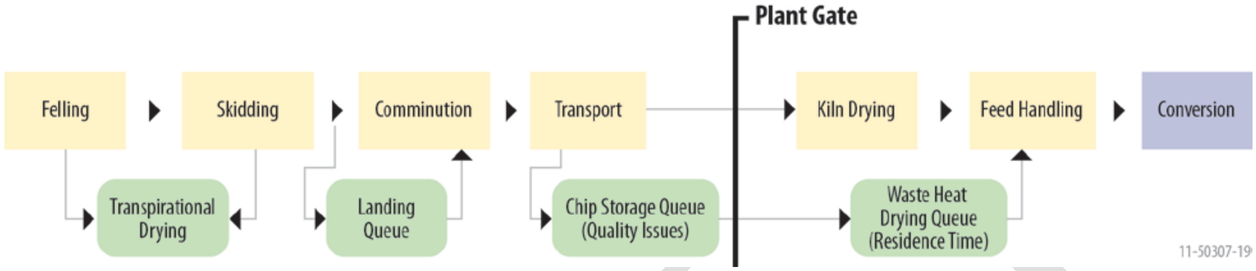

Figure 2-26. Schematic showing an example of hot vs. cold logging systems. The cold logging system, which includes both green circles and yellow boxes, incorporates queuing into the systems.

In Finland, it has been found that, over shorter distances, it is more efficient to move the bulky residues as opposed to chipping at the landing because the logistics are simplified when the loose residue truck can move independently from the chipper (Ranta and Rinne 2006). However, there are a variety of tradeoffs to consider, including landing space, cost of moving the chipper, production cost of the fixed versus mobile chipper, as well as the difference in costs for transporting the residues as opposed to chips.

The grinder/chipper would have a similar operational window as the Harvest and Collection operation. Weather conditions may prevent truck access to the landing, which would limit the grinder/chipper operational window.

Base Case Conventional Preprocessing Cost Analysis A breakdown of the costs associated with each piece of equipment used in the Preprocessing unit operation identifies significant cost components that are valuable for making individual comparisons and identifying areas of research potential (Table 2-14). These costs are reported in terms of DM tons.

Table 2-14. Static model costs for major Preprocessing equipment in the Base Case Conventional scenario. Costs are expressed in 2010 $/DM ton unless otherwise noted. Total operation cost is the sum of ownership, operating, and DM loss cost.

	Chipper	Total Cost per DM ton for Preprocessing
Installed Equipment Quantity (# of machines)	6	
Installed Capital	3.23	3.23
Ownership Costs	*1.52*	*1.52*
Operating Costs	*4.44*	*4.44*
Labor	1.10	1.10
Non-Labor	3.33	3.33
Dry-matter loss Costs	--	--
Energy Use (Mbtu/DM ton)	101.6	101.6

From Table 2-14, the total Preprocessing cost for pulpwood sized trees is $6.02/DM ton, which is the sum of ownership, operating, and dry matter loss costs. The Preprocessing operation consumes very high amounts of diesel fuel to run the chipper (reflected in the energy consumption of the flail and chipper).

2.1.3 Base Case Conventional Transportation

Transport and delivery are key elements of forest activities, and the way they are organized has implications for the production system as a whole (Hubbard et al. 2007). After comminution, the chips are ejected into the back of a chip van and transported via truck to the biorefinery (Figure 2-27). Increased bulk density resulting from the chipping process greatly enhances the economics of the Transportation operation. One of the challenges associated with transportation of woody biomass is that it is commonly about 40–50% water, making this operation inefficient.

Figure 2-27. Transportation supply logistic processes and biomass format intermediates for the Base Case Conventional design. *(Note: Green ovals represent biomass format intermediates and yellow rectangles represent processes modeled in this report)*

2.1.3.1 Base Case Conventional Transportation Format Intermediates

During the Transportation operation, the format of the material remains a chip (Table 2-15).

Table 2-15. Attributes of Transportation format intermediates for the Base Case Conventional system.

	Transported Chips
Yield (DM tons/day)	2330
Format Output	chips
Bulk DM Density Output	20 lb/ft^3
Output Moisture (% w.b.)	50%

Biomass Deconstruction, Fractionation, and Physical Property Changes

In the Base Case Conventional Transportation operation, the physical characteristic of the material is not altered.

Format and Bulk Density Impact on Supply System Processes

The low dry matter bulk density of biomass increases the cost of transportation because air and water are major components of the transported volume. Also, the complex texture of the material makes handling technically difficult (Hubbard et al. 2007). Bulk density may be increased and the problems associated with the material’s texture reduced by compaction (Angus-Hankin et al. 1995) or by comminution via chipping, grinding, or shredding. However, in systems where the trees are chipped during the preprocessing operation, comminuting biomass may introduce new problems by decreasing durability and increasing dry matter loss during storage (see Section 2.4). Transportation is a key component of woody biomass supply systems, and transportation methods affect the entire production system (Hubbard et al. 2007). Dry matter bulk density varies dramatically depending on format (Figure 2-28), and a particle size and distribution are key factors that depend on the equipment used to make the chips.

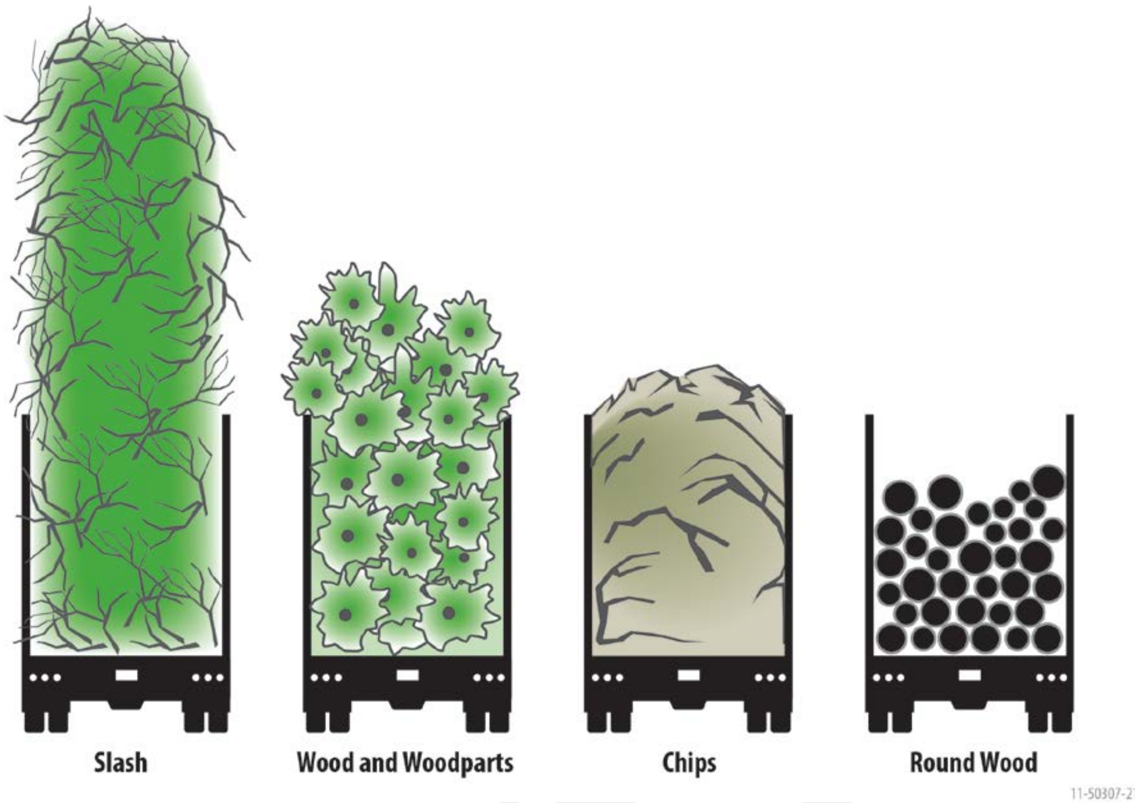

Figure 2-28. Volume differences of the same weight material by different product types (adapted from Schroeder 2007). Roundwood is denser than chips because there is less air space.

Comminuted woody materials are transported in enclosed or covered box trailers known as vans. Chip vans come in a variety of sizes and configurations, so they can be matched with the density of the material being hauled to maximize efficiency. Vans in the southern U.S. are usually designed for a capacity of 80,000 lb (Hubbard et al. 2007). Depending upon the weight of the road tractor and the trailer itself, this means that they can carry a legal payload of about 42,000 to 52,000 lb. The cubic yard capacity of the trailer is matched to the material being hauled. To achieve the maximum weight capacity for lighter material, the bulk van must have more volume capacity (Hubbard et al. 2007). Western states often have higher weight limits, so larger 148 yd^3 possum-belly vans (Figure 2-29) are more common in the west.

Figure 2-29. Possum belly chip van or trailer (Photo credit: D. Brad Blackwelder).

Most vans have a volume of 97 to 131 yd^3, with the 120 yd^3 size being common in most areas. Vans designed to carry wood shavings can hold over 150 yd^3. The bulk density at which the capacity of the truck is reached varies by truck configuration and state road limits (Table 2-16).

Table 2-16. Bulk density required to maximize various load capacity configurations to accommodate a range of load limits.

	Load Limits		Payload	
Truck Configurations	Length (ft)	GVW (lb)	Max Weight (lb)	Trailer Volume (ft^3)
48-ft Possum-belly Chip Trailer	48[a]	80,000[a]	48,110	3,940
53-ft Possum-belly Chip Trailer	53[b]	80,000[a]	46,880	4,371
48-ft Flat-bottom Chip Trailer	48[a]	80,000[a]	48,110	3,940
53-ft Flat-bottom Chip Trailer	53[b]	80,000[a]	46,880	4,371
48-ft Live-bottom Trailer	48[a]	80,000[a]	48,110	3,940
53-ft Live-bottom Trailer	53[b]	80,000[a]	46,880	4,371

a. Federal minimum trailer length or gross vehicle weight (GVW) that states must allow on National Network (NN) highways.
b. Common state maximum trailer length allowable on National Network (NN) highways.

Many states allow a 53-ft semi trailer on national network roads, which leads to a lower target bulk density. Potential truck configurations are shown in Figure 2-30.

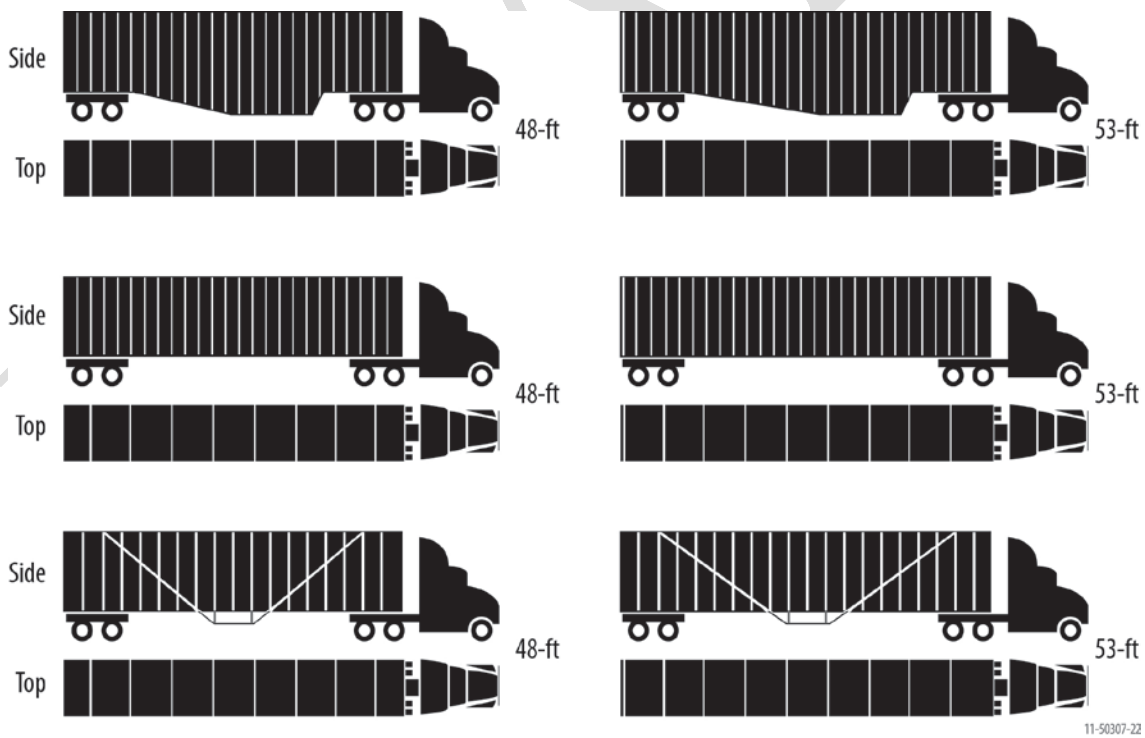

Figure 2-30. Truck configurations for a 48-ft and 53-ft chip-van trailer carrying chips. The possum-belly trailer (top) requires more clearance and, therefore, is only suitable when the landing is appropriate. A live bottom trailer for carrying chips is shown as the bottom icon.

The bulk density of the woodchips may increase during loading and transport due to settling. McDonald et al. (1995) found that the density of green pine chips and bark increased during transport (using vibrations to simulate transportation vibrations), while the density of hardwood chips remained approximately the same.

As mentioned above, one option to increase density during transport is compaction. Compaction has shown significant benefits to pre-transport size reduction (Table 2-17, Angus-Hankin et al. 1995).

Table 2-17. Impact of compaction on bulk density (McDonald et al. 1995 and Angus-Hankin et al. 1995).

	Wet Bulk Density (lb/ft^3)	% Increase Over Uncompacted
Uncompacted residues	8.7	—
Loader compacted residues	10.6	21
Compaction device	18.7	214
Baled residues	18.7	214
Chipped biomass	22.2	243
Compacted using waste press	22.3	255

Biomass Moisture Impact on Supply System Processes and Material Stability

Transportation cost is related to biomass moisture content, as well as the amount of void space left between particles in the material as a result of the chip shape and size. Figure 2-31shows an example of this relationship.

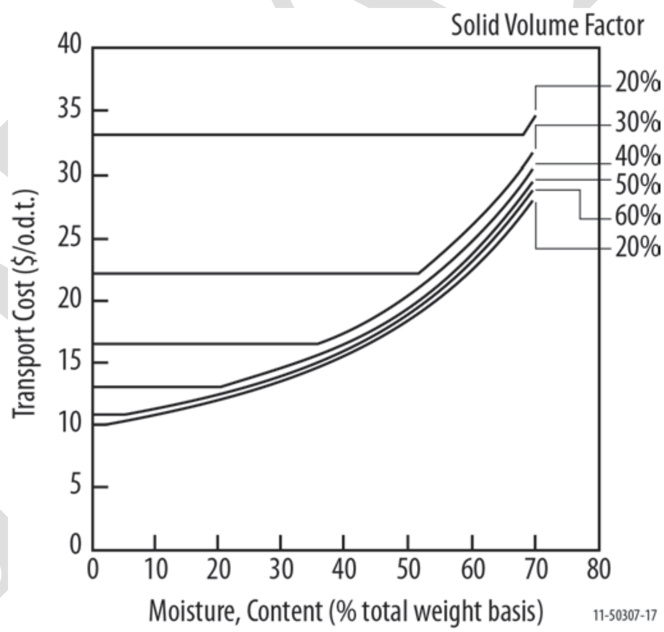

Figure 2-31. Relationship between transportation costs and moisture content considering various solid volume factors. A higher solid volume factor indicates more dense packing (Recreated with permission from Pottie and Guimier 1985).

The more void space, the higher the transport cost will be up to the point at which the truck reaches maximum weight capacity. Loose residues do not have enough density to reach the weight capacity. Also, transport costs decrease with decreasing moisture content until the truck weight capacity is met; however, for loose residues, the void space is so high that the load is never near weight capacity until moisture is very high (over 60% MC) (Pottie and Guimier 1985).

2.1.3.2 Base Case Conventional Transportation Equipment

Trucks transport most forestry products and harvesting material. About 90% of the pulpwood delivered to U.S. mills in 2005 arrived by truck (Hubbard 2005). Trucks for transporting forest commodities are either tractor-trailer or fixed truck type. Most goods in the South are currently transported in 80,000-lb gross vehicle weight (GVW) road tractor-trailer combinations. These combinations use standard highway road tractors, six- to ten-wheel tandem-axle highway trucks with either a conventional (i.e., engine in front of compartment) or cab-over-engine design. Typical road tractors weigh about 12,000 to 20,000 lb and can include provisions for hydraulic power for trailer functions such as operating self-unloading floors. Road tractors are designed to pull cargo trailers. These trucks are designed for greater capacity and offer the versatility of changing the type, size, and configuration of cargo space (Hubbard et al. 2007). Transportation equipment used in the conventional design is summarized in Table 2-18.

Table 2-18. Transportation equipment specifications for the Base Case Conventional system.

	Transport
Equipment	Chip Van
Rated Capacity	120 yd^3/ load
Operational Efficiency (%)	100 %
Dry matter loss (%)	0%
Operational Window	
Hr/day	14
Day/yr	300

Transportation

Selection of the truck used in delivery depends on several variables, including format of the material being hauled, loading location, unloading method, and the volume of material to be transported. Three types of trucks are commonly used for delivery of wood fuels: (1) dump trucks, (2) live-bottom (self-unloading) semitrailer vans, and (3) standard semitrailer vans, with the choice of truck dependent on the quantity purchased and the equipment available for unloading trucks (Badger 2002). Dump trucks and live-bottom trucks have the advantage of being able to unload themselves directly onto storage piles. Standard semitrailer vans require truck dumpers. Smaller and less expensive dump systems only raise the trailer van for dumping, a process that requires decoupling the tractor and semitrailer and, therefore, consumes time. Larger dump units can tilt the whole truck and can thereby unload in a matter of minutes and in approximately one-half the time of a trailer-only dumper. Minimizing unloading times is important because the haulers can impose financial penalties for excessive unloading times, although this may be rare (Badger, 2002). Dump trucks are rarely used, however, due to the low payload size relative to their operating costs.

The type of wood delivery system is determined, to a large extent, by the quantity of wood needed. Installations less than 8 thermal gigawatts (GW_t) may have wood delivered in dump trucks, live-bottom trailer vans, or regular trailer vans (GLRBEP 1986, Trulove 2002). Dump trucks are preferred for short-haul situations. Installations larger than 8 GW_t have wood delivered in regular semi-trailer vans and use dumpers capable of tilting the whole truck (GLRBEP 1986).

Chip vans used for transport of forest products are enclosed box trailers generally 8 to 8.5 ft in width and 12 ft or less in height when pulled by a road tractor. Bulk vans have either an open end or an open top (Figure 2-32). Open-top bulk vans are usually loaded with front wheel loaders from the side, or with a conveyor. Open-end bulk vans are generally used with chippers that blow chips into the van through the tailgate. The tailgates allow loading and reduce or eliminate flying material while in transit (Hubbard et al. 2007).

(a) (b)

Figure 2-32. Top-loaded and rear-loaded chip vans. Note that the top-loaded chip vans have removable tarps to comply with most state regulations (Photo credit: D. Brad Blackwelder, INL).

Transportation is an area where use of vans or covered containers for chips and covered hauling of logs can reduce the operational costs of the transportation due to moisture absorption as well as additional subsequent drying operational expenditures (Moller 2007).

Often the most cost-effective way to transport wood chips is to comminute directly into a chip trailer (Rummer and Klepac 2003; Rawlings et al. 2004). However, many remote landings are not accessible to chip vans because of their poor ground clearance and significant off-tracking issues. One solution to this is to convert a conventional stinger-steered log truck for chip hauling. Figure 2-33 shows a stinger-steered chip trailer developed by USFS San Dimas Technology and Development Center. This trailer will hold about 88 yd^3 of chip with a payload up to 22 tons. It is 13 ft-3 in. tall, making it highway-legal in all 50 states.

Figure 2-33. Stinger-steer chip van developed by San Dimas for accessing materials at remote landings (Photo credit: D. Brad Blackwelder, INL).

Container trailers are designed to hold bulk material, and the container is designed to be handled full. Because of this, they are built with sturdy walls and supports, and their total capacity in cubic volume is less than bulk vans or log trailers. They can be left on a site and filled as desired and then removed and replaced with an empty container at the same time. They can also be used as storage at the end user's site. In addition, container trailers may be more suitable for collecting yards where road access is limited or where smaller volumes are present (Hubbard et al. 2007).

Equipment Capacity and Operational Efficiency

Most goods in the southern states are currently transported in 80,000-lb GVW road tractor-trailer combinations that usually have a tare or empty combined weight, of 26,000 lb.

Dry matter losses

Transport losses can also be assumed to be 0% (Hamelinck et al. 2005, Suurs et al. 2002).

Operational Window

For this scenario, Transportation operation runs 14 hours per day, 6 days per week, except during plant shutdown for maintenance.

2.1.3.3 Base Case Conventional Transportation Cost Analysis

Cost Summary

A breakdown of the costs associated with each piece of equipment used in the Transportation operation identifies significant cost components that are valuable for making individual comparisons and identifying areas of potential research (Table 2-19). These costs are reported in terms of DM tons entering each process.

Table 2-19. Static model costs for major Transportation equipment in the Base Case Conventional scenario. Costs are expressed in 2010 $/DM ton. Total operation cost is the sum of ownership, operating, and DM loss cost.

	Transport	Total Cost per DM ton for Transportation
Equipment	Chip Van	
Quantity of Equipment (# of machines)	61 trucks	
Installed Capital	14.05	14.05
Ownership Costs	*2.34*	*2.34*
Operating Costs	*11.99*	*11.99*
Labor	5.68	5.68
Non-Labor	6.31	6.31
Dry-matter loss Costs	*0*	*0*
Energy Use (Mbtu/DM ton)	132.8	132.8

From Table 2-20, the total Transportation cost for pulpwood sized trees is $14.33/DM ton, which is the sum of ownership, operating, and dry matter loss costs.

2.1.4 Base Case Conventional Receiving and Handling

Once the whole tree chips are transported to the biorefinery, chips are unloaded using a truck tipper into a hopper, cleaned to remove metal pieces and dirt, and conveyed using a circular stack reclaimer

(Figure 2-34). One of the challenges associated with receiving and handling of woody biomass is that it is commonly about 40–50% water, making these operations inefficient.

Figure 2-34. Receiving and Handling supply logistic processes and biomass format intermediates for the Base Case Conventional design. *(Note: Green ovals represent biomass format intermediates and yellow rectangles represent processes modeled in this report)*

Cleaned chips are stored prior to further processing.

2.1.4.1 Base Case Conventional Receiving and Handling Format Intermediates

During this operation, the format of the material remains a chip (Table 2-20). Chips are cleaned to remove any contaminants that might damage the conversion process, such as metal.

Table 2-20. Attributes of Receiving and Handling format intermediates for the Base Case Conventional system.

	Cleaned Chips
Yield (DM tons/day)	2330
Format Output	chips
Bulk DM Density Output	20 lb/ft^3
Output Moisture (% w.b.)	50%

2.1.4.2 Biomass Deconstruction, Fractionation, and Physical Property Changes

In the Base Case Conventional Receiving and Handling operation, the physical characteristics of the material are not altered beyond the removal of contaminants.

Format and Bulk Density Impact on Supply System Processes

Plant Receiving and Handling

The handling and queuing of bulk feedstock depend on the physical properties of the material, specifically particle size distribution, particle shape, texture, and moisture content (Mattsson and Kofman 2003, Hubbard et al. 2007), and the design of the equipment used in the various processes. Conducting these processes is complicated because most existing handling and conveying technologies are designed for operation with granular materials, such as food grains or minerals, or heavy bulk solids such as coal. In the case of grains, these materials typically have small, uniform particle sizes, high densities, and almost negligible compressibility. By contrast, the wood feedstocks proposed for use in biofuel production may have large particle size variations, low densities, and can be highly compressible.

The most economical way to convey, feed, and store biomass feedstocks is in standard systems that use gravity flow. The ability of the feedstock to flow through a particular assembly system is a function of the feedstock physical properties and the design of the structure. The material properties that determine how easily a feedstock will flow through a structure include its bulk density, its tendency to bridge, and the frictional forces it exerts on itself and the structure wall. These properties are, in turn, impacted by the feedstock's particle size and distribution, particle shape and distribution, moisture content, temperature, and the pressure it has experienced as a function of time.

Flowability

The two main factors that affect the flowability of woodchips are moisture content and consistency of woodchip sizes. According to the pulpwood facility operators, handling systems work best with woodchips with MC less than 30% (wet basis); woodchips with a higher MC do not flow easily, and blockages occur in handling equipment (Webster 2007).

Increasing particle size makes the chips less likely to clump together due to exposed surface area, which contains exposed moisture or resin. However, as moisture and resin content are reduced or dissipated, a smaller size becomes advantageous. Smaller, drier chips are easier and more cost efficient to transport and handle as the product nears the end of the process cycle. Careful consideration based on the species, location, storage methodology, and final use is necessary to reduce inefficiency and maximize profit (Webster 2007).

Mattsson and Kofman (2003) studied the influence of cutting and storage methods on the tendency to bridge for chips and chunks made from 3- to 5-yr-old willow shoots harvested in January and December in Denmark. Shoots were cut with four different machines to produce five fuel assortments with nominal particle length from 2.8 to 20 cm and stored outdoors in 160 m^3 loose volume piles. Some piles were uncovered, some covered with plastic, and two were sealed in an airtight silage plastic film enclosure. The bridging tendency was measured at the end of May and September by determination of how wide a "bridge" of fuel over a slot opening could be before it collapsed. With a 50-cm-thick layer of fuel above the slot opening, the bridge width varied between 5.8 cm for the small chips and 100 cm for the large chunks. Most of the variation was due to two factors: the percentage of particles longer than 10 cm and moisture content.

Biomass Moisture Impact on Supply System Processes and Material Stability

The moisture content has minimal impact on the Receiving and Handling operation. If the equipment is weight limited by capacity (which is not the case in the Base Case Conventional system), then higher moisture may result in additional Receiving and Handling equipment being required. Very dry material might increase dust; however, the modeled dust collection system would be sufficient to mitigate the air quality concerns.

2.1.4.3 Base Case Conventional Receiving and Handling Equipment

At the biorefinery, material is weighed, unloaded, and cleaned before storage and queuing. Receiving and Handling equipment used in the Base Case Conventional design are summarized in Table 2-21.

Table 2-21. Receiving and Handling equipment specifications for the Base Case Conventional design.

	Unloading/Handling/Dust Collection	Chip Cleaning
Equipment	Truck tipper and hopper, circular stacker and overpile reclaimer, dust collection, moisture meter	Electro magnet
Rated Capacity	280 t/hr	18 DM t/hr
Operational Efficiency (%)	100%	100%
Dry matter loss (%)	0%	0%
Operational Window		
Hr/day	14	14
Day/yr	300	300

Weighing

Typically the entry point for truck unloading operations will be a set of drive-on scales, and this is the point where product delivery costs are determined. Scales may be mechanical or electronic or a combination of both. Mechanical scales are more commonly used due to their lower maintenance costs. Sometimes conveyor belt scales are used for determining weights, but these systems are less accurate, more time consuming, and more expensive to operate (Badger 2002).

Unloading

Prolonged unloading times will result in increased costs from down time. Trucks also arrive randomly and often with other trucks. It is therefore common to design woody biomass handling facilities such that they are able to accommodate half the daily volume of deliveries in one-third of the business day (GLRBEP 1986; Makansi 1980). Other remedies include providing 24-hour dumping accessibility and installation of multiple dumping stations.

Small-scale users frequently use self-unloading semi-trailer vans that are equipped with a live floor that “walks” the load from the van and allows one person to unload a van within 10 minutes (Figure 2-35). Walking floors consist of a series of narrow, hydraulically operated floorboards that run lengthwise in the truck bed. Some small-scale facilities use a self-unloading trailer as their fuel storage system, and simply activate the walking floor as fuel is needed. To convey material, a series of adjacent boards will move toward the rear together and then retract one at a time to minimize pile contact area. Trailers can range from 10 to 15 m in length and carry between 20 and 30 tonnes of wood (GLRBEP 1986). The advantage of self-unloading is offset by the self-unloading van cost (Jiles 2002).

Figure 2-35. Unloading mechanism found in a live-bottom trailer. The tracks on the floor of the trailer shift back and forth in opposite directions to move material along (Photo credit: D. Brad Blackwelder, INL).

Intermediate-scale installations producing less than 8.5 GW_t of steam may also use a lighter duty hydraulic dumper for unloading fuel. These dumpers use a frame to tilt the semi-trailer van on its rear axle, a process that requires decoupling the tractor and semitrailer and, therefore, consumes time. However, this disadvantage is offset by the cost of the dumper (which includes a live bottom hopper) (Farley 2002).

Large-scale installations commonly use hydraulic dumpers that can lift and tilt the whole truck up to an angle of 75 degrees in a few minutes. These dumpers may require the trailer to be backed onto the unloader, or allow the truck to pull onto the dumper in a drive-through arrangement. For back-on systems, trucks back onto the lifting platform and are held in place by the frame of the lifting device. Dumping is completed in 3 to 5 minutes. A drive-through system has the truck drive across a grate. A frame then lifts to hold the trailer with its tractor in place during the dumping process (Farley 2002, Brammer 2002).

Figure 2-36. Whole-truck tipper unloading 120 yd^3 van loaded with comminuted wood to be further size-reduced and pelletized (Photo credit: D. Brad Blackwelder, INL).

Loading and unloading transports can be one of the limiting factors in delivering biomass. This can take as little as 3.5 minutes in some trucking methods (Suurs 2002) or hours based on material type and loading equipment used. Normally, woodchips or shavings are blown directly from the grinder into the truck trailer, so the truck loading time is directly related to the productivity of the grinder. When there are multiple transfers, loading and unloading of materials, costs for labor, energy and equipment increase. Minimal transfer time is crucial, and further study should be done to estimate how this affects production profits.

Cleaning

Removing metals and other debris as soon as possible from the biomass reduces the risk of the foreign material damaging handling equipment and conversion systems. Metals present during storage can also lead to fires caused by self-heating (Section 2.1.5.1). Ferrous metals are removed with a magnet.

A stationary magnet mounted above a conveyor is used to remove occasional ferrous tramp metal. This magnet will usually have either a metal plate or a canvas “plate” between the magnet and the conveyor to facilitate removal of the metal. Self-cleaning magnets mount between the belts of a rapidly moving conveyor, mounted above and perpendicular to the wood conveyor, so that any metal that is attracted to the magnet is swept to the side by the magnet’s conveyor. These magnets are used for applications with excessive loadings of ferrous metal pieces such as at wood recycling centers (e.g., recycling pallets), but generally not at wood-to-energy plants because the wood fuel delivered to power plants is normally free of excessive metal (Gralnick 2002) (Figure 2-37).

Figure 2-37. Magnet over a conveyor at a paper mill (Photo credit: D. Blackwelder, INL).

A third method is to use a magnetized head pulley on the belt conveyor carrying the wood. The movement of the belt throws the wood forward while the metal sticks to the head pulley. The metal is carried around the pulley until the movement of the belt carries it away from the influence of the magnet, where it drops into a collection box below. Head pulley magnets are not feasible at pulley diameters below 30 cm, as the small pulley diameters do not allow enough room to provide adequate magnet strength. A 30-cm-diameter pulley can handle wood materials of 7.6 to 20 cm in depth. A 60-cm-diameter pulley can handle material depths up to 15 and 17.8 cm in depth (Gralnick 2002).

Figure 2-38. Entrained metal fragments can be of various sizes. The metal can potentially damage equipment and also increases the risk for spontaneous combustion (Photo credit: Regensw Sustainable Energy Agency 2008).

Non-ferrous metals cannot be removed with magnets; however, some plants use non-ferrous metal detectors to detect the presence of non-ferrous metals and stop the wood-carrying conveyor. The metal can then be visually identified by an operator and removed. The detectors operate on the eddy current principle and must be located on the conveyor so that the metal frame of the conveyor does not interfere with its operation. Sometimes a plastic conveyor bottom is installed in the section of conveyor where the detector is mounted to prevent interference from the metal frame.

Dust Collection

Dust generated from truck traffic and unloading, screening, conveying, and all operations except grinding are of little concern unless they cause an obvious problem. If dust is a problem, it is associated with very dry climates, windy conditions, and fine, dry wood waste. Enclosing unloading and other processing operations, especially storage systems, can prevent fugitive dust, but may require installation of dust collection systems. Excessive dust levels in enclosed structures can pose a health and explosion hazard (Badger 2002).

Conveying

Biomass characteristics (including moisture content, shape, particle size and distribution), incline, and conveying distance are critical considerations when considering conveyors. Conveyance equipment can include front-end loaders, conveyors, and elevators (Schmidt 1991) and can generally be classified as mechanical or pneumatic (GLRBEP 1986). Conveyor operation and reliability is crucial to move material between operations. Table 2-22 lists the advantages and disadvantages of the various types of conveying equipment (Badger 2002).

Table 2-22. Advantages and disadvantages of wood fuel conveying systems (Badger 2002, GLRBEP 1986, Makansi 1980).

Type	Cost	Advantage	Disadvantages
Belt conveyors	Highest capital cost/energy efficient	Any type of fuel	Limited to ~15-degree incline; light dry particles are easily blown off
Screw conveyors	High capital cost/energy efficient	When site space is a premium, easily used on inclines	Not suitable for large pieces or stringy wood
Chain/drag conveyors	Medium capital cost/energy efficient	Rugged and adaptable to plant conditions	High maintenance; possible fire hazard; limited to ~18-degree inclines
Bucket conveyors	Medium capital cost	Applicable for inclines and vertical transport	Not suitable for long horizontal runs
Oscillating conveyors	Low capital cost/energy efficient	Dense, bulky, and stringy wood fuels; horizontal transport	Not applicable for small light fuels such as sawdust; limited incline
Pneumatic conveyors	High operating (energy) cost	Small, lighter fuels, (i.e., finely hogged dry waste, sawdust, and sanderdust); long distances	Not applicable for larger particles; fugitive dust problems

Belt conveyors (Figure 2-39) are among the most commonly used to transport virtually all types of wood fuels (Badger 2002). Belt conveyors consist of a rubber belt that operates in a loop supported on rollers, usually in a U-shaped frame to allow them to carry large quantities of material. Sometimes elastic sidewalls and flights are added to increase capacity and to allow use on inclines. Maximum recommended incline is usually 15 degrees (Badger 2002). Outside belt conveyors should be covered to reduce potential dust, moisture pickup, and ice formation problems.

Figure 2-39. Enclosed belt conveyor at Smurfit Stone paper mill, Montana (Photo credit: D. Brad Blackwelder, INL).

Screw conveyors or augers (Figure 2-40) are commonly used in woodchip combustion plants (Gislerud et al. 1988). They are used for elevating or metering fuel into the conversion device. This is a big advantage over other types of conveyors, especially belt conveyors. Although there are many types of screw conveyors, feeding screw conveyors can feed specified volumes of material with reasonable accuracy (Gislerud et al. 1988). They are also sometimes used to reclaim fuel from storage systems. However, screw conveyors are relatively expensive, can only transport materials in a straight line, have high wear, and tend to jam easily (Badger 2002). Screw conveyors have trouble handling stringy materials or wood fuel particles larger than 5 cm. They are usually mounted in an open-topped, U-shaped trough, which minimizes jamming and allows access to the material in case a jam occurs (Badger 2002).

Chain conveyors can consist of either large box-links, which serve as the conveyor flights, or single or double chains with flights (Figure 2-40). In all cases, the flights lie in a trough containing the moving material. Chain conveyors are versatile and rugged, and their primary applications are in live bottom equipment and for feeding fuel to a conversion device. Chain conveyors may be used to meter fuel into the conversion device. Chain conveyors are less sensitive to load variations and overloading than belt conveyors. Their operational energy requirements are relatively low, and their cost falls between belt and screw conveyors (Badger 2002). Properly designed drag chain systems can move material up slopes of up to 18 degrees, but have high wear and maintenance requirements (Makansi 1980). Flight conveyors are suitable for inclines up to 30 degrees. Neither drag chains nor flight conveyors are recommended for applications exceeding 15 m in length, although this is sometimes exceeded in practice (Makansi 1980, Badger 2002).

Bucket conveyors are used when vertical lift of a solid fuel is required, space is expensive or limited, and the particles to be moved are relatively small and uniform. They have relatively low operational energy requirements, but they have higher than average maintenance costs and a higher initial cost (Badger 2002). Still, bucket conveyors are the most economical way to convey materials that only have to be moved vertically.

Oscillating or vibrating conveyors are trough-shaped and can handle a wide variety of fuels with a broad particle size range without jamming. These conveyors transport material by rapidly moving the trough in upward and forward motions, and they are generally limited to conveying over short, horizontal distances (Badger 2002; Giserlud et al. 1988). Oscillating conveyors can also separate larger particles from the smaller ones, if desired (Gislerud et al. 1988).

Pneumatic conveyors are used to move small, light particles, such as sawdust, and consist of a positive displacement blower, transport piping, a rotary airlock to inject fuel into the pipe, and a cyclone to separate the fuel from the conveying air at the terminal end. The cyclone can be eliminated if the system is feeding fuel into a suspension-fired boiler (Badger 2002). Pneumatic conveyance is often used to bring fuel into the silo (Gislerud et al. 1988). Pneumatic conveyors are often used in systems that mill woody biomass to a fine particle size, such as required for pyrolysis (Jones et al. 2008).

Pneumatic systems can move material vertically, horizontally, or up inclines; are more flexible in arrangement than mechanical conveyors; and usually require less expensive installation. They are ideally used for distances over 500 ft (especially in straight runs) and where the conversion device is a suspension burner (Badger 2002). Pneumatic conveyors have high energy requirements (roughly 10 times that of belt conveyors) and wear rapidly, especially if non-wood materials are present (Makansi 1980). The energy requirements and wear also increase dramatically as the particle size of the conveyed material increases. Depending on fine particulates present and environmental regulations, a secondary dust collection system may be required after the cyclone. However, pneumatic systems dry the product during conveyance by 3 to 6% (for 50% moisture content wood) (Badger 2002).

Figure 2-40. Bruks circular stacker reclaimer at the Green Circle pellet mill in Cottondale Florida. The contained, white conveyor at the top drops clean chips on the green conveyor going to the right. Simultaneously, the bucket reclaimer is pulling chips off the pile on the left and depositing them on the lower, contained conveyor, which is taking them to the pelleting facility (Photo credit: Bruks 2010).

Dry Matter Losses

Receiving and Handling losses are assumed to be 0% (Hamelinck et al. 2005, Suurs 2002).

Operational Window

For this scenario, Receiving and Handling operations run 24 hours per day, 7 days per week except during plant shutdown for maintenance.

2.1.4.4 Base Case Conventional Receiving and Handling Cost Analysis

Cost Summary

A breakdown of the costs associated with each piece of equipment used in the Receiving and Handling operation identifies significant cost components that are valuable for making individual comparisons and identifying areas potential research (Table 2-23). These costs are reported in terms of DM tons entering each process.

Table 2-23. Static model costs for principle Receiving and Handling equipment in the Base Case Conventional scenario. Costs are expressed in 2010 $/DM ton. Total operation cost is the sum of ownership, operating, and DM loss cost.

	Unloading/Handling/ Dust Collection/ Cleaning	Chip Cleaning	Circular Stack Reclaimer	Total Cost per DM ton for Receiving and Handling
Equipment	Scale, truck tipper & hopper, dust collection, moisture meter	Electro magnet		
Quantity of Equipment (# of machines)	–	12	1	
Installed Capital	4.47	0.32	2.52	7.31
Ownership Costs	*0.72*	*0.04*	*0.26*	*1.02*
Operating Costs	*0.98*	*0.01*	0.39	*1.38*
Labor	0.81	0	0.03	0.84
Non-Labor	0.43	0.01	0.10	0.53
Dry-matter loss Costs	*0*	*0*	*0*	*0*
Energy Use (Mbtu/DM ton)	13.3	0.024	2.06	15.36

From Table 2-23, the total Receiving and Handling cost for pulpwood sized trees is $2.39/DM ton, which is the sum of ownership, operating, and dry matter loss costs.

2.1.5 Base Case Conventional Storage

Storage encompasses all processes associated with piling, pile turning, and ambient drying of the woody biomass (Figure 2-41). It also includes any costs associated with storage site preparation, such as construction of an asphalt pad, silo, or other storage structure. The Base Case Conventional design includes storage on an asphalt pad.

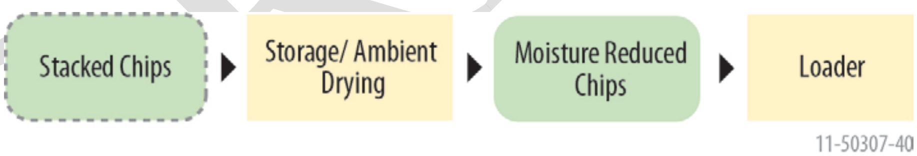

Figure 2-41. Base Case Conventional Storage supply logistics processes and format intermediates. *(Note: Green ovals represent format intermediates, and yellow rectangles represent individual modeled processes.)*

Cleaned chips are piled and stored until required for further processing. A “first in, first out” system is used.

2.1.5.1 Base Case Conventional Storage Format Intermediates

The dry matter losses resulting from storage are assumed to be 2%. These are a combination of biological and mechanical losses, the majority coming from the latter (Table 2-24).

Table 2-24. Characteristic of storage format intermediates in the conventional scenario.

	Stacked Chips	Moisture Reduced Chips
Yield (DM ton/day)	2330	2285
Format Output	Chips	Chips
Bulk DM Density Output (lb/ft^3)	15	15
Output Moisture (% w.b.)	50	45

During storage, the chips lose 5% moisture through ambient drying, which is discussed below.

Biomass Deconstruction, Fractionation, and Yield

Environmental and Human Health

Various factors impact the degree of exposure to health risks, including species, wood format and particle-size distribution, season of the year, climate, duration, concentration, time of tree comminution, and moisture content, among other factors. For example, more micro-organisms are released from communited woody biomass and straw in spring than in autumn (Kotima et al. 1991), and smaller woody biomass pieces are shown to release more fungi than larger, bulkier ones (Pellikka and Kotima 1983). Wood briquettes and pellets are dusty, but the dust contains very small amounts of microbes. Hog fuel and woodchips, however, release less dust, but the dust has a high content of microbial components (NIC 2008).

There are numerous technical measures available to minimize airborne dust and other harmful emissions. Dust collection, ventilation, exhaust ventilation and negative pressure, curtains and walls to isolate dust-generating areas, fine water sprays, closed sections and remote-control equipments and machinery can be used (NIC 2008).

Gas Emissions

Emissions of volatile compounds and degradation products can occur during storage and transport of woody materials (NIC 2008, Wihersaari 2005); there is a higher risk for exposure to harmful emissions when the material is stored in an enclosed space (NIC 2008). For example, emissions of aldehydes, terpenes, carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO) have been found in bulk storages of comminuted woody biomass and pellets (Kuang et al. 2009, NIC 2008, Wihersaari 2005). Concentrations of CO approaching 1% by volume have been measured in silos (Blomqvist and Persson 2008), and several fatalities from CO poisoning have occurred in cargo spaces in ships during unloading (Svedberg et al. 2009). Wihersaari (2005) found the rate of greenhouse gas (GHG) production, particularly methane, to be significant. The rate of emissions production depends on many factors, including carbon-to-nitrogen ratio (and wood species), size of air space, temperature, humidity, particle size, volume, moisture content, and other factors that impact the microbial activity that is responsible for the majority of emissions (Wihersaari 2005).

Molds and Other Micro-organisms

Storage of wet-solid biofuel in a pile, especially freshly comminuted material such as hog fuel and woodchips, provides an environment favoring the growth of many species of bacteria and fungi (Gislerud, Gjolsjo, and Thorkildsen 1988, NIC 2008). The most common and abundant organisms that are detrimental to stored material are actinomycetes (bacteria) and molds (fast-growing fungi) (NCI 2008). These micro-organisms produce small, easily inhaled spores (<5 mm in diameter), which become airborne when the material is moved. Inhalation can cause allergic reactions and even lung diseases. More than 10^9 spores/m^3 air can be released from handling moldy spore-laden materials; therefore, it is recommended to use a suitable protective respirator or mask (Madsen et al. 2004, NIC 2008). The composition of the component, (for example, wood vs. foliage vs. bark, etc.), determines the availability of easily usable nutrients in the stored chips and therefore impacts microbial growth. Needles and bark, for example, have more soluble nutrients and higher nitrogen content than stem wood and, hence, provide a better substrate for fungal and bacterial growth (NIC 2008).

Organic Dust

There is always some dust present when handling woody biomass, especially when it is dry and/or has been comminuted, and the danger of the dust depends on its composition, concentration, particle size, and shape (NIC 2008, Madsen et al. 2004). Small air-borne particles (≤5 μm) are able to penetrate deep into lungs and may cause respiratory diseases. Organic dust or “bio-aerosols” from biomass feedstocks consists of live and dead bacteria and fungi, microbial components, enzymes, and plant fibers (NIC 2008). Long-term organic dust exposure increases risk of infectious disease, respiratory diseases such as asthma and chronic obstructive pulmonary disease (COPD), and cancer (NIC 2008). Using personal protective equipment, such as a suitable respirator, can greatly decrease the risk, as can engineering barriers designed to limit worker exposure.

Self-Heating and Fire Risk

The mechanisms of self heating and deterioration have been well studied in North America and Europe (Fuller 1985, Bergman 1974, Weiner et al. 1974, Springer 1979). Cellular respiration and microbial growth are the main biological activities that take place soon after comminuted woody biomass is piled and lead to heat release (Kubler 1987). The living cells in the wood (parenchyma cells) respire in an attempt to heal the tree, and as oxygen is consumed heat is released (Fuller 1985). This heat generation promotes bacterial growth, which increases heating further (Fuller 1985). As a result of limited air flow through the pile and the low conductivity of woody biomass, the heat accumulates over the next 1 to 4 weeks (Fuller 1985), reaching around 60°C (between 20 and 80°C, depending on the species of microbe), at which point most of the biological activities cease (Hall 2009, NIC 2008, Kubler 1987). The temperature increases further from subsequent physical and chemical processes such as water transport and adsorption, hydrolysis, chemical oxidation, and charring/pyrolysis (NIC 2008), causing well-known storage problems. These problems include dry matter loss, loss of fuel quality, and heat accumulation, which may ultimately lead to spontaneous ignition (NIC 2008, Pottie and Guimier 1985, Fuller 1985). At the extreme, tropical hardwood and whole tree chip piles have been reported to heat rapidly to temperatures of 50 to 80°C in 5 to 7 days (Fuller 1985, Springer 1979). Pyrolysis or chemical oxidation is likely once pile temperature exceeds 70°C (Hall 2009, Fuller 1985). Loss of fuel quality can be reflected in a reduction in the heating value, inhomogeneous fuel resulting from increased and uneven moisture, increased ash content resulting from organic matter loss, and a higher percentage of fine particles (NIC 2008). In summary, at lower temperatures and at early stages of storage, organisms such as mold and bacteria dominate deterioration; whereas, at later stages of storage, chemical reactions are most active.

When ground woody material is stored longer than a month, acid accumulation resulting from chemical reactions further deteriorates the chips, leading to dry matter loss (Fuller 1985). Because this acid-generating chemical reaction is exothermic, it also leads to increased pile heating (Fuller 1985). An acidic odor is often noticeable by chip pile operators when the acid is building up (Fuller 1985).

Chipping the fuel leads to an enormous increase in the exposed surface areas available for microbial growth and as a result of decreased permeability limits airflow through the pile, which reduces heat diffusion. Storage of larger particles (for example, chunk wood and small trees in bundles) is known to cause fewer problems than chips (NIC 2008, Pottie and Guimier 1985, Jirjis 1995, Nurmi 1995). Increased levels of fines (such as from bark) decrease airflow and further increase the fire hazard (Fuller 1985). The presence of nutrients such as leaves increases the rate of bacterial degradation and also increases heating (Fuller 1985).

Biomass with moisture contents between 25 and 50% (w.b.), such as woodchips, is more conducive to microbial growth and the resulting heat production and dry matter losses (Pottie and Guimier 1985, Hall 1980). Below a moisture content of 20%, bacterial and fungal activity is very limited (Hall 2009, Springer 1980, Pottie and Guimier 1985). Fungi and bacteria require moisture for degradation of the biomass, and the resulting microbial growth increases the temperature in the stored fuel. Exothermic reactions in wood chips have been detected in the range of 45 to 60°C and were attributed to the reactions of biological fermentation products (Li et al. 2006). Studies have shown that oxidative processes are faster in wood containing higher amounts of lignin (such as softwood) and that the presence of metals increases the oxidation rate (Kubler 1987, Pellikka and Kotima 1983). The temperature of a pile of chipped forest residues generally rises very rapidly after an initial period of 1 week (Wihersaari 2005).

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. Drying occurs to the extent that moist air leaves the pile. Self-heating can cause the moisture content in the pile to drop by 7% in 3 to 5 weeks (Hall 2009). 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). The factors that promote self-heating are moisture content between 25 and 50% (w.b.), pile height over 6 m, and long-term storage of comminuted materials (Hall 2009, Pottie and Guimier 1985, Hall 2009). The pile shape has more of an impact on temperature increase than height, as the shape determines the ventilating chimney effect in the pile (NIC 2008). The ideal pile shape maximizes outer surface area, and is an elongated pile (that is, long, flat conical piles) with a base-width twice that of the height of the stack (NIC 2008, Hall 2009).

Spontaneous ignition starts in the interior of the pile and occurs when heat production exceeds the heat dissipation in bulk material, causing the material to reach its auto-ignition temperature. The material does not need to be dry for this to occur, as water has been implicated in the formation of volatile products as a result of thermohydrolysis (Ball et al. 2004). Other researchers disagree and suggest that water evaporation leads to temporary thermal stability that ultimately gives way to thermal runaway and ignition after total water loss (Gray et al. 1984). These and earlier theoretical and empirical models (reviewed in Thomas and Bowes 1961) indicate that a lag-time exists between initial stages of self-heating and catastrophic thermal runaway that is different for different cellulosic materials. This lag-time is defined as the induction period, during which various chemical reactions (both endo- and exothermic) are theorized to occur. These reactions may lead to the formation of thermally stable cellulose decomposition products such as char, or volatile products such as levoglucosan, and gases such as CO (Ball et al. 2004). Theoretical modeling supports observations that biological self-heating may be sufficient to initiate combustion of cellulosic materials (Nelson et al. 2003).

Avoiding Fires

The most effective ways of decreasing risk of spontaneous ignition are to (1) avoid storing moist biomass in large piles, (2) avoid storage in warm areas, and (3) use piles according to age (first in, first out) to minimize storage time (NIC 2008, Pauner and Bygbjerg 2005, Fuller 1985). The results of several studies on fuel-chip storage in Finland and Sweden show that to minimize material losses resulting from microbial activity and potentially spontaneous ignition in long-term storage, the moisture content must be very low, usually under 20 % (w.b.), which is not possible without artificial drying (Wihersaari 2005). Drying the material before covered storage will greatly reduce the heating rate, but this incurs an additional expense and may not be necessary for short-term storage (Springer 1980).

Moisture gradients caused by mixing fuels of various MC may lead to spontaneous ignition and should therefore be avoided. Piles should be kept free from ignition sources. Metal objects in the pile may promote heating by acting as a catalyst for exothermic reactions (Hall 2009, NIC 2008, Pottie and Guimier 1985). An abundance of biologically degradable materials such as needles and bark increases the in-pile heating rate (Hall 2009, Springer 1980). Layers of dirt or dust on the pile can prevent heat from escaping and promote fires, as can large wind gusts that provide oxygen to the pile center (Hall 2009).

Storing material before comminution will reduce self-heating potential (Hall 2009, Fuller 1985) but increase transport and handling costs. Maintaining a pile height below 15 m (50 ft) for cleaned pulp chips and below 8 m (25 ft) for whole tree chips will reduce the fire hazard (Fuller 1985, Springer 1979, Kubler 1987). Outdoor piles should be separated from each other and from buildings by at least 15 m (FM global 1980), although local fire code requirements may vary. Mixing species of different deterioration rates may increase the risk of fire. For example, hardwoods and full-tree chips will increase the risk in a clean chip pile (Fuller 1985, Springer 1979). The pile should be monitored routinely for heating. Note that the probability of spontaneous ignition in clean, debarked chips stored according to accepted industrial procedures is low (Hall 2009).

Format and Bulk Density Impact on Supply System Processes

Impact of Structure

Conventional feedstock conveying and storage systems generally consist of cylindrical or rectangular structures integrated with a hopper that allows the material to converge and flow through the opening. As it converges, the material may experience a number of problems, ranging from unsteady flow to no flow. The controllable, steady flow from a bin or hopper depends on the slope angle and shape of the hopper, and the frictional forces within the material and the structure wall. The no-flow condition is generally caused by the material’s forming a stable arch, or bridge, within the structure that acts as an obstruction to flow. This bridge is a result of the cohesive strength of the material and the pressure exerted by the weight of the material lying above it in the facility. In general, the longer the material is in storage, the more cohesive it becomes. The combined influence of cohesive strength, internal friction, and bulk density of the material determines the diameter of the storage facility needed to allow unassisted flow.

Impact of Particle Size

Dry matter loss is particularly a problem in chipped material because chipping increases the surface area on which microbial activity can occur, the smaller particle size restricts air flow and prevents heat dissipation, and chipping releases the soluble contents of plant cells providing microbes with nutrients (Fuller 1985). Increases in ash content due to dry matter loss are also higher with chipped material, although the reasons for this remain unclear (Richardson et al. 2002). Due to risks of self-heating and dry matter loss, if it is necessary to store the feedstock for any length of time, the material should be stored as whole trees (Nurmi 1995). When trees are stored as logs, living cells remain viable for long periods of time (up to 6 months under certain conditions) (Fuller 1985).

Jirjis (1995) investigated the effects of particle size on the storage of stem wood in Norway. About 4 to 6 weeks after felling, the stems were chipped into small chips, with 44.5% of chips retained on a 0.24-in. screen, and large chips, with 42% collected on a 0.75-in. screen. The chips were stored in two 120-in. high piles, each containing 14,125 ft^3 material and stored from May through December. After storage, the moisture content was reduced from 40% (initial) to 30% on average. Total dry matter losses were slightly higher in the pile of large chips, 8.7% dry weight, compared with 7.5% in the small chip pile. Fungal activity was higher in the latter.

Jirjis (1995) also compared the storage of four different sizes of woodchips from summer-dried pine in Denmark. There were four 7000 ft^3 piles, containing chips (0.63 in. long), fine chunks (2 in. long), large chunks (6 in. long) and firewood (10 in. long). After a year of storage, heat generation was minimal in the large chunk and firewood piles, and mostly dependant on ambient conditions. Temperature development in the finer material was greater and less dependent on external conditions. Better drying was observed in larger piles, with a 9.5% reduction in moisture content. The average moisture content in chips was marginally changed, while a reduction from about 34 to 29.5% was measured in chunk wood. No conclusions were drawn regarding dry matter loss.

Impact of Angle of Repose on Pile Size

A Swedish study (Mattsson 1990) was conducted to determine the basic handling characteristics for several wood biomass types. Although the study focused on feeding systems, the data are applicable to loading, unloading, and transportation of the same materials. Basic handling characteristics were measured for sawdust, fuel pellets, fuel chips, hog fuel, and chunkwood. The aim was to find relationships between the basic handling characteristics and easily measurable fuel properties to facilitate the design of feeding systems in heating plants. The angle of repose was 25 to 55 degrees and increased with the increasing ratio of particle length-to-thickness and with increasing content of hooked or long particles. The angle of static friction (10 to 40 degrees), was affected more by the kind of surface than the fuel and followed the ascending order; coated plywood, urethane rubber, particle board, stainless steel, concrete, and rubber belt conveyor. The tendency to bridge varied considerably and increased with greater content of hooked or long particles, deeper fuel bed depth over the opening, and higher moisture content. The results indicate that more attention should be paid to particle shape (Mattsson 1990).

Biomass Moisture Impact on Supply System Processes and Material Stability

Available water is essential for the metabolic activities of fungi and bacteria that can lead to dry matter losses through material degradation, self-heating, and spontaneous ignition. The amount of dry matter loss is dependent on many factors, particularly initial moisture content (Wihersaari 2005), and ranges between about 0.4 and 4% per month for biomass of moisture above 20% (Hamelinck et al. 2005, Suurs 2002, Gislerud 1984, Pottie and Guimier 1985, Hall 2009), although figures of around 1 to 2% per month are common (Hall 2009, Hamelinck et al. 2005).

In tests carried out in Sweden (Wihersaari 1999), the initial moisture content was found to be proportional to dry matter loss; an initial moisture content of 42%, 51%, and 58% caused monthly dry matter losses of 1.1, 2.2, and 2.6% (w.b.), respectively, and total losses during a 6-month storage period of 6.6, 13.2, and 15.6% (w.b.), respectively. In another test lasting for 9 months, two initial chip moistures were tested: 32% (w.b.) and under 20% (w.b.), with monthly losses of 1.03 and 0.23 to 0.35 % (w.b.), respectively. Dry matter losses during storage were highest at the start of the storage period, immediately after the temperature had rapidly risen. The losses have been estimated to be 3.6% (w.b.) per week (measured during the second week of storage) and 0.4 to 0.7% (w.b.) per week thereafter (Wihersaari 2005). Hall (2009) found similar losses of 3.6% in the first week of storage. Note that Hall (2009) performed a study in New Zealand and found significant heating to be unlikely if the biomass is too wet (that is, >45% w.b.), as evaporated moisture from the heating would have an evaporative cooling effect.

Wihersaari (1999) found there to be a considerable difference in temperature behavior depending on the moisture content of the comminuted material. When the initial moisture content is under 40 %, the temperature rises fast, but then decreases after 1 to 2 months; when the initial moisture content is 50 to 65%, the core pile temperature usually remains high during the whole storage period. Wihersaari (1999) found another factor influencing the temperature behavior to be particle size. In piles with an average nominal size of 8 mm, the temperature rose rapidly to over 60ºC. When the average size was 30 mm, the temperature rose to 40 to 50ºC; and when the average size was 70 mm, the temperature did not rise above 30ºC. The difference is attributed to smaller particles' having larger surface area per unit volume, and airflow through the pile declines with decreasing particle size.

A study out of New Brunswick, Canada (Afzal et al. 2010) looked at the impact of storage structure on dry matter loss. Dry matter losses during 12 months[k] of storage of different forms of white birch chips ranging in size from 0.08 to 1 in., and piled to a height of 120 in. Bundles 120 in. in length, 20 in. in diameter were also stored (Afzal et al. 2010). Results are shown in Table 2-22.

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k. Note that this storage period is significantly longer than that assumed in this design case, and therefore the dry matter losses cited by Afzal et a. 2010 are much higher than what we have assumed.

Table 2-25. Impact of storage structure on dry matter loss over a 12-month period (Afzal et al. 2010).

	Dry Matter before Storage (lb)	Dry Matter after Storage (lb)	% Dry Matter Loss
Bundles	83.6	81.1	3
Covered woodchips	1.65	1.52	8
Woodchips piled with plastic sheath underneath	1.94	1.52	22
Woodchip pile uncovered	1.98	1.59	27

Afzal et al. (2010) also found the rate of moisture content increase from atmospheric inputs was lower in bundles than in an uncovered woodchip pile. The covered woodchip pile showed decreasing moisture content throughout the storage period and had almost uniform moisture distribution in the top, middle, and bottom part of the pile. Minimum moisture loss from the bundles was observed between February and April during the 1-year storage period.

White and Green (1978) studied the impacts of exposed bulk woodchip storage in piles at various locations. Although outdoor bulk piling is the most common for storing large quantities of green chips and other woody material, White et al. (1983a, 1983b, 1986) reported that woody fuels accumulate moisture when stored in this fashion. At ambient temperatures above 20ºC, dry matter loss occurred at a rate of about 1.5% per month. Frozen chips had virtually no dry matter loss.

Ambient Drying During Storage

In air drying, the rate of water removal depends on the conditions of the air, the properties of the biomass, and the design of the dryer. Moisture in the biomass can be held in varying degrees of bonding; easily-removed water is referred to as free water and more tightly-retained water referred to as bound water.

Idaho National Laboratory 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, is currently being compiled for submission to a peer-reviewed journal. Three mixtures of material examined were sifted ground chips (referred to in this study as the overs), whole ground trees (referred to in this study as unsorted), and the fines. The overs pile most closely resembles the 2010 design scenario.

Small-diameter Lodgepole pine trees from the Island Park area of Idaho in the Grand Targhee National Forest were harvested. These trees averaged 4-in. DBH. The trees were cut, hauledl, and comminuted the following day using a Roto Chopper MC 166 with hotsaw teeth on hotsaw rotor, with a 4-in. screen. The comminuted material was discharged directly into a Royer 616 electric-powered trommel screen with a 3/8-in. screen. Initial sampling was performed for each material screen where it discharged onto the conveyors. Material was conveyed directly into 135 yd3 walking floor trailers and again weighed at a grain elevator. The material was discharged onto the ground and stacked with an Insley Excavator, equipped with 1.25 yd3 bucket. In September of 2010, three storage piles were built consisting of unsorted material, 3/8-in.-minus material, and material greater that 3/8-in., respectively.

l. Note that one of the interesting observations from this study was the effectiveness of collection technique modification in decreasing ash content. Trees brought to the landing from the field were not dragged, but rather carried using a grapple. In comparison with a previous study, samples of fines and unsorted material had a significantly lower ash content than samples dragged.

Weather data was obtained from the Rexburg (KRXE) weather station, located approximately 10 miles northwest of the study site. The average precipitation in Rexburg from 1977 to 2005 for September, October, and November was 0.82, 1.07, and 1.09 in. respectively (Western Regional Climate Center 2010), indicative of the dry climate.

After 6 weeks of storage (November 3, 2010), each pile was sampled and sensors retrieved. Initial moisture content of the piles was approximately 50% (Table 2-26). 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 2-26. Changes in moisture content of comminuted materials during outdoor storage in Idaho.

Parameter	Fines	Unsorted	Overs
Initial Moisture Content (% w.b.)	51.85	52.32	51.43
Final Moisture Content (% w.b.)			
Average[a]	35.73	39.81	28.54
Minimum	10.57	12.53	10.07
Maximum	47.28	50.57	36.82

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

All piles lost over 10% of their initial bulk moisture content, which is well beyond the 5% assumed for this design scenario. There was significant movement of moisture in the piles (Figure 2-42). Therefore, although the total bulk moisture content of the pile was reduced, some local areas within the piles had higher final moisture contents than others.

Figure 2-42. 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 2-42). Self-heating is a significant contributor to moisture movement in the piles. During self-heating, warm moist 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 moisture 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, but allowing some moisture to evaporate from the pile’s surface. 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 piles with the most significant drying had the lowest resistance to air flow. The higher permeability allowed the moisture-laden air to pass, taking the moisture with it. Permeability of piles to air movement was measured as described by Ernston and Rasmuson (1992) using a 5-cm-diameter probe 100 cm in length. Pressure readings at nine different volumetric airflows were taken at nine heights along the slope of the pile. The smaller particle sizes in the fines and unsorted (Figure 2-43) restricts air flow and prevents heat dissipation (Fuller 1985).

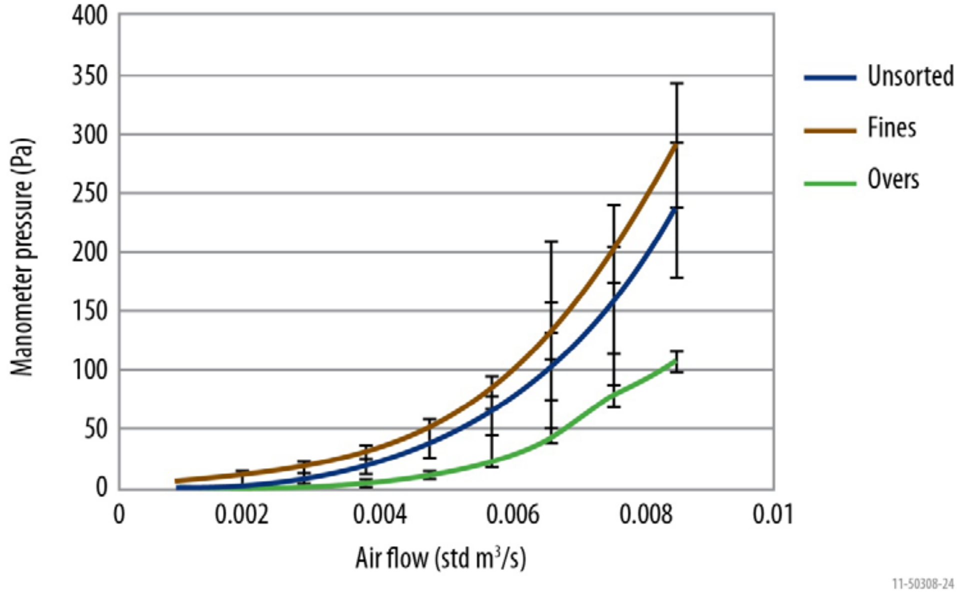

Figure 2-43. Resistance to air flow observed in the three piles studied.

The unsorted pile had the most even distribution of particle sizes, ranging from 10% in the ½-in. fraction to 24% in the 1/16-in. fraction (Figure 2-44). 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-in. particles; 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 in., with the majority of the fines being 1/16 in.. 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 (Pottie and Guimier 1985, Arthur et al. 1982).

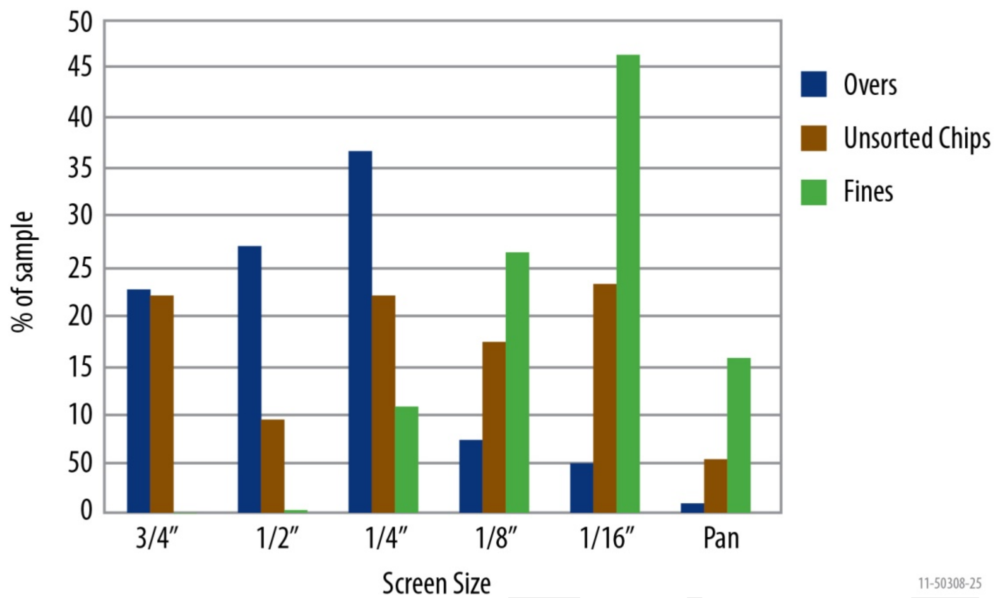

Figure 2-44. Particle size distribution in three piles of comminuted pine trees studied.

Forced Air Drying During Storage

Drying of woody biomass using ambient air or low temperature air can be effective and increase the energy density of the material (Phanphanich and Mani 2009).

Forced ventilation has been shown to decrease dry matter losses (Wihersaari 2005, Hall 2009). This, of course, incurs additional capital and operational cost. Kielder Forest Products, Ltd, (1991) conducted a study in northern England that dried 500 tonnes of chipped forest residues from 17-yr-old trees from an initial 52 to 35% moisture content using ambient air over a period of approximately 110 hr. Some site preparation was required to allow air to flow from the bottom of the piles out the top, and increasing pile depth increased airflow requirements.

One method for improving passive drying of comminuted woody biomass during storage is shown in Figure 2-45. In this method, a cover is placed over the side of the piles, with openings left at the top and bottom. This causes air to flow through the pile, drawing out moisture. A typical system using this method would involve leaf seasoning for 1 to 2 months, comminution, and subsequent storage, as shown in Figure 2-45. With an initial moisture content of 50 to 60% and 40 to 45% after leaf seasoning, this method could reduce the moisture to 35 to 40%. Without leaf seasoning (i.e., transpirational drying), chips from fresh whole trees contain fine organic matter that decomposes and blocks air circulation and, as a result, can actually add ambient moisture (Pottie and Guimier 1985).

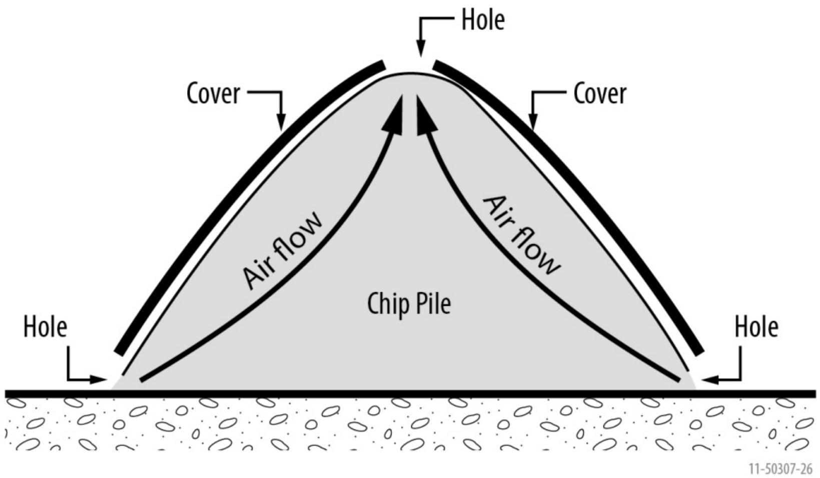

Figure 2-45. Small-scale passive drying method for chips (Recreated with permission from Pottie and Guimier 1985).

In addition to inducing an air flow into the pile, the cover will keep the pile from absorbing water during wet weather. This method is limited to small piles, as air will not flow through larger piles (Pottie and Guimier 1985).

Increased airflow provides the oxygen required for combustion and can increase microbial growth, but extensive airflow will cool the pile via convective heat loss. The question therefore arises as to whether or not it is beneficial to aerate the pile. Smaller particle size (that is, the size of sawdust) requires a higher pressure to move air through, limiting natural airflow, and the pile may be shaped to minimize wind loading (Hall 2009). Although compaction could lead to higher temperatures as heat builds up in the pile center, resulting in dry matter losses, the limited oxygen flow results in a low spontaneous-ignition risk (Hall 2009). For larger particle sizes such as woodchips, maintaining airflow through the pile usually will cool the material enough to avoid fires (Hall 2009). However, once a pile has started to heat to temperatures of over 70ºC, airflow should be restricted to reduce the risk of chemical oxidation, excess pile heating, and spontaneous ignition (Hall 2009).

Jirjis (1995) reported on a study of drying poplar with an initial moisture content of 57% during storage. Four insulated bins, 3-m high and 2.3 m in diameter, were filled with poplar chips and subjected to various conditions over 11.5 weeks. The study found that natural convection dried the material to a final moisture content of 44.9%, while drying by continuous ventilation with ambient air brought the material down to a final moisture content of 19.3%.

Removing the bark and other fines before storage has an impact on dry matter loss during this operation. The decay rate for hog fuel stored outdoors is three times that for woodchips stored under the same conditions (Pottie and Guimier 1985, Springer 1980) because the needles and bark are rich in nutrients that promote the growth of fungi and bacteria (Hall 2009, Springer 1980). Moist, fresh material needs to be turned approximately every 20 days, whereas dried, covered chips can be held unturned for over 6 months (Springer 1980).

Two studies carried out in Sweden observed dry matter loss in stored woody biomass. Green chips stored in a large pile for 7 months lost about 12 % DM, and bark stored in a large pile for 6 months lost about 26 % DM. The dry matter loss in the bark pile resulted in a 20 % decrease in energy content (Hubbard et al. 2007).

Gislerud and Gronlien (1978 and 1977) found that bark and foliage are generally responsible for the increased rate of deterioration of whole tree chips. They placed nylon mesh bags containing foliage, bark, whole-tree chips, and clean debarked chips in outside piles of whole tree chips and determined oven dry weight losses after storage. Weight loss during storage increased as follows: clean debarked chips < whole tree chips < bark< foliage. Foliage losses were about ten times higher than losses for clean, debarked chips.

Ventilating Piles using Tunnels

Jirjis (1995) examined the impact of placing a ventilation tunnel underneath a 7-m high pile of logging residue chips. It was concluded that the presence of the ventilation tunnel allows for most of the developed heat to dissipate, eliminating the risk of self-ignition. The moisture content of the fuel was also reduced. However the rapid decline in temperature to moderate levels at an early stage of storage created a favorable environment for the establishment and growth of various species of microfungi, despite the low moisture content. If the biomass had a higher initial moisture content, the microbial activity during the storage would probably have been much worse.

2.1.5.2 Base Case Conventional Storage Equipment

In the Base Case Conventional scenario Woody material is queued at the refinery with a 7-day supply. Longer storage could be incorporated into the system if necessary, for up to 1 month. The dry matter losses during storage are estimated to be 2%, which are from a combination of mechanical losses resulting from moving the material around using loaders, as well as biological losses (Table 2-27).

Table 2-27. Equipment performance parameters for the Base Case Conventional Storage scenario.

	Storage	Loader	Asphalt Pad
Equipment	N/A	Front-end loader	Asphalt Pad
Rated capacity	N/A	80 t/hr	25 days
Operational efficiency (%)	N/A	100%	100%
Dry matter loss (%)	1%	1%	0%
Operational Window			
Hr/day	24	14	24
Day/yr	5	300	365

The Base Case Conventional design scenario assumes an open-air storage environment, and therefore there are no additional structures constructed for storage.

Open-Air Storage[m]

Storing the biomass outdoors, uncovered, and unprotected, is referred to as open-air storage. An example is shown in Figure 2-46. Open-air storage of comminuted woody biomass should be avoided because of imminent risk of damage from moisture exposure (NIC 2008); however, this remains a popular storage strategy due to the low cost and generally quick turnover of woody biomass at refineries (such as paper mills, etc.). Uncovered piles may also dry, depending on the ambient conditions, including rainfall, temperature, and humidity (Springer 1980). Initial pile heating from bacterial and fungal activity will cause some drying; however, this activity often pushes moisture in to the upper layers (Hall 2009, Springer 1980).

m. Note that additional Storage options are presented in Appendix C.

Figure 2-46. Woodchips stored outdoors at a pellet mill in Alabama are vulnerable to moisture infiltration. In this photo, puddles of water near the chips are clearly visible (Photo credit: D. Brad Blackwelder, INL).

Equipment Used in Conventional Format Design Model

A front-end loader is used to move woody material around the grounds. The chips are queued in a large pile by a circular stack reclaimer. As material is to be used, it is pushed using a front-end loader on top of a grate covering a conveyor, where it is conveyed into the refinery.

Equipment Capacity and Operational Efficiency

Front-end loaders are commonly used to move biomass. They can be equipped with over-sized buckets to efficiently move and load low-density materials such as chips or hog fuel. They can be equipped with loader rake or grapple devices to handle slash, whole trees, and logs. Examples of different loaders used to move comminuted woody material around are shown in Figure 2-47 and Figure 2-48.

Figure 2-47. Tracked loader used to move chips during storage. The loader is equipped with an oversized bucket specialized for moving low-density, flowable materials (Photo credit: D. Brad Blackwelder, INL).

Figure 2-48. Case 629 front-end loader. Bucket has been modified by adding a screen to the top to increase payload (Photo credit: D. Brad Blackwelder, INL).

Loaders range in size from small skid steers to huge machines used in mining operations. Machines commonly used by logging operations or for moving comminuted materials are usually 150 to 200 hp and are articulated. Standard bucket capacity is around 3 yd^3, but for use with low density materials, they may be equipped with over-sized buckets up to 6 yd^3.

Operational Dry matter Losses

Some operational losses occur during loading and other handling operations associated with storage. Although these losses are often considered negligible, we have assumed a 3% dry matter loss for the Base Case Conventional scenario.

Operational Window

In the United States, chip inventory stored in piles is often used in as few as 15 days. Most mills average a 1-month inventory, with inventory increasing in the winter and decreasing in the summer to address disruptions due to weather[n] (McDonald and Twaddle 2000); however, these figures are regionally dependant.

In areas where weather or other conditions prevent year-round harvest, contractors cannot supply fuel year round. For example, for the South/Southeast U.S., the at-facility inventory would not include anything for regular shutdown periods, only for contingencies (for example, holiday shutdown).[o] Some areas would require more inventories; for example, California facilities would need about 2 or 3 months of inventory because there are very few rocked roads in the forests, so many harvest operations shut down during the rainy season. Fire-weather shutdowns are also typically longer in California than in Oregon. Any one contractor may operate only 120 to 180 days per year over 6 to 9 months, but some contractors will be operating while others are down due to local variations in road conditions, etc.

To guarantee an uninterrupted delivery of forest chips to the users, the woody biomass may have to be stored for several months during certain times of the year (Wihersaari 2005). Supply interruptions may be expected (as for limited seasonal access) or unexpected as an issue with truck supply (road closures, organizational hold ups such as a strike, etc.). McDonald and Twaddle (2000) conducted a survey of 191 wood-consuming mills in the U.S and found that around 60% had a maximum inventory time of less than 15 days, 15% had a maximum inventory time of 15 to 30 days, 12% had a maximum inventory time of 30

n. Personal communication Bruce Hartsough, UC Davis, July 2009

o. Personal communication Tom Gallagher, Auburn University.

to 60 days, 5% had a maximum inventory time of 60 to 90 days, and the remainder had an inventory time of more than 90 days. Less than 5% of respondents had a minimum inventory time of more than 90 days, and approximately 80% had a minimum inventory time of less than 15 days, suggesting the need to rapidly turn over inventory.

At the largest wood-fed biopower facility in the world in Peitarsari, Finland, chips are stored outside and uncovered year round; the plant does not run 100% on chips (it is co-fired with coal) and, therefore, they do not need that much storage to keep the plant running. Also, it is associated with a pulp mill, so there are additional sources of material.

McDonald and Twaddle (2000) conducted a survey of 191 wood-consuming mills in the U.S and found that about 60% stored chips in a maximum pile size of 25,000 green tons, 30% had a maximum size of 25,000 to 50,000 green tons, and the remainder had a maximum pile size between 50,000 and 100,000 green tons.

2.1.5.3 Base Case Conventional Storage Cost Analysis

Costs associated with the Base Case Conventional Storage operation include an asphalt pad and a loader to move material around the yard (Table 2-28).

Table 2-28. Static model costs for Storage equipment in the Base Case Conventional scenario. Costs are expressed in 2010 $/DM ton. Total operation cost is the sum of ownership, operating, and DM loss cost.

Equipment	Front-End Loader	Asphalt Pad	Total Cost per DM ton for Storage
Quantity of Equipment (# of machines)	2	1	
Installed Capital	0.32	0.02	0.34
Ownership Costs	*0.16*	*0*	*0.16*
Operating Costs	*0. 73*	*0.07*	*0.80*
Labor	0.28	0	0.28
Non-Labor	0.38	0.07	0.52
Dry-Matter Loss Costs	*1.92*	--	*1.92*
Energy Use (Mbtu/DM ton)	13.1	0	13.1

From Table 2-28, the total Storage cost for pulpwood sized trees is $2.89/DM ton, which is the sum of ownership, operating, and dry matter loss costs. Long-term storage is uncommon in operations that handle comminuted woody biomass. Therefore, the system generally only has a 7-day material queue at the plant, with the ability to expand storage out to 25 days on the asphalt pad. The loader is the only component of storage that incurs an operating cost, and it also the source of some dry matter loss (unrecovered material).

2.1.6 Summary of Costs for Base Case Conventional Feedstock Supply System

The determination of unit operation costs are described in previous sections, and are summarized in Table 2-29. The most cost-intensive unit operation is Harvest and Collection, followed by transportation.

Table 2-29. Summary of supply system costs for the Base Case Conventional Woody biomass scenario. Costs are presented in 2010 dollars per DM ton. Total operation cost is the sum of ownership, operating, and DM loss cost.

	Harvest & Collection	Preprocessing	Transportation	Receiving and Handling	Storage	***Total***
Installed Capital	27.52	3.63	14.05	7.33	0.35	***52.88***
Ownership Costs	*8.16*	*1.58*	*2.34*	*1.03*	*0.17*	***13.27***
Operating Costs	*19.61*	*4.44*	*11.99*	*1.36*	*0.80*	***38.20***
Dry-matter loss Costs	—	—	*0*	*0*	*1.92*	***1.92***
Energy Use (Mbtu/DM ton)	154.8	101.6	132.8	15.4	13.1	*417.67*
Total Logistics Cost[a]	***27.77***	***6.02***	***14.33***	***2.39***	***2.89***	**53.40**

[a]Sum of operating, ownership and dry matter loss cost.

Whole tree chipping of pulpwood-sized trees results in a total delivered cost of biomass of $53.40/DM ton, which includes Harvest and Collection using conventional pulpwood equipment, chipping the whole tree, and transporting that material to the biorefinery at a moisture content of 50%. At the biorefinery, the material is received and stored for conversion.

An important item of note is that the material that arrives at the biorefinery does not conform to any material specification. The chipped woody material will be high ash due to dirt entrained during collection, as well as the ash naturally found in the bark. As well, the chips arrive at the biorefinery at 50% MC, and although there is assumed to be some ambient drying during storage, the moisture at the point of reactor infeed is still 45%. This is too high for many thermochemical conversion processes. As well, there would be a large particle size distribution, as bark is friable and forms small particles during chipping and handling. Although whole tree chipping is a cost-effective way of bringing a large amount of woody biomass to the biorefinery and reducing in-field biomass losses associated with delimbing and debarking, the resulting material will be challenging to accommodate in many bioenergy processes.

2.2 Low-Ash/Low-Moisture Conventional Woody Feedstock Supply System

An important consideration when designing a biomass feedstock supply system is the quality of material that is delivered to the biorefinery. In the Base Case Conventional scenario, no material specification is met. However, in the case of the Low-Ash/Low-Moisture Conventional feedstock supply system, the biomass is delivered to the infeed 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 system, as conversion efficiencies rely on feedstock that consistently meets their infeed requirements. For the Low-Ash/Low-Moisture Conventional scenario, a gasification modeled by the National Renewable Energy Laboratory is used to determine the required material spec (Phillips et al. 2007). As an additional constraint, the Low-Ash/Low-Moisture scenario design must meet the DOE cost target of $46.37/DM ton, in order to meet biofuels production chain cost targets. 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. Both the gasification and pyrolysis processes are outlined in Section 2.3, "The Conversion Interface".

The scope of Low-Ash/Low-Moisture Conventional 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 whole-cut southern pine trees on private commercial lands. The trees are delimbed and debarked, as is common in pulpwood operations. The Low-Ash/Low-Moisture Conventional design, unlike the Base Case Conventional presented in Section 2, meets a material specification for a selected gasification process (Phillips et al. 2007). Figure 2-1 shows the process flow for the Low-Ash/Low-Moisture Conventional woodchip system.

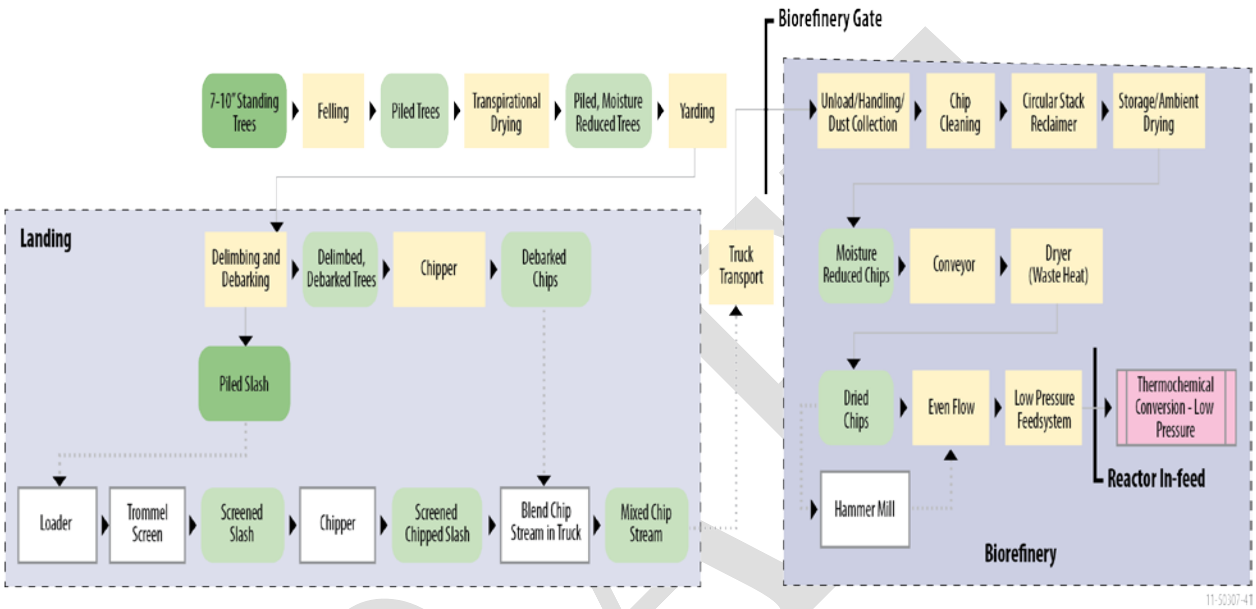

Figure 2-49. Order of unit operations in the Low-Ash/Low-Moisture Conventional feedstock supply system. Operations occurring at the landing and biorefinery are shown in a grey square. *(Note: Yellow rectangles represent individual modeled processes, green ovals represent changes in format intermediates, and white rectangles represent alternate processes that were not modeled.)*

In the Low-Ash/Low-Moisture Conventional design, trees are harvested, and then transpirationally dried prior to collection. The dried trees are delimbed/debarked, then ejected into a chip van for transport to the biorefinery. At the biorefinery, chips are received, cleaned, dried, and fed into the modeled conversion process of gasification. An alternate design that recycles the slash stream (shown as white boxes in Figure 2-49) will also be presented.

The Low-Ash/Low-Moisture Conventional system is presented by discussing each major supply system unit operation in the respective order of appearance in the design. The units of operation in the conventional system are as follows:

- Harvest and Collection
- Preprocessing
- Transportation
- Receiving, and Handling
- Storage
- In-Plant Handling

As there is the potential to vary the order of certain operations (e.g., chipping the delimbed, debarked logs at the biorefinery rather than at the landing), other alternatives will also be discussed. The backbone of the modeled supply system design is the flow and format changes of biomass material as it passes through the individual supply system processes, from the production location to the biorefinery conversion processes (Figure 2-1).

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. Within each unit operation section of this report, the modeled attributes of all biomass material intermediates (hereafter referred to as “format intermediates”) are identified, and variances in those attributes are discussed to provide a better understanding of how supply system performance is, or may be, affected by feedstock format intermediate attributes. Additionally, the specific machinery modeled for the processes of each unit operation is described in terms of its respective purpose and function.

The modeled feedstock system is designed to supply a biorefining facility with 800,000 DM tons of biomass annually (Table 2-1). 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 2-30. Low-Ash/Low-Moisture Conventional 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[c]	5.8 miles
Distance from Landing to Biorefinery	50 miles

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

b. Extra tonnage harvested to account for supply system losses.

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

In many cases, it is clear that the performance of one supply system process is significantly impacted by the performance of another. As such, both the individual unit operations report sections and the overall integrated supply system design are concluded with an integrated summary analysis of cost, performance, and logistics based on stated format intermediate attributes and equipment operational assumptions.

Conventional systems aim 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.

2.2.1 Low-Ash/Low-Moisture Conventional Harvest and Collection

Harvest and Collection encompasses all processes associated with moving the biomass from the location of production, in this case the tree stand, to the queuing location (Figure 2-50). In forestry operations, queuing usually occurs at a landing. Harvest and Collection processes generally consist of tree felling, gathering, and moving from the field to the landing. The yellow boxes in Figure 2-50 identify the specific processes being performed. However, depending on a number of variables, the specific processes, equipment, and associated costs may vary significantly from one feedstock to another. Many of the variables that impact the selection of processes and equipment are based on the feedstock, location, and the biomass material format changes between process operations. The dark and light green ovals in Figure 2-50 identify the feedstock and its format as it moves from one process to the next within the supply system. Although the modeled feedstock is southern pine pulpwood, the same harvesting and collection equipment may be used for various whole tree harvesting.

Figure 2-50. Low-Ash/Low-Moisture Conventional Harvest and Collection supply logistics processes and format intermediates. *(Note: Green ovals represent format intermediates, and yellow rectangles represent individual modeled processes.)*

In the Low-Ash/Low-Moisture Conventional Harvest and Collection operation, pulpwood trees are cut using a feller buncher, and then piled in the forest. Piled trees are transpirationally dried to reduce moisture. The moisture reduced trees are yarded using a skidder, and then piled at the landing near the chipper.

Beyond pulpwood operations, there are a number of other potential sources for woodchips, including

- Thinnings on private, non-commercial lands (generally having a more random distribution than private commercial lands, among other differences)
- Fire-suppression thinnings in national forests
- Clear-cut small and large trees to prepare land for other uses
- Select harvest of dead or diseased trees
- Woody residue remaining after the harvest of saw logs
- Trees grown as a dedicated energy crop.

Larger, higher value trees are generally used for lumber production; however, depending on market conditions, this timber may also be available to produce chips.

In conventional whole-tree pulpwood operations, whole trees are cut and skidded from the stump to the landing. The residues (also called slash) consist of tops and limbs that accumulate when trees are delimbed and bucked (cut into lengths and sorted by hardwood/softwood, sawtimber/pulpwood.) In this scenario, the limbs are not removed, which increases the total material available, as the dry matter losses are significantly reduced.

Cut-to-length (CTL) harvesting systems, commonly used in Europe and popular in some areas of the United States, use specialized harvesters that can fell, delimb, and cut logs to length, and the residue accumulates at the stump rather than the landing. These residues can be left in the forest to dry or be removed soon after harvest when logs are extracted. Whole tree skidding, in which slash is transported to the landing in the same operation as the wood, has been shown to be more efficient and is modeled herein. At the landing, logs are chipped and transported to the biorefinery for further processing prior to conversion.

2.2.1.1 Low-Ash/Low-Moisture Conventional Harvest and Collection Format Intermediates

The size, distribution, and type of woody biomass significantly affect Harvest and Collection operations, and many systems and operations are used to harvest and collect woody biomass. As was used for the Base Case Conventional design, a typical operation for harvesting and collecting pulpwood sized trees (i.e., approximately 7 to 10 in. DBH, Figure 2-3) within the Low-Ash/Low-Moisture Conventional system involves removing the woody biomass from the field and forwarding the material to the landing. In the modeled scenario of southern pine trees at a commercial plantation, trees are cut and piled near the point of harvest; then the piles are forwarded to the landing. The intermediate formats of the feedstock play critical roles in determining both the type and size of equipment to be used and the timeliness of the operation necessary to control the feedstock as it moves through the supply system. Table 2-31 identifies the woody biomass attributes of the feedstock format intermediates used as inputs and outputs of the Harvest and Collection equipment.

Table 2-31. Attributes of Harvest and Collection format intermediates for the modeled Low-Ash/Low-Moisture Conventional scenario.

	Standing Whole Trees	Piled Trees	Piled, Moisture-Reduced Trees	Piled, Moisture-Reduced Trees at Landing
Biomass Anatomical Output	Standing whole trees	Cut whole trees	Cut whole trees	Cut whole trees
Yield (DM ton/acre)	20	20	20	20
Format Output	Standing tree	Pile	Pile	Pile
Bulk DM Density Output	—	8 lb/ft^3	8 lb/ft^3	8 lb/ft^3
Output Moisture (% w.b.)	50	50	35	35

See Section 2.2 for further description of the Harvest and Collection operation format intermediates with respect to the Low-Ash/Low-Moisture Conventional design.

Format and Bulk Density Impact on Supply System Processes

See Section 2.2 for further description of the Harvest and Collection operation format and bulk density impacts with respect to the Low-Ash/Low-Moisture Conventional design.

Biomass Moisture Impact on Supply System Processes and Material Stability

See Section 2.2 for further description of the Harvest and Collection operation biomass moisture impacts with respect to the Low-Ash/Low-Moisture Conventional design.

Passive, In-Field Drying

It is not common practice to dry pulpwood, pre-commerical thinning, or residues in the field. When woody material is dried, either in the field or at the landing, it is necessary to return with trucks and/or a chipper, increasing production costs (Leinonen 2004). However, drying the biomass as early in the supply chain as possible offers many advantages (Pottie and Guimier 1985, Hall 2009):

- Reduction of transportation costs (see Section 2.1.3 for a discussion on factors influencing transport economics). Note that drying to reduce transport costs is only beneficial to the point where the truck is filled to volume capacity; nevertheless, there would be some cost savings due to a lighter load.

- Reduction of fungal and spore growth, which would result in dry matter loss and increased spontaneous combustion risk
- Reduction of moisture, which can cause material to freeze together and make handling very difficult
- Reduction of moisture, increasing grinding efficiency, although this reduces chipper efficiency (see Section 2.1.2.2 on chipper and grinder performance)
- Elimination of leaves and needles, which fall off more easily when handled dry and will return nutrients to the soil.

However, in-field drying ties up inventory and can increase dry matter losses if it is wet in the area. In addition, the reduction in moisture is often limited. Leaving the biomass in the field increases the risk of insect attack and can pose a fire risk if storage is located at the point of felling (Pottie and Guimier 1985).

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). In this process, cut 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 cut if the branches and leaves are left on (Figure 2-51). This loss of water can significantly affect moisture concentration in most species of cut trees, depending mostly on season of felling, species, and diameter (Johnson and Zingg 1969, Hubbard et al. 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). In-field drying increases needle and leaf loss, which returns nutrients to the soil (NIC 2008, Hartsough et al. 2002).

Figure 2-51. A bundle of transpirationally dried trees in Auburn, Alabama (Photo credit: Christopher Wright, INL, July 2010). Note that bundling is not part of the Low-Ash/Low-Moisture Conventional design; however, the impact of transpirational drying is clearly visible.

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 in. 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 to 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 in. DBH Loblolly pine trees. The study showed significant drying both in the winter and summer months. The study looked at both whole trees and delimbed trees.

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 2-51 shows an example of trees transpirationally dried in Alabama.

Patterson and Post (1980) found that paper birch trees had a significant moisture loss, while red oaks had no significant change over a 3-week period in the same region. Rogers (1981) found that in-field drying for 3 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. Garrett (1985) looked at moisture loss after felling in 13 species of trees, including both hard and softwood, over a 14-day period in New England from July to September. The average moisture loss was 4% w.b. (generally between 3 and 5%), but varied by species group, and the greatest moisture loss occurred in the first 36 hours. 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 to 50% initial moisture content to 30 to 35% final moisture content for birch, and from 25 to 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 moisture content.

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 transpirationally dried in Minnesota from April to November, and moisture content was sampled at monthly intervals. The average moisture content of the tops cut in April dropped from an initial moisture of 99 to 42% (oven dry basis) at the end of July. However, July cut trees only lost moisture in the first month, dropping from an average of 90 to 47 % (oven dry basis), and then moved back up to 48% moisture content in the second month.

Drying will be less effective if the trees are stored in piles and 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 et al. 2007). Woody biomass stored as large pieces generally has less dry matter loss than chipped wood and has less pile heating (Hall 2009). Finally, in-field drying is beneficial to the soil (Hall 2009).

Losses can also occur as a result of material degradation. When material is left in the field to dry, exposure to wet weather increases decomposition. The onset of the wet season accelerates decomposition and releases available nutrients (Swift et al. 1981). Wetting and drying cycles can also accelerate the mineralization of labile nutrients, such as those stored in microbial biomass, and also increase the rate of turnover of more recalcitrant and protected organic pools of litter and surface soil (Van Veen et al. 1984, Cabrera 1993). Another potential source for material loss is wildlife consuming the leaves, etc., for food or to use for nesting.

2.2.1.2 Low-Ash/Low-Moisture Conventional Harvest and Collection Equipment

See Section 2.2.1.2 for further description of the equipment used in the Low-Ash/Low-Moisture Conventional design. Table 2-32 shows the Harvest and Collection equipment specifications for the Low-Ash/Low-Moisture Conventional design.

Table 2-32. Harvest and Collection equipment specifications for the Low-Ash/Low-Moisture Conventional design.

Operation	Felling	Transpirational Drying	Skidding
Equipment	Tracked carrier with a rotary head feller buncher		Wheeled grapple skidder
Haul Distance	N/A	N/A	400 m
Rated Capacity	20 t/hr/machine	N/A	15 t/hr/machine
Field Efficiency (%)	65%	N/A	65%
Operational Window			
Frequency	Every 6 years	N/A	N/A
Hr/day	8	N/A	8
Day/year	220	N/A	220

Equipment Used in Low-Ash/Low-Moisture Conventional Design Model

See Section 2.2.1.2 for further description of the equipment used in the Low-Ash/Low-Moisture Conventional design.

Equipment Capacity and Operational Efficiency (Field Efficiency)

See Section 2.2.1.2for further description of the capacity and operational efficiency of the equipment used in the Low-Ash/Low-Moisture Conventional design.

2.2.1.3 Operational Dry matter Losses (Complement of Loss = Harvest Efficiency)

See Section 2.2.1.2for further description of the operational losses with respect to the Low-Ash/Low-Moisture Conventional design. As in Section 2.1.1.2, all costs incurred to get the material into the format of a debarked chip when leaving the landing will then be attributed to that mass of chipped biomass.

Operational Window

See Section 2.1.1.2 for further description of the operational window with respect to the Low-Ash/Low-Moisture Conventional design.

2.2.1.4 Low-Ash/Low-Moisture Conventional Harvest and Collection Cost Analysis

Cost Summary

A breakdown of the costs associated with each piece of equipment used in the Harvest and Collection operation identifies significant cost components that are valuable for making individual comparisons and recognizing areas of research potential (Table 2-33). These costs are reported in terms of DM tons entering each process, respectively.

Table 2-33. Static model costs for major Harvest and Collection equipment in the Low-Ash/Low-Moisture Conventional scenario. Costs are expressed in 2010 $/DM ton unless otherwise noted. Total operation cost is the sum of ownership and operating cost.

	Felling	Transpirational Drying	Skidding	
Equipment	Tracked carrier with a rotary-head feller buncher		Medium grapple skidder (wheeled)	Total Cost per DM ton for Harvest and Collection
Installed Equipment Quantities (# of machines)	38	N/A	50	
Installed Capital	11.76	N/A	10.24	21.99
Ownership Costs	*5.80*	*N/A*	*1.53*	*7.33*
Operating Costs	*3.67*	*N/A*	*8.42*	*12.10*
Labor	1.16	N/A	1.55	2.71
Non-Labor[a]	2.51	N/A	4.20	6.71
Energy Use (MBTU/DM ton)	68.0	N/A	90.7	158.76

[a]sum of fuel and material cost

From Table 2-33, the total Harvest and Collection cost for pulpwood sized trees is $19.43/DM ton, which is the sum of ownership and operating costs. A large portion of the costs are operating costs, which include labor and fuel costs. Because each tree has to be harvested individually, harvesting is a labor-intensive operation.

Hartsough and Stokes (1990) identified key parameters for any harvesting system, including material type (trees vs. residues), piece size, and amount removed in green tons/acre. They observed that for practically all analyzed systems, cost increased as the piece size was reduced, and cost decreased as the total volume removed per acre was increased. Additional studies (Holtzscher and Lanford 1997, Kluender et al. 1997) showed that stand treatment and diameter size were two of the primary factors in determining harvesting costs.

Sensitivity Analysis

To perform sensitivity analysis, we selected multiple variables of interest and assigned ranges to them, which followed a triangular distribution. A symmetric distribution was applied where appropriate, i.e., when it was the best approximation of an actual distribution. Powersim was then set to output costs per dry matter ton to Excel. The process of sensitivity analysis was done seven times, once varying all parameters, and six times varying only parameters pertinent to each process: Harvest and Collection, Preprocessing, Transportation, Receiving and Handling, Storage, and In-Plant Receiving. The Monte Carlo method was used, using the Risk Analysis Clone capability in Powersim. Excel was used to generate the histograms, the range of each analysis was divided into thirty “bins,” and the frequency function was used to count the number of occurrences between two bin points.

The histogram generated for the Low Ash/Low Moisture Harvest and Collection operation is shown in Figure 2-52.

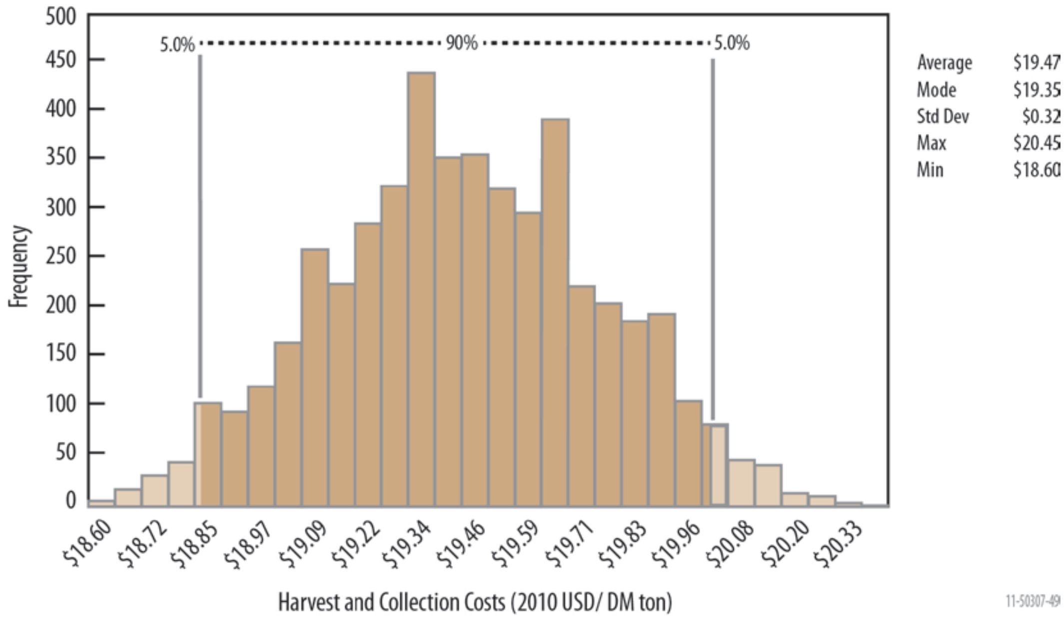

Figure 2-52. Low-Ash/Low-Moisture Conventional woody biomass supply chain cost distribution histogram for the Harvest and Collection operation for pulpwood. Costs are expressed in 2010 $/DM ton.

The histogram is not a smooth bell curve, as there are “jumps” wherever a piece of equipment has reached maximum capacity and another piece of equipment is needed. From Figure 2-52, the average cost for the Harvest and Collection operation is $19.47 ± 0.32/DM ton, so the static model cost of $19.43/DM ton fits within this range. The histogram shows that with 90% confidence the Harvest and Collection unit operation ranges between $18.30 and $20.45/DM ton. This operation contributes a significant cost to the woody biomass logistics cost, even at the low end of this range where the feller and skidder equipment efficiencies are assumed at their highest. The mode value of this cost range is $19.35/DM ton.

2.2.2 Low-Ash/Low-Moisture Conventional Preprocessing

The transport and handling costs of moving whole trees are greatly reduced by comminution at the landing and prior to transport, as the packing density is greatly increased. The branches and/or bark can be removed prior to comminution through various techniques, including using a stroke-boom delimber or iron gate for larger trees, or a flail chain. A flail shredder is modeled in the conventional design. The delimbed and debarked logs are loaded into the trucks and then taken to the biorefinery for further processing.

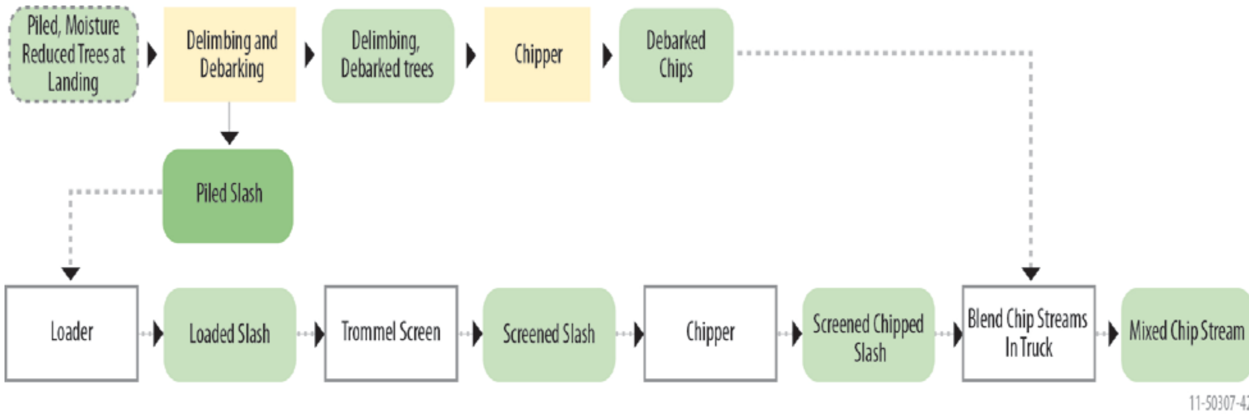

Figure 2-53. Preprocessing supply logistic processes and format intermediates for the Low-Ash/Low-Moisture Conventional design. *(Note: Green ovals represent format intermediates and yellow rectangles represent processes modeled in this report. White boxes show alternate designs not modeled in this report).*

Whole trees that were piled at the landing during Harvest and Collection are loaded into the flail shredder to remove bark and braches. The material is then chipped and loaded into a chip van for transport to the biorefinery. An alternate design shown in Figure 3-6 shows the branches removed during flailing could potentially be fed back into the chipper to increase biomass availability.

2.2.2.1 Low-Ash/Low-Moisture Conventional Preprocessing Format Intermediates

After the biomass is brought to the landing and piled by a skidder, the skidder feeds the material through a flail shredder, which removes the branches, tops, and much of the bark. The removal of bark also results in lowering the ash content since bark is high in ash content and may be contaminated with dirt. The delimbed trees are loaded into a chipper. The chips have a lower moisture content due to the transpirational drying, however approximately 35% (wet basis) of the transported mass is water (Table 2-34).

Table 2-34. Attributes of Preprocessing format intermediates for the Low-Ash/Low-Moisture Conventional design.

Operation	Delimbed, Debarked Trees	Debarked Chips
Tree Stream		
Yield (DM tons/day)	2330	2330
Format Output	Delimbed, debarked trees	Chips
Bulk DM Density Output (lb/ft^3)	12	15
Output Moisture (% w.b.)	35	35

The branches and bark removed during flailing have a higher ash content due to high-ash dirt embedded in the bark for collection.

Biomass Deconstruction, Fractionation and Physical Property Changes

A flail chain removes the limbs of the trees, producing debarked logs. Different parts of the tree have different chemical composition. Bark contains elevated levels of minerals associated with ash compared to clean wood. Most common species of trees have bark with an ash content of 3 – 8%, with a whole tree consisting of 15 to 20% bark (Ragland and Baker 1987). Ash promotes fouling in thermochemical conversions processes because it volatilizes and recondenses on particles and surfaces, making them sticky. Bark has much higher ash content then wood, largely due to calcium oxide. Hardwood species tend to be more problematic than softwood due to a higher potassium content (Ragland and Baker 1987). The bark also holds dirt, which is high in ash. Wind can blow soil onto bark, and skidding can also result in high levels of soil contamination. Sandy soils may be virtually 100% ash, but soils with high amounts of organic material will contain less ash (Ragland and Baker 1987). Depending on the species, ash content in the wood ranges from less than 1% (pine, for example) to almost 3% (hardwoods) (Pettersson 2007, Alakangas et al. 1999, Ragland and Baker 1987). An alternate design involves putting the branches ejected from the flail into the chipper, producing a mixed stream of cleaned, pulpwood chips and chipped branches. Although this would raise the ash level of the resulting mixture, the ash level could potentially remain below that required for thermochemical conversion, which is <1% (Phillips et al. 2007, add Jones et al. 2009).

The greatest concentration of plant nutrient elements occurs in the parts of the tree where photosynthesis takes place, such as foliage. Depending on species, foliage comprises between 4 and 9% of tree green mass (Hakkila and Parikka 2002). Biomass extraction will inevitably result in nutrient loss from the forest. In comparison with conventional stem-only harvesting, each percentage increase in biomass recovery from crown mass with foliage incurs an increased nutrient loss amounting to 2 to 3 % for pine, 3 to 4 % for spruce, and 1.5 % for leafless hardwoods (Hakkila 2004).

Different tree species exhibit considerable variation in hardness and friability. Trees of the same species, but of different sizes or grown under different environmental conditions, can have noticeably different comminution characteristics (see Section 2.1.1.1). Different trees will produce different chips with different particle-size distributions, depending on the tree species, age, moisture content, and weather conditions, among other factors. The design scenario assumes we are chipping transpirationally dried pulpwood pine trees with a moisture content of 35%.

Format and Bulk Density Impact on Supply System Processes

See Section 2.2.2.1 for a discussion of format and bulk density with respect to the Low-Ash/Low-Moisture Conventional scenario.

Biomass Moisture Impact on Supply System Processes and Material Stability

Debarking

Dry trees are again more brittle and, therefore there is higher loss of stemwood when debarking dry trees with a flail debarker. Debarking smaller diameter trees with a flail also results in proportionally more stemwood loss due to splintering and bolewood breakage.

See Section 2.1.2 for a discussion of comminution with respect to the Low-Ash/Low-Moisture Conventional design.

2.2.2.2 Low-Ash/Low-Moisture Conventional Preprocessing Equipment

Flail and chipper efficiency depends on many factors, including operator experience, tree size, and tree moisture content.

Table 2-35. Preprocessing equipment specifications for the Low-Ash/Low-Moisture Conventional design.

	Delimbing and Debarking	Chipping
Rated Capacity	50 t/hr/machine	50 t/hr/machine
Operational Efficiency (%)	100%	60%
Dry matter loss (%)	—[a]	—[a]
Operational Window		
Hr/day	8	8
Day/yr	250	250

[a]See Section 2.2.1.3 for a discussion of treatment of dry matter losses for Harvest and Collection, and Preprocessing at the landing.

Section 2.1.2 has a discussion of chipping that applies to the Low-Ash/Low-Moisture Conventional design.

Debarking/Delimbing

Flail debark/delimbers remove limbs and bark and are used prior to chipping to produce clean chips. The machine consists of two or more parallel steel rods with chains mounted on them. The rods spin at high speed, and the log to be delimbed/debarked passes between the rods so that the rapidly spinning chains contact the limbs and bark of the tree removing them by blunt force. A row of chains screen the material (Figure 2-54).

The bark and smaller limbs are removed by whipping the logs with steel chains. The impact force of the chains should be enough to remove the bark, but should minimize the loss of the underlying wood. Typical rotational speeds range from 300 to 500 rpm. Many factors affect the successful removal of the bark, including tree species and age, moisture content, weather conditions, processing equipment, and chain speed (Lappalainen et al. 2001). Flails are less effective in the winter than the summer because bark bonds to the underlying wood more strongly during cold weather months (Lappalainen et al. 2001). Target removal rates for debarking are for less than 1% bark in the remaining wood content. Flail and chip systems produce about 2.9% more clean chips than other systems (Watson et al. 1993).

Figure 2-54. Flail shredder screen in Greenville, Alabama. The screen stops larger pieces from passing through the flail (Photo credit: Christopher Wright, INL, July 2010).

Chain flail delimber-debarkers (CFDD), teamed with in-woods chippers, can produce pine chips comparable in quality to those produced in the wood yards (Watson et al. 1991). CFDDs can either be mobile or portable, and both can be teamed with chippers for in-woods use. A grapple arm is used to feed the trees into the flail. The amount of delimbing/debarking can be changed by varying the speed of the flail drums, the size (diameter of the rod used to make the links) of the flail chains, and sometimes by the number of flail drums in use. (Some DDCs have three flail drums, and one can be turned off if not needed.)

Figure 2-55. Flail shredder in Greenville, Alabama (Photo credit: Christopher Wright, INL, July 2010). The slash stream produced from delimbing and debarking trees is visible in the lower photograph.

There are other options for delimbing and debarking trees. For larger trees, delimbing is typically performed on trees that are transported as logs for dense and efficient transportation. A stroke boom delimber consists of a boom with a grapple and saw mounted on it. A stationary grapple and saw are mounted on the main body of the machine. To delimb a tree the boom is tilted down and extended to pick up a tree with the forward grapple. The tree is normally grasped somewhere near the middle of the stem. The butt of the tree is placed in the rear grapple. The grapple arms have delimbing knives just like the knives on a processor head. The boom then slides the front grapple along the stem, cutting limbs. The tree stem is held in place by the rear grapple. The tree is topped and bucked into log lengths by the saw on the boom. Gate delimbers remove limbs and some (very little) bark. Flail debarkers can also be used with larger trees.

In addition to flail debarking, there are other technologies available for debarking logs, such as drum debarking, ring debarking, ultra-high-pressure water, and others. All of these are fairly efficient at removing unwanted bark from timber at fixed installations.

Equipment has been commercialized to remove the bark from smaller, irregular pieces of wood prior to chipping. Tests of the Deal Processor and Fuji King debarker have demonstrated their ability to debark log yard residue, small diameter trees and tops, frozen wood and decadent cedar chunks to produce chips with less than 1% bark content (Araki 1995, Peetso 1995). Mountain Fir Chip Company's chipping plant in The Dalles, Oregon, has purchased such equipment to allow the production of higher-value pulp-quality chips from material such as orchard prunings or logging residues. The Simco/Ramic Pulpwood Sorter, based on technology originally developed for the food processing industry, is another example of a new technology which has been developed to upgrade the value of chips from fuel grade to pulp grade. It has been shown to remove about 75% of the bark or stained wood from off-specification chips, with a 75% to 80% recovery of pulp quality chips (Araki 1995, Bruce and Sinclair 1996).

Comminution Screens

To control the size of material being created, drum chippers and grinders have screens after the comminution device (i.e., after the knives or hammers) (Figure 2-56). There is a fairly narrow clearance between the hammers/knives and the drum screen. As material is comminuted, it is flung into the screen. Material too large will not pass and will be re-ground. Smaller pieces will pass through the screen.

Figure 2-56. Various sizes of grinder screens (Photo credit: Erin Searcy, INL).

Within the wood processing system, there are multiple locations where monitoring the particle size is critical to achieving optimal performance. The first stage grinder, chipper, or shredder at the landing may be followed by further preprocessing, such as hammer milling. Various screening methods are available to ensure a uniform particle size is supplied to the downstream processes in the system. Screen types include drum or trommel screen, disc screen, sifting screens, vibratory screen, or the particles may be separated by elutriation which uses fluid (usually air) to separate the particles by density.

Trommel Screens

The Low-Ash/Low-Moisture Conventional scenario has an alternate design shown in Figure 2-58 which recycles the slash stream thrown out of the flail back into a trommel screen, and then into the chipper.

The basic purpose of the trommel screen is to separate material based on size. Trommel or drum screens consist of a large, revolving cylinder that is sheathed with a screen (Figure 2-57 and Figure 2-58). The cylinder is slightly sloped so that material that is loaded into the upper end of the drum moves by gravity through the cylinder as it turns. As material goes through the cylinder, small material falls through openings in the screen onto a conveyor below for further processing. The screen openings are sized to remove material of a targeted size. Trommel screens are very effective at separating dry material, but plug and require maintenance and cleaning when handling wetter material. Controlling the dust or fines from this type of screen is an issue. Trommel screening is one of the most important primary unit operations in advanced refuse processing systems for separating combustible and non-combustible components (Wheeler and Barton 1989). High ash content may also be an issue. Past experience has shown that screening performance of trommels is generally related to the amount of material which is passing over the screen plate per unit time, rather than either the quantity of the material removed to undersize or the overall feed rate to the screen (Wheeler and Barton 1989).

Trommel screens come in various sizes, depending on the scale of operation. Prices for a trommel screen vary dramatically (i.e., by an order of magnitude), depending on size of the screen, horsepower, transportation options, and accessories, including conveyors and hydraulic lifts.

Figure 2-57. Magnum Komptech trommel, used to separate chips (Photo from Wikipedia.com 2010)

Figure 2-58. Vermeer Wildcat 521 Cougar trommel screen (Photo credit: Vermeer).

Unloading of Material

Material unloading is described in Section 2.2.2.2 and 2.1.4.3.

2.2.2.3 Equipment Capacity and Operational Efficiency

Debarking

A flail is used to remove branches and bark, reducing the ash in the chips and meet conversion in-feed requirements (Phillips et al. 2007 and Jones et al. 2009). This creates a stream of cleaned logs to be passed through the chipper, which may increase the throughput as compared to a whole tree being fed into the chipper. However, chipper throughput may also be power limited. The branches ejected from the flail could be fed through in a separate stream in an alternate design scenario.

Comminution[p]

Comminution is described in Section 2.1.2.2 and in Appendix B.

Screening

Hartmann et al. (2006) found that for horizontal screening systems, the particle width was a more decisive dimension than the particle length. This is because long and thin particles can pass the screen holes vertically. Such conclusions were also made for particles of less than 5 mm sieved by metal wire cloth screens. The vertical passage of particles is reduced by using rotary screening equipment, where the passage through the screen holes is limited by the retention time of a hole below a particle during each rotation. Consequently, long and thin particles are partly kept from passing through the openings. This is an intentional part of the design, and therefore the rotary screen is a measuring system for a deliberate

p. Note that additional comminution options are presented in Appendix A.

incomplete screening. For comparable results, it is however important that the screening time, which is determined by a combination of angle and rotation speed, is always kept constant (Hartmann et al. 2006).

The degree to which oversized particles pass the screen holes vertically is described in Hartmann et al. (2006). As the sample length increases, the portion of misplaced material also increases for all types of screens tested for woodchips. Hog fuel screening shows a similar trend, although when using image analysis as a sorting method, the results vary. For larger size classes (i.e., larger screen portions), the mass of particles that do not belong on the sieve relative to the total mass of the fraction is higher than for smaller ones. Above 45 mm almost all particles are longer than the hole diameter through which they pass. As expected, the total level of particle misplacement is largely higher for hog fuel than for wood chips, and this was true for all devices tested (Hartmann et al. 2006).

Dry matter losses

See Section 2.1.2 for further description of the operational losses with respect to the Low-Ash/Low-Moisture Conventional design. All costs incurred to get the material into the format of a debarked chip when leaving the landing will then be attributed to that mass of chipped biomass. An example of the application of this approach is the introduction of a flail shredder at the landing to remove branches and bark in order to lower the ash content of the chips that leave the landing. The material that the flail shredder removes is out of the ash spec range, and subsequently not part of the marketable portion of the biomass. Rather than treating this as a dry matter loss, the accounting of all costs getting material to the landing exit are simply attributed to mass of material that leaves the landing on spec.

During flailing, the branches and bark of the trees are knocked off, and normally result in dry matter losses of approximately 20%. An alternate design (Figure 2-49) to reduce these losses would be to feed the branches into the chipper, however this is not the modeled design. The idea behind this recycling is that some of the material (friable bark, needles, smaller branches, etc.) are not picked up by the grapple and therefore are considered losses. In this alternate design, approximately 25% of the slash would be lost to dry matter loss. Of the 75% of the slash stream that would be fed into the trommel, 20% would be lost as dry matter loss.

During comminution in the field, it is not common to have a dust collection system. Therefore, there are some material losses through dust, in addition to those from material falling out of the chipper/grinder, or being propelled beyond the truck after comminution. Although not a lot of information is available on dry matter losses during comminution at the landing, Hamelinck et al. estimate dry matter losses to be around 2% for both chipping and grinding (Hamelinck et al. 2005). The reason for the lack of literature is the difficulty in attaining accurate measurements of initial dry matter content and final dry matter content. Again, these losses are attributed to a product of getting the material to meet the required spec, and are considered as unrecoverable in the Low-Ash/Low-Moisture Conventional design.

Operational Window

See Section 2.1.2 for a description of the operational window with respect to the Low-Ash/Low-Moisture Conventional design.

2.2.2.4 Low-Ash/Low-Moisture Conventional Preprocessing Cost Analysis

Cost Summary

A breakdown of the costs associated with each piece of equipment used in the Preprocessing unit operation identifies significant cost components that are valuable for making individual comparisons and identifying areas of research potential (Table 2-36). These costs are reported in terms of DM tons entering each process.

Table 2-36. Static model costs for major Preprocessing equipment in the Low-Ash/Low-Moisture Conventional scenario. Costs are expressed in 2010 $/DM ton unless otherwise noted. Total operation cost is the sum of ownership, operating, and DM loss cost.

	Delimbing and Debarking	Chipper	Total Cost per DM ton for Preprocessing
Installed Equipment Quantity (# of machines)	7	7	
Installed Capital	2.55	3.76	6.31
Ownership Costs	*0.45*	*1.61*	*2.06*
Operating Costs	*6.00*	*4.60*	*10.60*
Labor	1.15	1.15	2.30
Non-Labor	4.86	3.46	8.32
Energy Use (Mbtu/DM ton)	116.39	105.81	222.51

From Table 2-36, the total Preprocessing cost for pulpwood sized trees is $12.66/DM ton, which is the sum of ownership and operating costs. The Preprocessing operation consumes very high amounts of diesel fuel to run the flail and the chipper (reflected in the energy consumption of the flail and chipper).

Sensitivity Analysis

To perform sensitivity analysis, we selected multiple variables of interest and assigned ranges to them, which followed a triangular distribution. A symmetric distribution was applied where appropriate, i.e., when it was the best approximation of an actual distribution. Powersim was then set to output costs per dry matter ton to Excel. The Monte Carlo method was used, using the Risk Analysis Clone capability in Powersim. Excel was used to generate the histograms, the range of each analysis was divided into thirty “bins,” and the frequency function was used to count the number of occurrences between two bin points.

The histogram generated for the Preprocessing operation is shown in Figure 2-59.

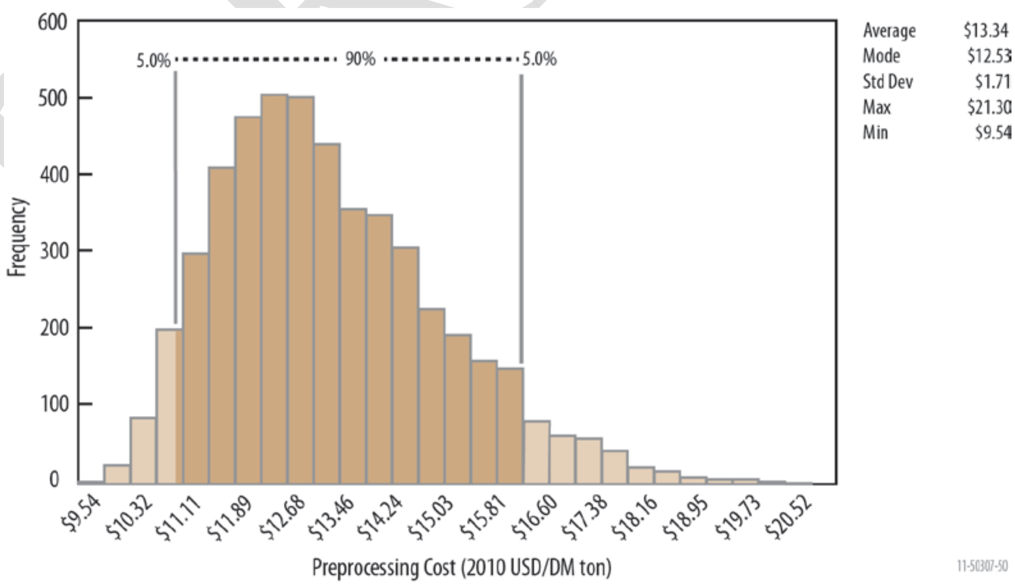

Figure 2-59. Low-Ash/Low-Moisture Conventional woody biomass supply chain cost distribution histogram for the Preprocessing operation for pulpwood. Costs are expressed in 2010 $/DM ton.

The histogram is not a smooth bell curve, as there are "jumps" wherever a piece of equipment has reached maximum capacity and another piece of equipment is needed. From Figure 2-59, the average cost for the Preprocessing operation is \$13.34 ± 1.71/DM ton, so the static model cost of \$12.66/DM ton fits within this range. The histogram shows that with 90% confidence the Preprocessing unit operation ranges between \$9.54 and \$21.30/DM ton, making this operation a significant cost contributor to the woody biomass supply chain. Ensuring a high utilization efficiency of the flail and chipper help to reduce costs of this operation. The mode value of this cost range is \$12.53/DM ton.

2.2.3 Low-Ash/Low-Moisture Conventional Transportation

Transport and delivery are key elements of forest activities. The way they are organized has implications for the production system as a whole (Hubbard et al. 2007). After comminution, the debarked chips are ejected into the back of a chip van and transported via truck to the biorefinery (Figure 2-60). Increased bulk density resulting from the chipping process greatly enhances the economics of transportation and handling.

Figure 2-60. Transportation supply logistic processes and biomass format intermediates for the Low-Ash/Low-Moisture Conventional design. *(Note: Green ovals represent biomass format intermediates, yellow rectangles represent processes modeled in this report)*

2.2.3.1 Low-Ash/Low-Moisture Conventional Transportation Format Intermediates

During this operation, the format of the material remains a chip (Table 2-37). Chips are cleaned to remove any contaminants that might damage the conversion process, such as metal. As well, the material is screened to remove any additional ash that was not removed using the trommel screen at the landing, resulting in a 1% loss in material.

Table 2-37. Attributes of Transportation format intermediates for the Low-Ash/Low-Moisture Conventional system.

	Transported Chips
Yield (DM tons/day)	2330
Format Output	chips
Bulk DM Density Output	20 lb/ft^3
Output Moisture (% w.b.)	35%

Biomass Deconstruction, Fractionation, and Physical Property Changes

In the Low-Ash/Low-Moisture Conventional Transportation operation, the physical characteristic of the material is not altered.

Format and Bulk Density Impact on Supply System Processes

See Section 2.1.3 for a description of format and bulk density impact on Transportation with respect to the Low-Ash/Low-Moisture Conventional scenario.

Biomass Moisture Impact on Supply System Processes and Material Stability

See Section 2.1.3 for a description of the biomass moisture impact on Transportation with respect to the Low-Ash/Low-Moisture Conventional scenario.

2.2.3.2 Low-Ash/Low-Moisture Conventional Transportation Equipment

See Section 2.2.3 for a description of transportation equipment with respect to the Low-Ash/Low-Moisture Conventional scenario. Transportation equipment used in the Low-Ash/Low-Moisture Conventional design is summarized in Table 2-38.

Table 2-38. Transportation equipment specifications for the Low-Ash/Low-Moisture Conventional design.

	Transport
Equipment	Chip Van
Rated Capacity	3,600 ft^3/ load
Operational Efficiency (%)	100 %
Dry matter loss (%)	0%
Operational Window	
Hr/day	14
Day/yr	300

In the alternate Low-Ash/Low-Moisture Conventional design shown in Figure 2-49, screens would be used to reduce the amount of high-ash smaller particles.

Disc Screens

Disc screens are another type of screen widely used for segregating or separating specific-size particles. Disc screens are made with a number of parallel shaft assemblies, each containing a number of equally spaced discs or rollers. The shafts run the width of the screen. As the material passes over the shafts, the distance between the discs or rollers allows material smaller to fall through the rollers. Oversized material passes over the screen and can be returned to the grinder for further processing. Disc screens tend to be self-cleaning and typically clog less than other screen types. Dust collection can be more easily adapted to this type of screen to control the dust associated with the process. Keating (1976) reports production rates up 1250 m^3 per hour at 14 KW.

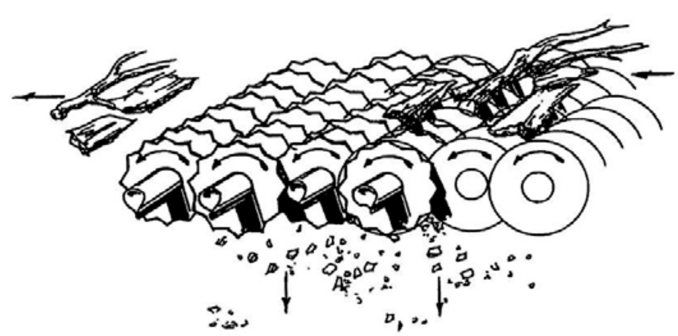

Figure 2-61. Disc screen used to remove overs from a chip stream (Reprinted with permission from Pottie and Guimier 1984).

Vibratory Screens

Vibratory screens, or shaker screens, are more commonly used with rock or coal. Shaker screens consist of a rectangular screen frame mounted on an incline that continuously shakes or vibrates in a reciprocating motion. Material is fed onto the screen on the upper end of the screen, and the shaking and gravity carry the material down the screen. Holes in the screen allow the appropriately sized material to fall through while oversized material passes over the screen. The screen is vibrated vigorously to cause the flowing material to bounce rapidly up and down. This shakes the finer material off of the larger material and allows it to pass through the mesh panel. The larger particles continue to bounce off the end of the mesh panel at the rear of the screen. Shaker or vibrating screens tend to plug easily with moist materials like woody biomass. The capacity of moist material can be increased by drying first.

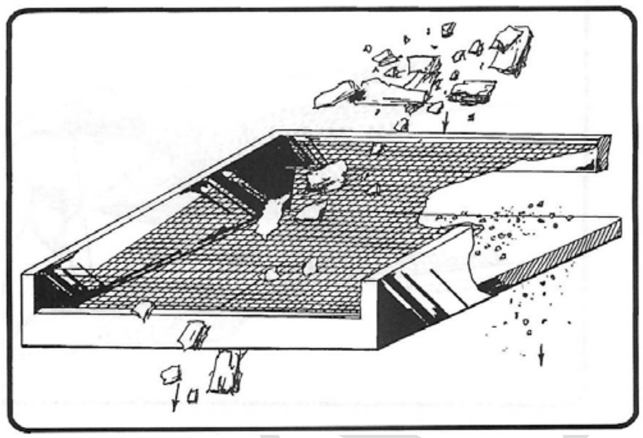

Figure 2-62. Vibratory screen used to separate out overs (Reprinted with permission from Guimier and Pottie 1984).

These screens are incorporated into this design to sift out the smallest size fraction, which is commonly higher in dirt and bark, and therefore ash.

Equipment Capacity and Operational Efficiency

See Section 2.1.3.2 for a description of Transportation equipment with respect to the Low-Ash/Low-Moisture Conventional design.

Dry matter losses

Transport losses can also be assumed 0% (Hamelinck et al. 2005, Suurs et al. 2002) in the Low-Ash/Low-Moisture Conventional design.

Operational Window

For this scenario Transportation operations run 14 hours per day, 6 days per week except during plant shutdown for maintenance.

2.2.3.3 Low-Ash/Low-Moisture Conventional Transportation Cost Analysis

Cost Summary

A breakdown of the costs associated with each piece of equipment used in the Transportation operation identifies significant cost components that are valuable for making individual comparisons and identifying areas potential research (Table 2-39). These costs are reported in terms of DM tons entering each process.

Table 2-39. Static model costs for major Transportation equipment in the Low-Ash/Low-Moisture Conventional scenario. Costs are expressed in 2010 $/DM ton. Total operation cost is the sum of ownership, operating, and DM loss cost.

	Transport	Total Cost per DM ton for Transportation
Equipment	Chip Van	Chip Van
Quantity of Equipment (# of machines)	40 trucks	40 trucks
Installed Capital	8.16	8.16
Ownership Costs	*1.11*	*1.11*
Operating Costs	*8.17*	*8.17*
Labor	3.94	3.94
Non-Labor	4.23	4.23
Dry matter loss Costs	*0*	*0*
Energy Use (Mbtu/DM ton)	129.05	129.05

Table 2-39 shows the total Transportation cost for pulpwood sized trees is $9.28/DM ton, which is the sum of ownership, operating, and dry matter loss costs.

Sensitivity Analysis

To perform sensitivity analysis, we selected multiple variables of interest and assigned ranges to them, which followed a triangular distribution. A symmetric distribution was applied where appropriate, i.e., when it was the best approximation of an actual distribution. Powersim was then set to output costs per dry matter ton to Excel. The Monte Carlo method was used, using the Risk Analysis Clone capability in Powersim. Excel was used to generate the histograms, the range of each analysis was divided into thirty “bins,” and the frequency function was used to count the number of occurrences between two bin points.

The histogram generated for the Transportation operation is shown in Figure 2-63.

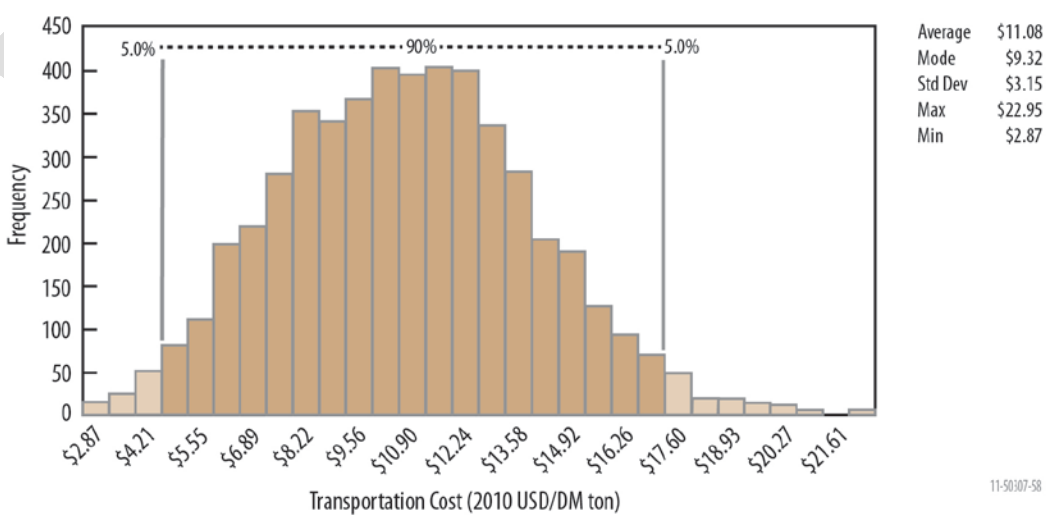

Figure 2-63. Low-Ash/Low-Moisture Conventional woody biomass supply chain cost distribution histogram for the Transportation operation for pulpwood. Costs are expressed in 2010 $/DM ton.

The histogram is a relatively smooth bell curve that skews somewhat to the left. The reason for the skew is that the range of potential transport distance was high, from 20 miles to 100 miles. From Figure 2-63, the average cost for the Transportation operation is \$11.08 ± 3.15DM ton, so the static model cost of \$9.28/DM ton fits within this range. The standard deviation is also relatively high, which is again due to the large potential range of transportation distances as well as the large range for loading time. The histogram shows that the Transportation unit operation cost ranges between a minimum of \$2.87 and a maximum of \$22.95/DM ton. The large range indicates the importance of accurately determining the transportation distance. A high transportation distance can highly inflate the delivered biomass cost. The mode value of this cost range is \$9.32/DM ton, which is close to the static model value.

2.2.4 Low-Ash/Low-Moisture Conventional Receiving and Handling

Once at the biorefinery, chips are unloaded using a truck tipper into a hopper, cleaned to remove metal pieces and dirt, and conveyed using a circular stack reclaimer.

Figure 2-64. Receiving and Handling supply logistic processes and biomass format intermediates for the Low-Ash/Low-Moisture Conventional design. *(Note: Green ovals represent biomass format intermediates, yellow rectangles represent processes modeled in this report)*

The operation is similar to that shown in Section 2.1.4 for the Base Case Conventional design.

2.2.4.1 Low-Ash/Low-Moisture Conventional Receiving and Handling Format Intermediates

During this operation, the format of the material remains a chip (Table 2-40). Chips are cleaned to remove any contaminants that might damage the conversion process, such as metal. For the alternate design scenario, the material is screened to remove any additional ash that was not removed using the trommel screen at the landing, resulting in a 0.5% loss in material. This alternate scenario is not modeled.

Table 2-40. Attributes of Receiving and Handling format intermediates for the Low-Ash/Low-Moisture Conventional system.

	Transported Chips	Cleaned Chips	Stacked Chips
Yield (DM tons/day)	2330	2330	2330
Format Output	chips	chips	chips
Bulk DM Density Output	20 lb/ft^3	20 lb/ft^3	20 lb/ft^3
Output Moisture (% w.b.)	35%	35%	35%

Biomass Deconstruction, Fractionation, and Physical Property Changes

In the Low-Ash/Low-Moisture Conventional Receiving and Handling operation, the physical characteristic of the material is not altered beyond the removal of contaminants.

Format and Bulk Density Impact on Supply System Processes

See Section 2.1.4.1 for a description of the impact of format and bulk density on Receiving and Handling in the Low-Ash/Low-Moisture Conventional scenario.

Biomass Moisture Impact on Supply System Processes and Material Stability

See Section 2.1.4 for a description of the impact of biomass moisture on Receiving and Handling in the Low-Ash/Low-Moisture Conventional scenario.

2.2.4.2 Low-Ash/Low-Moisture Conventional Receiving and Handling Equipment

See Section 2.1.4.3 for a description of the equipment used in the Receiving and Handling operation in the Low-Ash/Low-Moisture Conventional scenario. Receiving and Handling equipment used in the Low-Ash/Low-Moisture Conventional design are summarized in Table 2-41.

Table 2-41. Receiving and Handling equipment specifications for the Low-Ash/Low-Moisture Conventional design.

	Unloading/Handling/ Dust Collection	Chip Cleaning
Equipment	Truck tipper & hopper, dust collection, moisture meter	Electro magnet
Rated Capacity	280 t/hr	18 DM t/hr
Operational Efficiency (%)	100%	100%
Dry matter loss (%)	0%	0%
Operational Window		
Hr/day	14	14
Day/yr	300	300

Disc Screens

Disc screens are another type of screen widely used for segregating or separating specific-size particles. Disc screens are made with a number of parallel shaft assemblies, each containing a number of equally spaced discs or rollers. The shafts run the width of the screen. As the material passes over the shafts, the distance between the discs or rollers allows material smaller to fall through the rollers. Oversized material passes over the screen and can be returned to the grinder for further processing. Disc screens tend to be self cleaning and typically clog less than other screen types. Dust collection can be more easily adapted to this type of screen to control the dust associated with the process. Keating (1976) reports production rates up 1250 m^3 per hour at 14 KW.

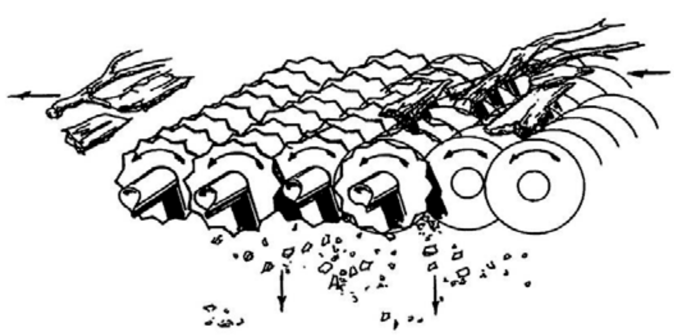

Figure 2-65. Disc screen used to remove overs from a chip stream (Reprinted with permission from Guimier and Pottie 1984).

Vibratory Screens

Vibratory screens, or shaker screens, are more commonly used with rock or coal. Shaker screens consist of a rectangular screen frame mounted on an incline that continuously shakes or vibrates in a reciprocating motion. Material is fed onto the screen on the upper end of the screen, and the shaking and gravity carry the material down the screen. Holes in the screen allow the appropriately sized material to fall through while oversized material passes over the screen. The screen is vibrated vigorously to cause the flowing material to bounce rapidly up and down. This shakes the finer material off of the larger material and allows it to pass through the mesh panel. The larger particles continue to bounce off the end of the mesh panel at the rear of the screen. Shaker or vibrating screens tend to plug easily with moist materials like woody biomass. The capacity of moist material can be increased by drying first.

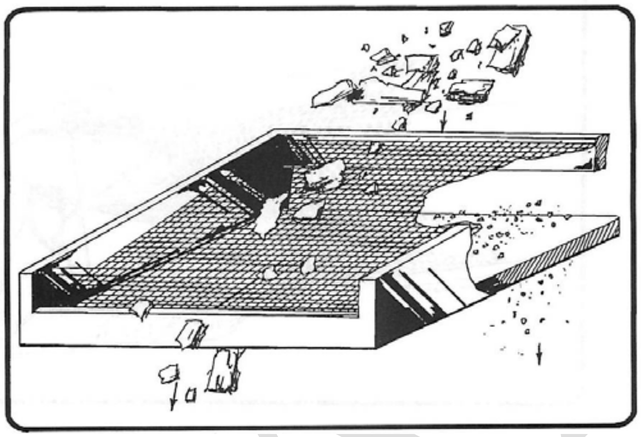

Figure 2-66. Vibratory screen used to separate out overs (Reprinted with permission from Guimier and Pottie 1984).

These screens are incorporated into this design to sift out the smallest size fraction, which is commonly higher in dirt and bark, and therefore ash.

Equipment Capacity and Operational Efficiency

See Section 2.1.4.3 for a description of Receiving and Handling equipment with respect to the Low-Ash/Low-Moisture Conventional scenario.

Dry matter losses

Receiving and Handling losses can also be assumed 0% (Hamelinck et al. 2005, Suurs 2002). For the alternate design shown in Figure 2-49, there would be an approximately 0.5% dry matter loss assumed resulting from using the vibratory screens for ash reduction.

Operational Window

For this scenario Receiving and Handling operations run 24 hours per day, 7 days per week except during plant shutdown for maintenance.

2.2.4.3 Low-Ash/Low-Moisture Conventional Receiving and Handling Cost Analysis

Cost Summary

A breakdown of the costs associated with each piece of equipment used in the Receiving and Handling operation identifies significant cost components that are valuable for making individual comparisons and identifying areas potential research (Table 2-19). These costs are reported in terms of DM tons entering each process.

Table 2-42. Static model costs for major Receiving and Handling equipment in the Low-Ash/Low-Moisture Conventional scenario. Costs are expressed in 2010 $/DM ton. Total operation cost is the sum of ownership, operating, and DM loss cost.

	Unloading/Handling/ Dust Collection/Cleaning	Chip Cleaning	Circular Stack Reclaimer	Total Cost per DOM ton for Receiving and Handling
Equipment	Scale, truck tipper & hopper, dust collection, moisture meter	Electro magnet		
Quantity of Equipment (# of machines)	—	12	1	
Installed Capital[a]	3.73	0.9	2.50	7.16
Ownership Costs[b]	*0.70*	*0.12*	*0.29*	*1.10*
Operating Costs[c]	*1.24*	*0.01*	*0.13*	*1.39*
Labor	0.82	0	0.24	1.06
Non-Labor	0.39	0.01	0.13	0.53
Dry-matter loss Costs	*0*	*0*	*0*	*0*
Energy Use (Mbtu/DM ton)	12.72	0.97	1.93	15.62

From Table 2-42, the total Receiving and Handling cost for pulpwood sized trees is $2.49/DM ton, which is the sum of ownership, operating, and dry matter loss costs.

Sensitivity Analysis

To perform sensitivity analysis, we selected multiple variables of interest and assigned ranges to them, which followed a triangular distribution. A symmetric distribution was applied where appropriate, i.e., when it was the best approximation of an actual distribution. Powersim was then set to output costs per dry matter ton to Excel. The Monte Carlo method was used, using the Risk Analysis Clone capability in Powersim. Excel was used to generate the histograms, the range of each analysis was divided into thirty “bins,” and the frequency function was used to count the number of occurrences between two bin points.

The histogram generated for the Receiving and Handling operation is shown in Figure 2-68.

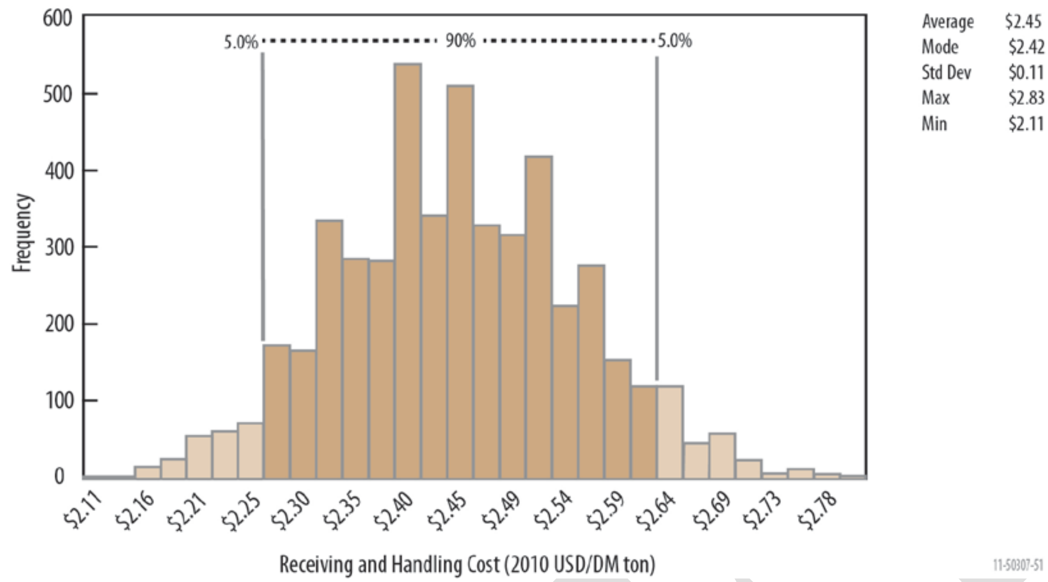

Figure 2-67. Low-Ash/Low-Moisture Conventional woody biomass supply chain cost distribution histogram for the Receiving and Handling operation for pulpwood. Costs are expressed in 2010 $/DM ton.

The histogram is not a smooth bell curve, as there are significant "jumps" wherever a piece of equipment has reached maximum capacity and another piece of equipment is needed. From Figure 2-67, the average cost for the Receiving and Handling operation is $2.45 ± 0.11/DM ton, so the static model cost of $2.49/DM ton fits within this range. The histogram shows that the Receiving and Handling unit operation cost ranges between a minimum of $2.11 and a maximum of $2.83/DM ton. The mode value of this cost range is $2.42/DM ton. The Receiving and Handling operation has a relatively low cost impact on the woody biomass supply chain. There is a fairly high level of certainty in the cost components, and the components are quite large and their cost is distributed over a high amount of dry matter ton throughput. This is also a reason for the large jumps- moving to a new piece of equipment will result in a lot of excess, unused capacity.

2.2.5 Low-Ash/Low-Moisture Conventional Storage

Storage encompasses all processes associated with piling, pile turning, and ambient drying of the woody biomass. It also includes any costs associated with storage site preparation, such as construction of an asphalt pad, silo or other storage structure. The conventional design includes storage on an asphalt pad. The storage operation for the Low-Ash/Low-Moisture Conventional scenario is summarized in Figure 2-68.

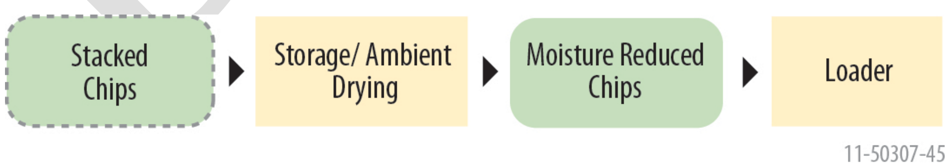

Figure 2-68. Low-Ash/Low-Moisture Conventional Storage supply logistics processes and format intermediates. *(Note: Green ovals represent format intermediates, while yellow rectangles represent individual modeled processes.)*

Cleaned chips are piled and ambient dried to reduce moisture content from 35% to 30%. The dried chips are queued and then loaded into the next unit operation, preprocessing.

2.2.5.1 Low-Ash/Low-Moisture Conventional Storage Format Intermediates

The dry matter losses resulting from storage are assumed to be 2%. These are a combination of biological and mechanical losses, the majority coming from the latter (Table 2-43).

Table 2-43. Characteristic of storage format intermediates in the Low-Ash/Low-Moisture Conventional scenario.

	Stacked Chips	Moisture Reduced Chips
Yield (DM ton/day)	2330	2285
Format Output	Chips	Chips
Bulk DM Density Output (lb/ft^3)	20	20
Output Moisture (% w.b.)	35	30

During storage, the chips lose 5% moisture through ambient drying, which is discussed in Section 2.1.5.1.

Biomass Deconstruction, Fractionation, and Yield

See Section 2.1.5 for a discussion of deconstruction and fractional yield with respect to the Storage operation in the Low-Ash/Low-Moisture Conventional design.

Format and Bulk Density Impact on Supply System Processes

See Section 2.1.5 for a discussion of format and bulk density with respect to the Storage operation in the Low-Ash/Low-Moisture Conventional design.

Biomass Moisture Impact on Supply System Processes and Material Stability

See Section 2.1.5 for a discussion of biomass moisture with respect to the Storage operation in the Low-Ash/Low-Moisture Conventional design.

Very dry biomass material has a tendency to absorb moisture from the storage environments (Stahl et al. 2003). As a consequence the biomass has to be stored carefully in closed vessels. Even short time handling has to be performed in a completely dry atmosphere, and correct handling is required for reliable analytical results. Stahl et al. (2003) looked at the moisture uptake of rice and wheat straw, and found that the rate of moisture uptake can be higher when biomass is dried at temperatures of >110°C. The material typically starts losing its hydrophilic nature typically when dried at temperature >200°C.

2.2.5.2 Low-Ash/Low-Moisture Conventional Storage Equipment

Woody material is queued at the refinery with a 7 day supply (Table 2-44). Longer storage could be incorporated into the system if necessary, for up to a month. The dry matter losses during storage are estimated to be 2%, which are split between mechanical losses resulting from moving the material around using loaders, and biological losses.

Table 2-44. Equipment performance parameters for the Low-Ash/Low-Moisture Conventional Storage scenario.

	Storage	Loader	Asphalt Pad
Equipment	N/A	Front-end loader	Asphalt Pad
Rated capacity	N/A	80 t/hr	25 days
Operational efficiency (%)	N/A	100%	100%
Dry matter loss (%)	1%	1%	0%
Operational Window			
Hr/day	24	14	24
Day/yr	5	300	365

The Low-Ash/Low-Moisture Conventional design scenario assumes an open-air storage environment, and therefore there are no additional structures constructed for storage.

See Section 2.1.5.2 for further description of storage equipment options.

Equipment Used in Conventional Format Design Model

A front-end loader is used to move woody material around the grounds. The chips are queued in a large pile by a circular stack reclaimer. As material is to be used, it is pushed using a front-end loader on top of a grate covering a conveyor, where it is conveyed into the refinery.

Equipment Capacity and Operational Efficiency

See Section 2.1.5.2 for a discussion of equipment with respect to the Low-Ash/Low-Moisture Conventional design.

Operational Dry matter Losses

Some operational losses occur during loading and other handling operations associated with storage. Although these losses are often considered negligible, we assumed a 3% dry matter loss for the Low-Ash/Low-Moisture Conventional design.

Operational Window

See Section 2.1.5 for a discussion of operational window with respect to the Low-Ash/Low-Moisture Conventional design.

2.2.5.3 Low-Ash/Low-Moisture Conventional Storage Cost Analysis

Costs associated with the Storage operation in the Low-Ash/Low-Moisture Conventional design include an asphalt pad and a loader to move material around the yard (Table 2-45).

Table 2-45. Static model costs for Storage equipment in the Low-Ash/Low-Moisture Conventional scenario. Costs are expressed in 2010 $US/DM ton. Total operation cost is the sum of ownership, operating, and DM loss cost.

Equipment	Storage	Loader Front-End Loader	Asphalt Pad	Total Cost per DM ton for Storage
Quantity of Equipment (# of machines)	N/A		1	
Installed Capital	N/A	0.32	0.03	0.35
Ownership Costs	*N/A*	*0.13*	*0.04*	*0.17*
Operating Costs	*N/A*	*0.80*	*0.00*	*0. 80*
Labor	N/A	0.31	0	0.31
Non-Labor	N/A	0.49	0	0.49
Dry matter Loss Costs	*0.43*	*0.43*	*0*	*0.86*
Energy Use (Mbtu/DM ton)	N/A	13.08	N/A	13.08

From Table 2-45, the total Storage cost for cleaned pulpwood chips is $1.83/DM ton, which is the sum of ownership, operating, and dry matter loss costs. Long-term storage is uncommon in operations that handle comminuted woody biomass. Therefore, the system generally only has a 7-day material queue at the plant, with the ability to expand storage out to 25 days on the asphalt pad. The loader is the only component of storage that incurs an operating cost, and is also the source of some dry matter loss (unrecovered material).

Sensitivity Analysis

To perform sensitivity analysis, we selected multiple variables of interest and assigned ranges to them, which followed a triangular distribution. A symmetric distribution was applied where appropriate, i.e., when it was the best approximation of an actual distribution. Powersim was then set to output costs per dry matter ton to Excel. The Monte Carlo method was used, using the Risk Analysis Clone capability in Powersim. Excel was used to generate the histograms, the range of each analysis was divided into thirty “bins,” and the frequency function was used to count the number of occurrences between two bin points.

The histogram generated for the Storage operation is shown in Figure 2-69.

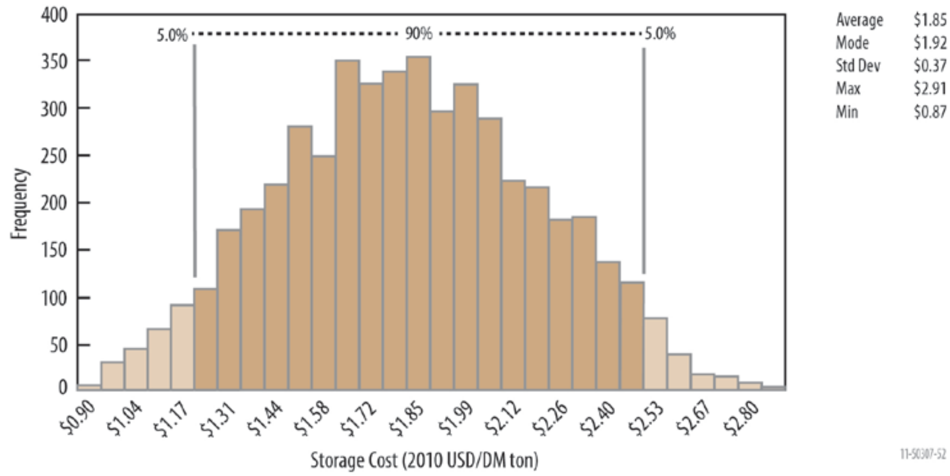

Figure 2-69. Low-Ash/Low-Moisture Conventional woody biomass supply chain cost distribution histogram for the Storage operation for pulpwood. Costs are expressed in 2010 $/DM ton.

The histogram is not a smooth bell curve, as there are “jumps” wherever a piece of equipment has reached maximum capacity and another piece of equipment is needed. From Figure 2-70, the average cost for the Storage operation is $1.85 ± 0.37/DM ton, so the static model cost of $1.83/DM ton fits within this range. The histogram shows that the Storage unit operation cost ranges between a minimum cost of $0.87/DM ton and a maximum cost of $2.91/DM ton. The mode value of this cost range is $1.92/DM ton, which is near the static value. This operation has a relatively low cost impact on supply chain costs, but it is critical to the supply chain in terms of ensuring that there is sufficient biomass to run the conversion process in case of supply chain upset.

2.2.6 Low-Ash/Low-Moisture Conventional In-Plant Handling

Material leaving storage and queuing enters into the In-Plant Handling operation (Figure 2-70). An initial preprocessing operation occurs at the landing, where trees are delimbed, debarked, and chipped. During In-Plant Handling at the biorefinery, a second preprocessing operation occurs to further dry and, if necessary, size reduce the material so as to meet conversion infeed requirements. For the modeled scenario, chips are formatted to meet a specification for indirect gasification (Phillips et al. 2007).

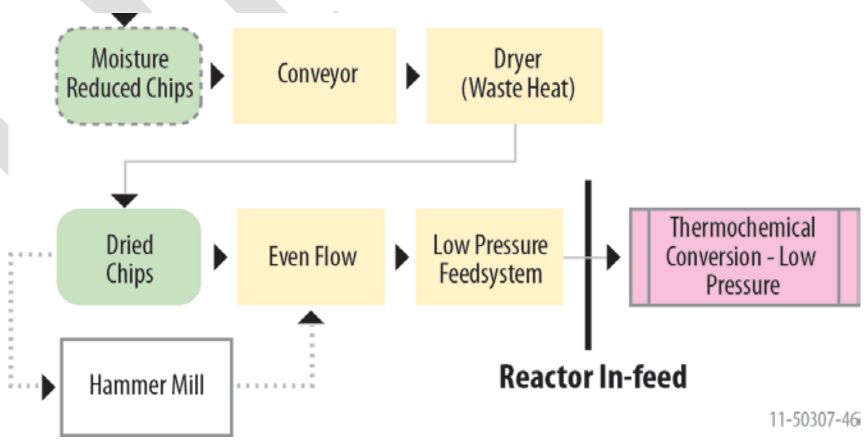

Figure 2-70. In-Plant Handling supply logistic processes and biomass format intermediates for the Low-Ash/Low-Moisture Conventional scenario. *(Note: Green ovals represent biomass format intermediates, yellow rectangles represent processes modeled in this report, while white boxes represent processes not modeled. The pink rectangle represents the thermochemical conversion process.)*

For the Low-Ash/Low-Moisture Conventional design, chips are loaded into a waste-heat dryer to reduce the moisture content to a level appropriate for thermochemical conversion (Phillips et al. 2007), and then queued for conversion.

2.2.6.1 Low-Ash/Low-Moisture Conventional In-Plant Handling Format Intermediates

In the Low-Ash/Low-Moisture Conventional system, chips are loaded from queuing and dried using a waste-heat dryer from an initial moisture content of 30 to 10%, which meets the infeed requirements for the modeled gasification scenario (Phillips et al. 2007) (Table 2-46).

Table 2-46. Attributes of In-Plant Handling format intermediates for the Low-Ash/Low-Moisture Conventional system.

	Loaded Chips	Dried Chips
Yield (DM tons/day)	2285	2285
Format Output	Chips	Dried Chips
Bulk DM Density Output	20 lb/ft^3	20 lb/ft^3
Output Moisture (% w.b.)	30	10

Biomass Deconstruction, Fractionation, and Physical Property Changes

After drying, no additional size reduction is required for gasification, however some thermochemical processes require a smaller particle size and would need another comminution step. For example, pyrolysis conversion would require a hammer mill after the dryer. Milled wood has a higher bulk density than woodchips; however, it poses some handling challenges due to its very small, dusty, and light-weight particles.

Format and Bulk Density Impact on Supply System Processes

Dry matter bulk density does not change during this operation. However, if a hammer mill were required the density would change, the magnitude of which depends on the final particle size. Although not modeled for the Low-Ash/Low-Moisture Conventional scenario, further reducing the biomass using a hammer milling process is a necessary pretreatment for some processes. Advantages of hammer milling include easier handling and drying of bulk material, potentially higher density, ability to pelletize, potentially facilitation of material sorting by size through separation, and an increase in reactive surface area of biomass particles that are exposed to biochemical processing (Miu et al. 2006).

Final physical properties of the product depend on the application. Particle size can vary in a wide range of values, from higher sizes for densification process as briquetting (5 to 10 mm) or pelleting (~5 mm) (Gil et al. 2004) to lower particle size in other technologies, such as direct combustion, biofuels (1 to 2 mm) (3 to 6 mm) (Cadoche and Lopez et al. 1989) or co-firing in coal power plants (0.8 to 6 mm) (Spliethoff and Hein et al. 1998, Wagenaar and Heuvel 1997).

Biomass Moisture Impact on Supply System Processes and Material Stability

Drying

For the Low-Ash/Low-Moisture Conventional design, wood entering the dryer at 30 % moisture content is further dried to increase the energy density to a level appropriate for the modeled thermochemical conversion scenario (Phillips et al. 2007). The energy density of woody biomass increases linearly with decreasing moisture content, rising from approximately 0 MJ/kg at approximately 87% moisture content to a maximum of about 18 MJ/kg (LHV) at 0% moisture (Pottie and Guimier 1985) (Figure 2-71). However, the very rapid initial increase in heating value with decreasing moisture content becomes much less significant at lower moisture contents. For example, Pottie and Guimier (1985) showed the LHV at 90% moisture to be 0 MJ/kg, and just over 15 MJ/kg at about 60% moisture. However, the change in heating value when going from 60 to 30% moisture is only 2.5 to 4 MJ/kg.

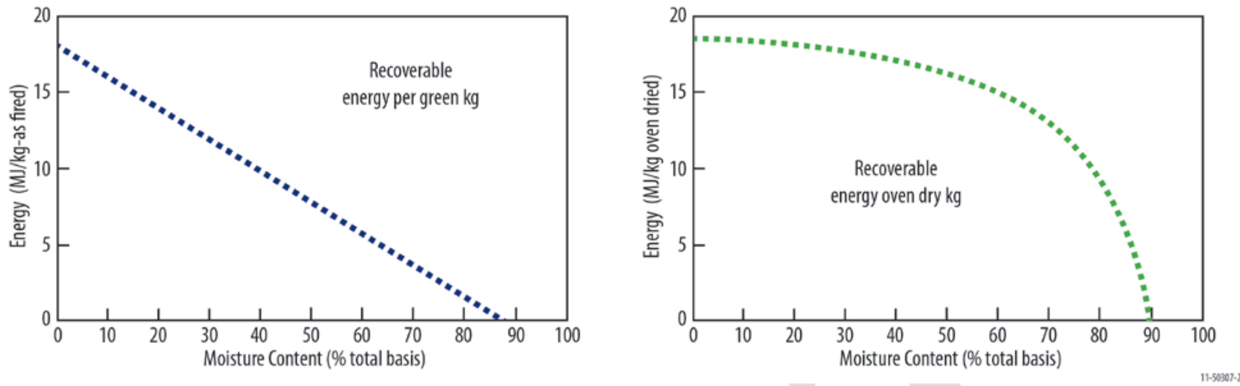

Figure 2-71. Relationship between moisture content of woody biomass and recoverable energy per green ton (a) and recoverable energy per dry ton (b) (Recreated with permission from Pottie and Guimier 1985).

During drying, the water that is loosely held will be removed most easily. Phanphanich and Mani (2009) looked at drying time of forest residues at several temperatures to determine experimental drying curves (Figure 2-72). The initial part of the graph in Figure 2-72 indicates the removal of free water from the biomass for all temperature scenarios. Thus, drying rates would decrease as moisture content decreases, as more loosely bound water is removed first. In general, water is removed faster at higher temperatures than at lower temperatures. Figure 2-72 shows that at 80°C, it required less than 3 hours to dry the material from an initial moisture of 60% to a final moisture content of 4%, while at 40°C it took almost 5 hours to dry the residue from 60 to 22%.

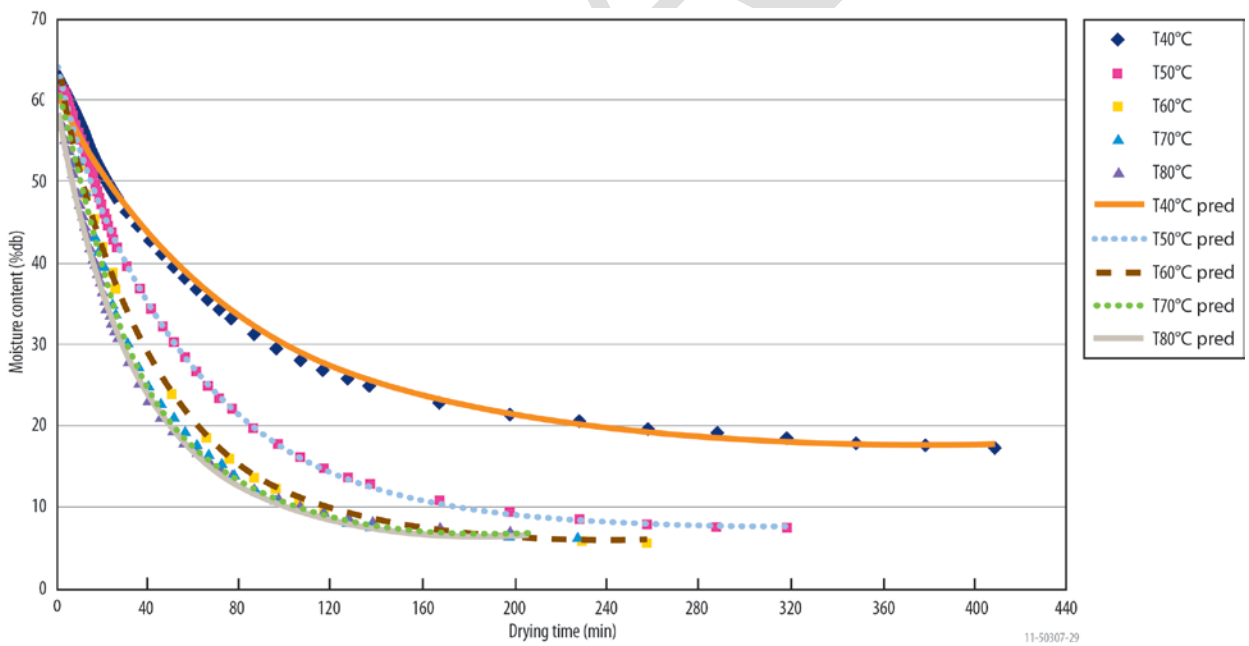

Figure 2-72. Drying rate of forest residues at various drying air temperatures (Phanphanich and Mani 2009). “Pred” indicates predicted values based on drying model produced by Henderson and Pabis (1961).

The drying curve for biomass is divided in two general parts, a constant rate period and falling rate period. During the constant-rate period, which normally has the highest drying rate, water is evaporated from what is effectively a free water surface. As drying proceeds, the surface moisture content decreases and further drying can only occur as water from the interior travels to the surface, and is thus diffusion limited. The situation is complex, with moisture gradients controlling the observed drying rates. Actual rates can be measured, showing in the idealized case a constant rate continuing up to the critical moisture content and, thereafter, a declining rate as the biomass on continued drying approaches the equilibrium moisture content of the environment. The rate of drying approaches zero as the material reaches equilibrium moisture content with the drying air, which prevents further moisture loss.

Drying processes are energy intensive due to the large quantity of heat required. This energy requirement reduces overall conversion efficiency unless waste heat can be captured from other processes and directed toward drying (Roos 2008). Heat sources within a biomass plant may include hot producer gas, turbine exhaust, heat exchanger exhausts and combustion of by-products. These heat sources can be used in a variety of different process dryers (Ståhl et al. 2004). Dryer types used in drying biomass fuels include rotary, conveyor, cascade, and flash dryers. When selecting a dryer and designing a system, it is important to consider many factors in addition to energy efficiency, such as environmental emissions, operation and maintenance concerns, and recovery of marketable co-products.

Low Temperature/Waste Heat Drying

Drying the biomass fuel improves the combustion efficiency (Table 2-47), increases steam production, reduces net air emissions, and improves boiler operation. The biomass needs to be drier than the 30% received moisture content before it is further used in a boiler or gasifier, or further processed for pelletization.

Table 2-47. 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 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, a lower moisture content helps in getting a uniform flame and in achieving complete combustion. Drying also has an impact on storage stability (see Section 2.2.6.1). Table 2-47shows the effect of water content and heating value of wood which affects the boiler efficiency.

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 using the waste heat for drying may be lower than 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.

Combined heat and power (CHP), also called cogeneration, is one example of how system efficiency can be improved by reusing the waste heat. CHP plants produce electricity and heat from a single fuel sources such as biomass/biogas, natural gas, coal or oil. CHP provides distributed generation of electrical and/or mechanical power; waste-heat recovery for heating, cooling, or process applications; and seamless system integration for a variety of technologies, thermal applications, and fuel types into existing building infrastructure.

The hallmark of all well-designed CHP system is an increase in the efficiency of fuel use by using waste heat recovery technologies which capture a significant proportion of heat created as a byproduct in electricity generation. The waste heat generated can be used for drying the biomass received. The reuse of waste heat can improve the economics of using biomass fuels, as well as produce other environmental benefits. More than 60 % of current biomass-powered electricity generation in the United States is in the form of CHP.

Thermal Drying Systems

Fuel dryers can be generally classified according to their drying media, i.e., the stream that passes through the material to be dried. Drying media which are normally used are superheated steam, hot air or flue gas. Table 2-48 indicates the dryer classifications.

Table 2-48. Dryer classifications (Roos 2008).

Classification	***Alternatives***
Drying media	Flue gas, hot air or superheated steam
Firing	Direct- or indirect-fired
Heat transfer media	Flue gas, hot air, steam, or hot water
Pressure	Atmospheric, vacuum or high pressure
Heat source	Dryer burners, boiler (flue gas or steam), recovered waste heat from facility processes

Flue-gas dryers use heat from combustion products for drying, and drying is constrained by the heat available in the flue gas and the quantity and moisture of material to be dried. Drying potential can be estimated using the gas quantity, temperature, fuel quantity, moisture content and the additional constraint that flue-gas temperature must be kept above the water-vapor dew point to avoid corrosion of the infrastructure. The maximum temperature is constrained by the concern for fires. However, most flue gas dryers operate at much higher temperatures than the combustion threshold because the flue-gas is depleted of oxygen relative to air (typically 5-10% O_2 by volume). Most systems will operate around 320ºC (608ºF) (Bruce and Sinclair 1996).

Table 2-49. Potential for drying wood refuse in flue gas (Bruce and Sinclair 1996). The table shows initial moisture in fuels, % wet basis.

	Flue-gas temperature leaving boiler, ºC		
Final moisture in biomass, % wb	100ºC	175ºC	260ºC
60	62	67	71
50	55	61	65
40	47	54	60
30	40	48	55

There are three commonly available flue-gas dryers; rotary, cascade, and flash. For more information on flue-gas dryers, see Bruce and Sinclair (1996).

Bin Drying Systems

The dryer used in this study is a waste heat dryer built form a modified continuous flow bin using a reclaimer arm, similar to that designed by Laidig Systems, Inc (Figure 2-73). Hot air enters an airspace at the bottom of the bin and flows through the woodchips. The top of the pile inside the bin is kept level to minimize channeling.

Figure 2-73. An example of a waste heat bin dryer, designed by Laidig Systems, Inc (www.laidig.com).

The bin dryer subjects woody biomass at 30% moisture to waste heat introduced through the bottom of the dryer (Figure 2-73). Inflowing air at 160°C dries the wood at a rate of 10 tons/hr. The material flows through the dryer with a retention time of 5 hours. The material flow rate through the dryer is maintained so that the temperature of air leaving the dryer is above the condensation point of the moisture and volatiles, or a conservative 90°C. The efficiency of the waste heat dryer can be increased by burning the volatiles for additional heat; however, this increases the capital cost of the system. The capital savings of a bin dryer over a rotary-drum dryer could potentially be significant.

Steam dryers use the heat in steam for drying and improve system thermal efficiency. The steam originating from the moisture driven off from the fuel is recirculated as the heat transfer medium. Steam dryers are newer than flue-gas dryers and come in a variety of forms. The recirculated steam used by steam dryers is reheated to superheated conditions by an external source, such as hot combustion gases, high-pressure steam, hot bed material from a fluid bed furnace or by means of a steam compressor. The quantity of excess steam generated (equal to the amount of moisture driven off) is at a lower energy level than the heat supplied. The advantage of steam drying over flue gas drying is its potential for greater efficiency. The recirculation of steam also facilitates the capture of volatiles driven off during drying. As a result, steam drying is currently a more active area of the development and growth (Bruce and Sinclair 1996).

Advantages of steam drying include low risk of fires, high energy efficiency, and better environmental control. However, the fuel moisture-derived steam contains contaminants volatilized from the wet fuel. The virtual absence of flue gas, air, or other non-condensable gases means that the latent heat of vaporization of the evaporated fuel can potentially occur at a single temperature governed by the dryer pressure (Bruce and Sinclair 1996). The use of excessively high temperatures in steam dryers will result in the volatilization of part of the fuel (with the contaminant level in the resulting condensate being excessively high) and loss of fuel heat content. The minimum temperature of the recirculating drying steam is a function of the operating pressure of the dryer. For efficient use of the dryer capacity, the steam must remain superheated (Bruce and Sinclair 1996).

The improved thermal efficiency of the steam dryer over the flue-gas dryer is only realized if the energy in the contaminated steam is returned usefully to the thermodynamic cycle. The resulting condensate contains organics, however, and requires appropriate treatment (Bruce and Sinclair 1996).

Steam drying technologies may be atmospheric or pressurized, have short to long residence time, be large or small, and take very different forms physically. As well, heat sources may be steam, flue gas, or a heat pump (Bruce and Sinclair 1996).

Hammer Milling

Again, although not required for the conventional design, many thermochemical conversion processes require finer particle sizes that necessitates an additional comminution step. Hammer milling reduces size by impacting the biomass and effectively shattering it into very small pieces. As dried biomass is more brittle, low-moisture biomass mills more efficiently then a high-moisture biomass. Therefore, the biomass is dried to 12% moisture content prior to hammer milling. After hammer milling, the biomass has a moisture content of approximately 10% and is ready for pelletization.

2.2.6.2 Low-Ash/Low-Moisture Conventional In-Plant Handling Equipment

Biomass in this operation has already undergone drying at several steps during the supply system, however a final drying step is required to bring the moisture content of the material down from 30% to 10%. This drying step is accomplished using a dryer that incorporates waste process heat (Table 2-50).

Table 2-50. In-Plant Handling equipment specifications for the Low-Ash/Low-Moisture Conventional design.

	Loader	Conveyor	Dryer	Even flow
Equipment		Conveyor	Bin dryer	Even flow bin
Rated capacity		40 ton/hour	12 ton/hr/machine	20,000 ft^3/hr
Operational efficiency (%)	100%	100%	100%	100%
Dry matter loss (%)	0	0	0	0
Operational window				
Hr/day	24	24	24	24
Day/yr	300	300	300	300

The material is conveyed out of storage and into the dryer. Material coming out of the dryer is sent to a surge bin where it is queued for conversion.

Equipment Capacity and Operational Efficiency

A front-end loader is used to bring the material out of storage and queuing, and load it onto the conveyer for drying. Note that the retention dryer also acts as a queue.

Drying Technologies

There are a variety of available drying technologies, including perforated floor bin dryers, super heated steam dryers, rotary dryers (direct and indirect fired rotary driers), conveyor dryers, cascade dryers, flash dryers and microwave dryers. A comparison between different type of driers in terms of feedstock requirements, capital cost, environmental emissions, energy efficiency and heat recovery and fire hazard is given in Table 2-51.

Table 2-51. Comparison of different drying systems. Letters in the table correspond to drying technologies as follows: (a) perforated floor bin dryers, (b) super heated steam dryers, (c) rotary dryers (direct and indirect fired rotary driers), (d) conveyor dryers, (e) cascade dryers, (f) flash dryers and microwave dryers.

Dryer Type	Feedstock Requirements	Capital & Operating Cost	O&M Requirements	Environmental Emissions	Energy Efficiency & Heat Recovery	Footprint	Footprint Fire Hazard
Rotary	a) Less sensitive to particle size. b) High content paper sludges tend to ball up. c) Coarse bark can be problematic		Low	More VOC emissions compared to lower temp dryers	Less opportunity to recover waste heat		Greater than lower temperature dryers
Conveyor	a) Fines may need to be screened out first and added back.	a) Comparable to rotary dryer, but may require less ancillary equipment for treatment of emissions b) Reduces the overall cost.	Greater than for rotary dryer.	Lower emissions of VOCs and particulates	High opportunity for heat recovery due to lower temperature.	a) Larger than comparably-sized rotary dryer. b) Multi-pass conveyors save space and can have comparable footprint to rotary dryer.	Low
Cascade	a) Requires fairly uniform particle size. b) Can handle large particle size.	Higher than rotary dryers.	Subject to corrosion and erosion		a) Heat recovery is difficult. b) High blower costs.	Smaller footprint than rotary and conveyor dryers.	Medium. Risk after the dryer and in shut down
Flash	a) Requires small particle size.	Higher than rotary dryers	Subject to corrosion and erosion		a) Heat recovery is difficult. b) High blower costs	Smaller footprint than rotary and conveyor dryers.	Medium
Superheated Steam	a) Requires small particle size.	High.	High. Subject to corrosion.	a) No air emissions. b) Condensate requires treatment.	a) Very efficient if low-pressure steam is recovered. b) No heat losses from heating air.	Smaller footprint than rotary and conveyor dryers.	No fire hazard

A significant limitation in all dryers is the lack of uniformity in product moisture content when drying a fuel with a large range in particle size, though rotary dryers with their long residence time do a better job (Bruce and Sinclair 1996). Rotary dryers have a rotating drum that is heated, and/or heated air is passed through the unit. Inside the drum, there are often baffles or louvers to channel the hot air, cascade the material, and help move the material through the drum. This type of dryer is widely used and is the most common type of dryer used to dry chips (Roos 2008).

Figure 2-74. Rotary drum dryer used at a wood processing facility (Photo credit: D. Brad Blackwelder, INL).

Other dryers that may be used on biomass include microwave dryers and steam dryers. Microwave drying is a rapid dehydration technique which improves drying rates and precision when applied to biomass (Brammer and Bridgwater 1999). The drying rate of biomass when using a microwave oven is more than 5 times quicker than when using an electrical oven and, depending on the conversion platform being fed, microwave drying may improve feed stock quality. For example, the heating value of bio-oil from microwave-dried biomass is increased with less water content, and more primary pyrolysis products reserved in the bio-oil (Wang et al. 2007).

Superheated steam dryers have a closed-loop pneumatic conveying system. The wet biomass is introduced into the flow of pressurized superheated steam using a plug screw, rotary valve, or similar device. Superheated steam dryers have several advantages over air dryers. Conditions in the dryer eliminate the possibility of oxidation or combustion reactions. Steam dryers have higher drying rates than air and gas dryers. Steam drying decreases fire and explosion danger and allows for the recovery of volatile compounds with the use of condensers. However, they are very complex, and small steam leaks greatly reduce their energy efficiency (Ståhl et al. 2004).

Table 2-52. Comparison of various conventional drying technologies (Brammer and Bridgwater 1999).

Drying Technique	Belt conveyor	Rotary drum	Microwave	Superheated steam
Drying media	Hot gas	Hot gas	Microwaves	Steam
Temperature	200 to 400 F	500 to 800 F	214 F	250 to 660 F
Residence time	Medium	Medium		Short (2.5 min avg)

Hammer Milling

Additional comminution may be required for some thermochemical conversion processes, such as pyrolysis. Grinders, chippers, or shredders serve as the first line of size reduction for woody material. Hammer mills are used primarily as a second stage of grinding woody biomass. Hammer mills are employed to further reduce the woody biomass to the desired particle size by means of either fixed or swinging hammer designs, like those shown in Figure 2-75. Several domestic manufactures of hammer mills build mills in a variety of sizes including the Bliss Eliminator (ranges from 5 to 600 hp), Schutte hammer mills (range from 50 to 400 hp), and CPM Roskamp Champion (up to 500 hp).

Figure 2-75. Swinging type hammers in an industrial hammer mill.

Hammer mills generally operate at higher rotational speeds (up to 3600 rpm) than typical hogging equipment (800 to 1200 rpm) (CWC 1997). Energy consumption was measured by Esteban and Carrasco (2006) for grinding three woody feedstocks (poplar chips, pine chips, and pine bark). In this study, for the hammer milling process, energy consumption ranged from 1.2 to 1.7 kW h/dry ton for poplar chips, 1.0 to 1.1 kW hr/dry ton for pine chips, and 0.8 to 1.3 kW hr/dry ton for pine bark. The moisture content for the woody biomass was 11.9% for poplar chips, 14.3% for pine chips, and 13.2% for pine bark.

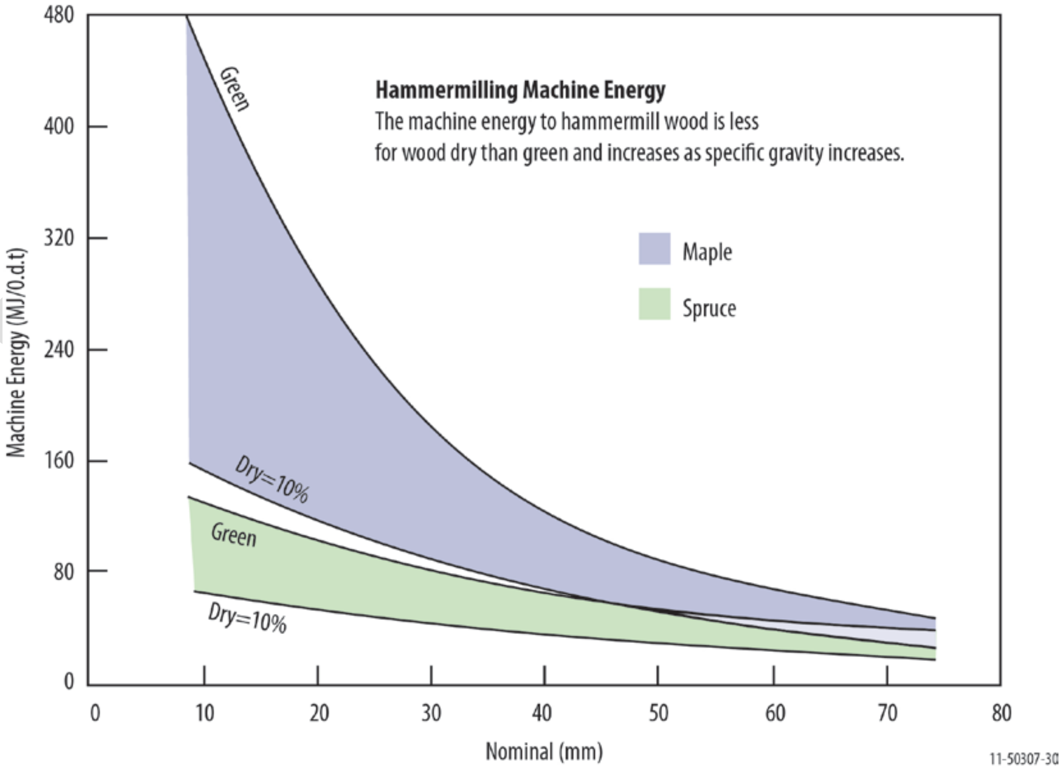

Figure 2-76. Energy consumption during hammer milling of maple and spruce (Recreated with permission from Pottie and Guimier 1985).

Dust Collection

The process of densification (whether it be chopping/grinding, drying, hammer milling, pelletizing, etc.) is energy intensive, and the process generates large amounts of fines that must be captured by the system. When part of a preprocessing operation, pneumatic conveyance systems are often used at the point of hammer milling and beyond to convey the milled material through the drying process, if necessary, and to the point of pelletizing or briquetting. The typical pneumatic system is composed of a cyclone, blower, and bag house to convey and collect the dust throughout the process. Hammer milling and pelletization are not part of the Conventional design.

Dry matter Losses

Dry matter losses during these operations are considered negligible.

Operational Window

The refinery operates 24 hours per day, 7 days per week.

2.2.6.3 Low-Ash/Low-Moisture Conventional In-Plant Handling Cost Analysis

Cost Summary

A breakdown of the costs associated with each piece of equipment used in the In-Plant Handling operation identifies significant cost components that are valuable for making individual comparisons and identifying areas of research potential (Table 2-53). These costs are reported in terms of DM tons entering each process.

Table 2-53. Static model costs for major In-Plant Handling equipment in the Low-Ash/Low-Moisture Conventional design. Costs are expressed in 2010 $/DM ton. Total operation cost is the sum of ownership, operating, and DM loss cost.

Equipment	Drying/Moisture Management	Even flow	Total Cost per DM ton for In-Plant Handling
Quantity of Equipment (# of machines)	3	2	
Installed Capital	5.19	0.41	5.60
Ownership Costs	*3.65*	*0.06*	*4.71*
Operating Costs	*0.61*	*0.01*	*0.62*
Labor	0.61	0	0.61
Non-Labor	0	0.01	0.01
Dry matter loss Costs	*0*	*0*	*0*
Energy Use (Mbtu/DM ton)	10.92	1.02	11.94

From Table 2-53, the total In-Plant Handling cost for pulpwood sized trees is $4.32/DM ton, which is the sum of ownership, operating, and dry matter loss costs. The dryer has a very low operating cost, as the heat source used is waste from the conversion process. This significantly reduces energy consumption in this operation.

Sensitivity Analysis

To perform sensitivity analysis, we selected multiple variables of interest and assigned ranges to them, which followed a triangular distribution. A symmetric distribution was applied where appropriate, i.e., when it was the best approximation of an actual distribution. Powersim was then set to output costs per dry matter ton to Excel. The Monte Carlo method was used, using the Risk Analysis Clone capability in Powersim. Excel was used to generate the histograms, the range of each analysis was divided into thirty "bins," and the frequency function was used to count the number of occurrences between two bin points.

The histogram generated for the In-Plant Handling operation is shown in Figure 2-77.

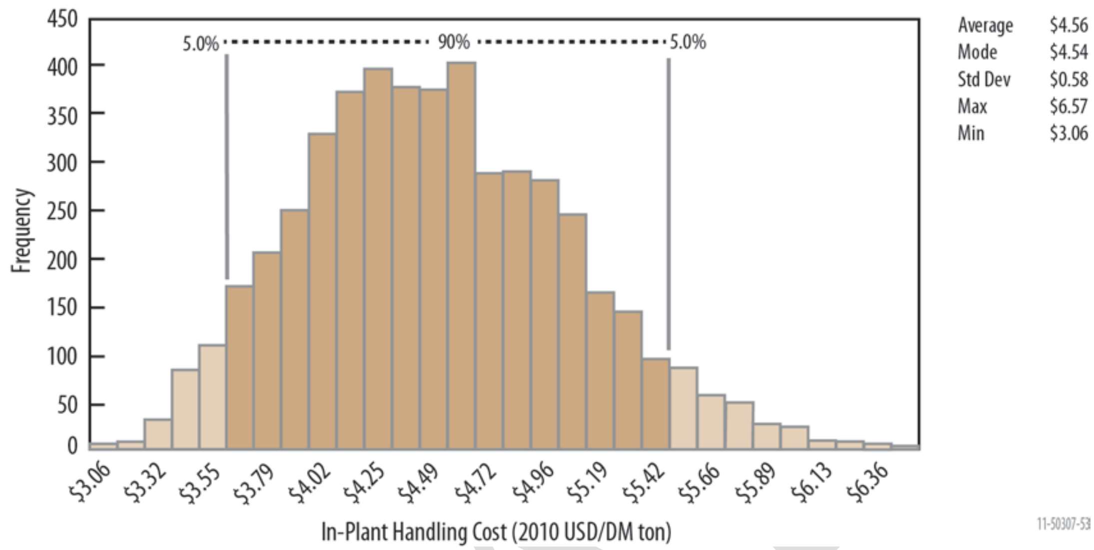

Figure 2-77. Low-Ash/Low-Moisture Conventional woody biomass supply chain cost distribution histogram for the In-Plant Handling operation for pulpwood. Costs are expressed in 2010 $/DM ton.

The histogram is not a smooth bell curve, as there are "jumps" wherever a piece of equipment has reached maximum capacity and another piece of equipment is needed. Also, the histogram is not in the shape of a typical normal distribution. From Figure xxx, the average cost for the In-Plant Handling operation is $4.56 ± 0.58/DM ton, so the static model cost of $4.32/DM ton is within this range. In the Low-Ash/Low-Moisture Conventional woody biomass supply chain it is assumed that 100% of the drying energy comes from waste heat during the In-Plant Handling operation. The histogram shows that the In-Plant Handling unit operation ranges between a minimum of $3.06/DM ton and $6.57/DM ton. The most frequently occurring value is $4.54/DM ton.

2.2.7 Summary of Costs for the Low-Ash/Low-Moisture Conventional Feedstock Supply System

The determination of unit operation costs are described in previous sections, and are summarized in Table 2-54.

Table 2-54. Summary of supply system costs for the Low-Ash/Low-Moisture Conventional Woody biomass scenario. Costs are presented in 2010 dollars per DM ton. Total operation cost is the sum of ownership, operating, and DM loss cost.

	Harvest &Collection	Prepro-cessing	Transportation	Receivin g and Handling	Storage	In-Plant Receiving	***Total***
Installed Capital	21.99	21.88	8.16	7.16	0.35	5.60	*65.14*
Ownership Costs	7.33	2.06	1.11	1.10	0.17	3.71	*15.47*
Operating Costs	12.10	10.60	8.17	1.39	0.80	0.61	*34.32*
Dry matter loss Costs	—	—	0	0	0.86	0	*0.86*
Energy Use (Mbtu/DM ton)	158.76	222.51	129.05	15.62	13.08	11.94	*580.6 6*
Total Logistics Cost[a]	***19.43***	***12.66***	***9.28***	***2.49***	***1.83***	***4.32***	***50.01***

[a]Sum of operating, ownership and dry matter loss cost.

The total supply system cost for the Conventional woody design is $50.01/DM ton in 2010 USD, assuming southern pine pulpwood is used as a feedstock. The majority of this cost comes from operating costs, which include labor, materials, and fuel costs. These costs can be reduced by increasing machine utilization, therein increasing throughput, as well as by increasing efficiency during operation, and matching capacity of the machine appropriately to the operation. Although Harvest and Collection have the highest operating cost per ton, Preprocessing, Transportation, and Receiving and Handling also have high operating costs. Ownership costs also comprise a significant portion of the total system costs, which is where capital depreciation comes in. This cost can in some cases be reduced by increasing machine utilization, as well as by designing equipment more appropriately priced for its task. Preprocessing has the highest ownership cost, due to the high equipment purchase cost and the somewhat low productive time of the equipment due to the nature of the operation. The final component of total system cost is dry matter losses. Although accounting methods result in no dry matter losses until after the chipper, some material is lost through mechanical losses and biological degradation during storage.

Three operations have very high energy use, which is a reflection of their high fuel consumption: Harvest and Collection, Preprocessing, and Transportation. Combined, these operations comprise over 90% of supply system energy consumption.

Sensitivity Analysis

To perform sensitivity analysis, we selected multiple variables of interest and assigned ranges to them, which followed a triangular distribution. A symmetric distribution was applied where appropriate, i.e., when it was the best approximation of an actual distribution. Powersim was then set to output costs per dry matter ton to Excel. The Monte Carlo method was used, using the Risk Analysis Clone capability in Powersim. Excel was used to generate the histograms, the range of each analysis was divided into thirty “bins,” and the frequency function was used to count the number of occurrences between two bin points.

For the first histogram, we varied all of the parameters as varied for the individual unit operations (Figure 2-78).

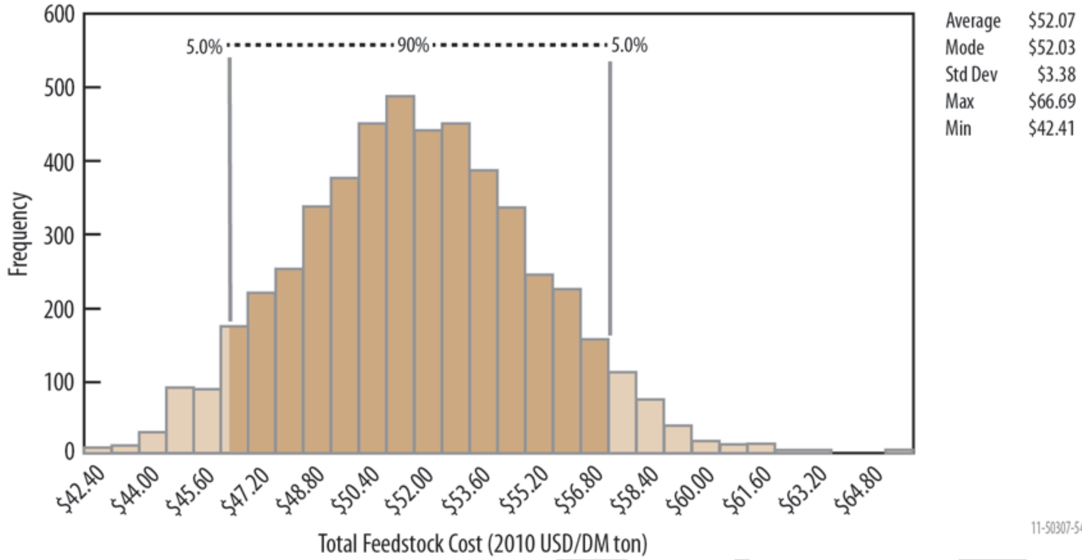

Figure 2-78. Low-Ash/Low-Moisture Conventional woody biomass supply chain cost distribution histogram for pulpwood. Costs are expressed in 2010 $/DM ton.

Looking at Figure 2-79, the histogram has a fairly even, normal distribution, with an average total logistics cost of $52.07 ± 3.38/DM ton. The histogram for total supply chain logistics cost shows that cost ranges between a minimum of $42.41/DM ton and a maximum of $66.69/DM ton, and the static value of $50.01/DM ton falls within this range.

The costs for the Low-Ash/Low-Moisture scenario were converted from 2010 USD into 2007 USD to ensure that the design can meet the DOE cost target of $46.73/DM ton (Figure 2-79).

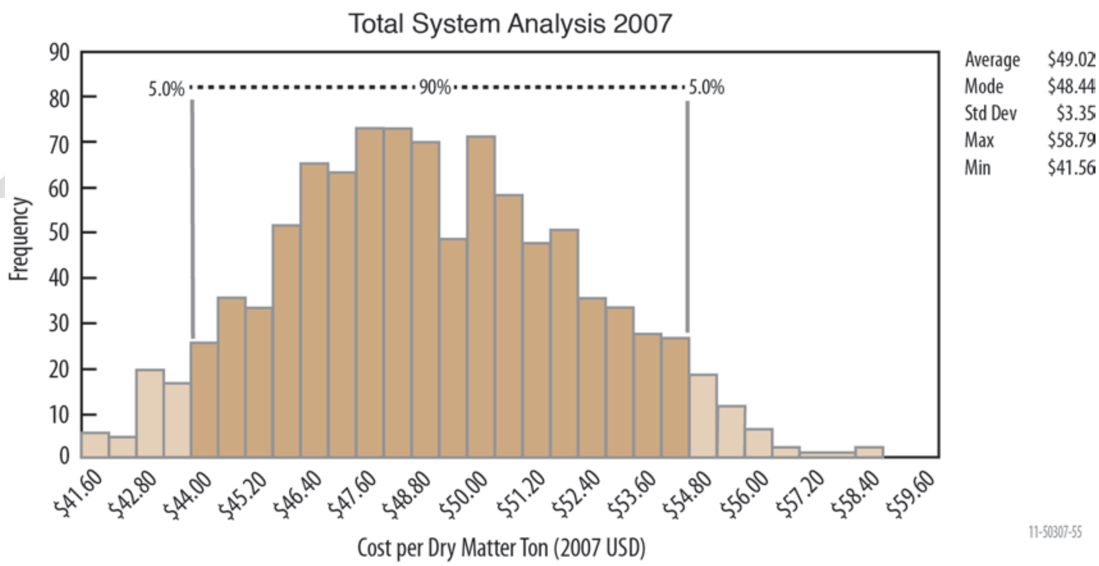

Figure 2-79. Low-Ash/Low-Moisture Conventional woody biomass supply chain cost distribution histogram for pulpwood. For this run, the range of dryer energy that comes from natural gas is not considered a variable, and all of the energy for drying is considered to be from waste heat (i.e., the design scenario). Costs are expressed in 2010 $/DM ton.

The histogram is fairly a smooth bell curve. From Figure 2-79, looking at the total supply chain costs , the average cost is $49.20 ± 3.35/DM ton, so the static model cost for the Low-Ash/Low-Moisture Conventional woody biomass supply chain of $46.37/DM ton fits within this range. The histogram shows that the total supply chain logistics range between a minimum value of $41.56 and a maximum value of $58.79/DM ton. The mode value of this cost range is $48.44/DM ton.

The Low-Ash/Low-Moisture Conventional woody biomass supply chain design presented herein can meet the DOE cost target of $46.37/DM ton while also meeting the material specifications required for gasification (Phillips et al. 2007). However, the design assumes the availability of a niche resource of southern pine pulpwood, which is not available in sufficient quantity to meet long term production goals. To incorporate the resources necessary to meet production goals, Advanced feedstock supply system designs are required (see Section1.1).

Ranking of Input Parameters

A single-point sensitivity analysis is a straight forward analysis to represent variations of a single variable, and was conducted on the Low-Ash/Low-Moisture Conventional woody biomass feedstock supply system design to identify and rank all input factors that affect the delivered feedstock cost. The analysis is the first step of the sensitivity analysis for the purpose of input variable selection and preliminary variable assessment, and it is performed by uniformly varying each identified variable by ±10% of the base value. The results of this analysis provided a ranking of input parameters according to the magnitude of their influence on the delivered feedstock cost. Based on the ranking of input variables, resulting from the single-point sensitivity analysis, we then defined each parameter's uncertainty using a probability distribution (Table 2-55).

Table 2-55. Range of variables for the tornado diagram and spider diagram. Costs are in 2007 USD.

Process	Variable	Units	Range		SET
Top Level					
	Natural Gas Cost	$/MMBTU	6.35	14.83	10
	Electricity Cost	$/kWh	0.0378	0.1173	0.06
	Diesel Cost	$/gallon	2.94	3.31	3.07
	Nat Gas (W/DRYER)	$/MMBTU	6.35	14.83	10
Harvest & Collection		TOTAL: 17.06			
	diesel cost				
	skidder distance	miles	0.1	0.45	0.3
	harvest labor	$/hr	-25%	25%	11.82
	collection labor	$/hr	-25%	25%	11.82
	feller eff	%	50	80	60
	skidder eff	%	50	80	60
Preprocessing 1		TOTAL: 11.33			
	preproc labor				
	diesel cost	$/gallon			
	chipper eff	%	50	80	75
	chipper moist in	%	25	50	30
	chipper capacity	tons/hr	42.5	57.5	50

Process	Variable	Units	Range		SET
Preprocessing 2		Total: 4.25			
	nat gas cost				
	% nat gas use	%			
	dryer moist in	%	20	50	30
	dryer eff	%	80	120	100
	dryer cap	tons/hr	37.5	62.5	50
	Preproc Labor	$/hr	-25%	25%	14.25
Transport		TOTAL: 8.44			
	diesel cost				
	load time	minutes	25.5	120	30
	DM loss	%	0	1	0
	transit Labor	$/hr	-25%	25%	17.48
	semi speed	mi/hr	42.5	57.5	50
	MC transit	%	20	50	30
	transit distance	miles	10	90	50
Storage		TOTAL: 2.34			
	diesel cost	$/gallon			
	Storage labor	$/hr	25%	25%	14.2
	loader capacity (S)	tons/hr	60	120	80
	DM loss	%	0	4	2
Handling and Queuing		TOTAL: 2.96			
	diesel cost				
	tipper capacity	tons/hr	82.2	111.2	96.7
	H&Q labor	$/hour	25%	25%	14.2
	loader capacity (H&Q)	tons/hr	60	120	80
	DM loss	%	0	0.5	0

The probability distribution represents either the inherent variability or the uncertainty of the input variables, as determined by the variability in collected field data, published data, consultations with expert reviewers. All inputs were validated through personal communication with industry experts. The most likely value included in each distribution is the benchmark value input to the feedstock model. The results of this analysis are represented in a tornado diagram in Figure 2-80, and provide a ranking of input parameters according to their magnitude of influence on the delivered feedstock cost.

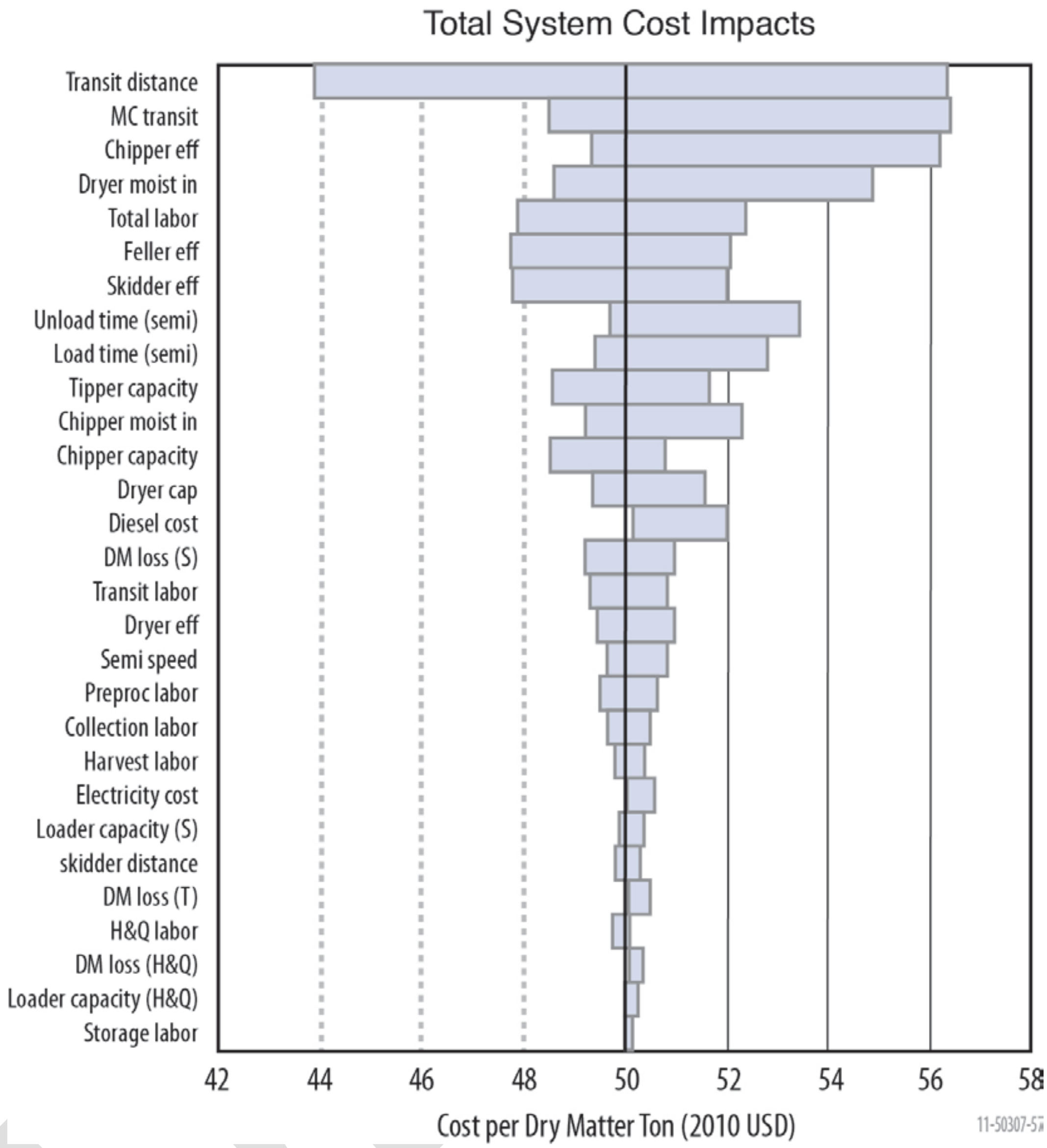

Figure 2-80. Tornado chart reflecting the final cost in dollars according to the distribution ranges defined for the Low-Ash/Low-Moisture Conventional woody biomass feedstock supply system. Costs are expressed in 2010 $/DM ton. Operations are abbreviated by S (Storage), H&Q (Handling and Queuing), and T (Transportation), where applicable.

The results in Figure 2-80 indicate that the parameter of highest influence include transportation distance, moisture content during transit, chipper efficiency, and moisture content of the material that is being input into the dryer. Other parameters significant to the cost include total labor, effeller efficiency, and skidder efficiency. Parameters of less influence include factors relating to lower cost operations including storage labor, and loader capacity and labor cost during Handling and Queuing. The range of potential transport distances assumed in the analysis was quite high, from 10 to 90 miles, and the range of potential moisture content during transport was also high, from 20% to 50%. These high ranges are reflected in the histogram. Other operations, such as collection and feller efficiency, are expensive operations, however there is less potential variability in these numbers. For example, it is impossible to have efficiencies for either of these parameters in excess of 90% (although a reasonable maximum was assumed to be 80%), and anywhere below, say, 40%, the equipment would likely not be used at all. Harvest window has a low impact, as the window is already very large (50 weeks per year).

The analyses also included a ranking of input parameters based on the statistical relationship between each parameter and the delivered feedstock cost. The most influential parameters from this ranking were further analyzed to produce the correlations shown in Figure 2-81, which represents the response of feedstock cost changes to these top parameters. This analysis was conducted by incrementing each parameter throughout the defined distribution (Table 2-55) while randomly varying the remaining parameters according to their own defined probability distributions. Thus, the impact of each parameter is determined individually, while also capturing the interdependence of the input parameters. This graph illustrates some interesting relationships (Figure 2-81). First, the slope of the response curve represents the statistical correlation (sensitivity) between the delivered feedstock cost and the input parameter. Second, the length (delta-X) of the response curve represents the magnitude of the variability or uncertainty (represented as the percentage change from the base value). Third, the delta-Y of the response curve represents the magnitude of the impact of the parameter on the delivered feedstock cost. Finally, the non-linearity of the response curve represents the interdependence of the input parameters, where more curvature of the response curve suggests broader interdependence.

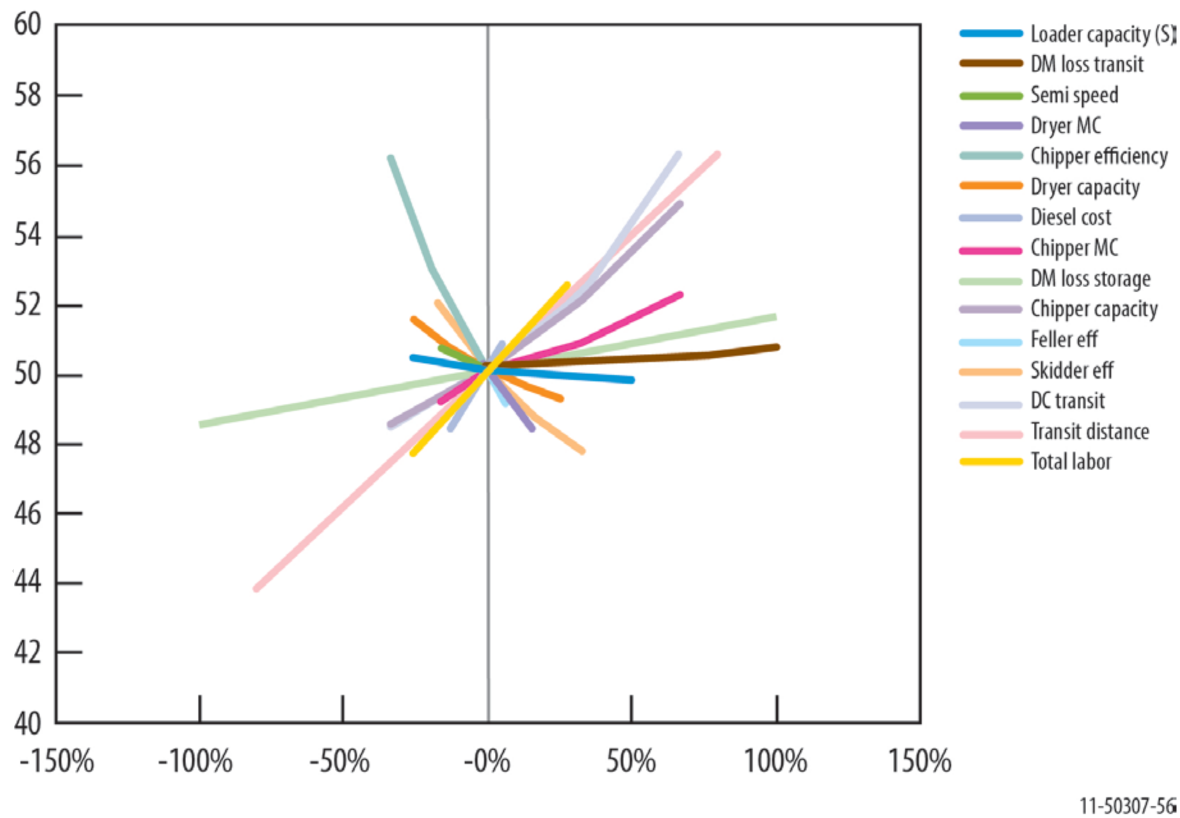

Figure 2-81. Relative impact of various parameters on the cost of supplying biomass though the Low-Ash/Low-Moisture Conventional woody biomass feedstock supply system.

The parameters of strongest correlation (sensitivity) between the cost of that parameter and the total feedstock cost include the amount of waste energy used for drying the feedstock inside the plant gate, as well as chipper efficiency and diesel cost. The parameters with the highest magnitude of variability or uncertainty include transportation distance, dry matter loss, and moisture content during transport. The height of the lines reflect the impact of the parameter on the delivered feedstock cost, and therefore the parameters with the highest impact include the amount of waste energy used for drying the feedstock inside the plant gate and collection efficiency. Finally, the most curved lines are those that have the highest level of interdependence, and include diesel cost and feller efficiency.

2.3 The Conversion Interface

Different conversion processes have different in-feed requirements. In general, thermochemical conversion processes are more efficient with a low moisture feedstock having small, consistent particle size. Another key parameter is ash content- high levels of ash may damage conversion equipment and lower conversion yields. The modeled conversion process for the Low-Ash/Low-Moisture Conventional scenario is gasification, and a brief explanation follows. For the complete design report for the modeled gasification process, see Phillips et al. 2007. Another example of a conversion process, fast pyrolysis, is also included. Gasification and fast pyrolysis have similar in-feed requirements, the only difference being that pyrolysis requires an additional hammer milling step prior to conversion. For the complete design report for the modeled fast pyrolysis process, see Jones et al. 2009.

2.3.1 Gasification and Feedstock Characteristics

Gasification is the process of using thermal energy to convert any carbon-based substance to synthesis gas (syngas) plus by-products in an oxygen-poor atmosphere. Syngas, a mixture of CO and H_2, can be burned for heat or electricity or can be catalytically converted to liquid fuels such as ethanol or Fischer-Tropsch fuels. Gas-phase by-products of the gasification process include water, CO_2, light hydrocarbons (such as CH_4, C_2H_4, C_2H_6, etc), heavier hydrocarbons or “tars”, and volatile sulfur and inorganic species, all of which must be removed from the gas stream for liquid fuel production. Removal of the hydrocarbon species generally involves catalytic reforming. Inorganic species (also known as ash) in the raw biomass feedstock can cause processing problems with downstream catalysts; often they are catalyst poisons such as hydrogen sulfide (H_2S) and ammonia (NH_3), which can volatilize at the high temperatures of gasification and enter the gas stream.

With the end in mind to minimize methane, light hydrocarbons, tars, and inorganic species in the syngas, the characteristics of the raw feedstock play a role in determining the quality of the raw syngas, that is, before any clean-up steps occur. Lowering unwanted products in the raw syngas reduces load on or the need for downstream clean-up operations, such as sulfur removal and tar and methane reforming. On one hand, gasification is often touted as being feedstock-flexible since syngas and hydrocarbon products from different feedstocks are similar at high gasification temperatures (greater than 800°C). On the other hand, physical properties such as inorganic content (ash), moisture, and particle size can vary widely depending on the feedstock itself, how it is harvested, how it is stored, and how it is prepared before the gasification step.

Several gasification studies have been conducted as part of the Thermochemical Conversion Platform of the Office of Biomass Program with regard to the effects of feedstock on gasification performance. Three comprehensive and relevant studies have been conducted at the National Renewable Energy Laboratory (NREL) over the past several years, which specifically study syngas production from different feedstocks, as well as the production of unwanted species (for liquid fuels production) such as methane, light hydrocarbons, and tars. A parametric study using four different feedstocks at several gasification temperatures was conducted on the pilot-scale gasifier, the results of which are thoroughly discussed in two journal articles (Carpenter et al. 2010; Jablonski et al. 2009). Another study at NREL in a new four-inch diameter gasifier focused on gas and tar production from larger (6 to 25 mm) particles of woody biomass at different temperatures (a journal article on this work is currently pending acceptance for final publication). A third study at NREL measured gas and tar production in the same four-inch gasifier of two, small particle-size fractions for seven different feedstocks, both woody and herbaceous (Gaston et al. 2010).

Carpenter et al. found that the low-sulfur feedstocks in the study produced raw syngas with significantly lower concentrations of H_2S (Carpenter et al. 2010), which are less taxing on downstream processing catalysts. They also concluded that light gas concentrations for the four different feedstocks converged at higher temperatures, indicating feedstock flexibility in terms of light gases. In a multivariate statistical analysis of the tar results from the same study, Jablonski et al. (2009) found that quantities and types of tar species converged at high temperatures, which also supports the feedstock-flexible notion. In these experiments, all feedstocks had very similar physical properties in terms of particle size and moisture content.

In the 4-in. gasifier study of four sizes of oak spheres, Gaston et al. found that larger particle sizes tends to yield more tar and char than smaller particles due to heat and mass transfer limitations within the particle. The larger particles saw slower heating rates, which produced more char, and more bi-molecular secondary reactions, which produced more tar (Gaston et al. 2011).

Lastly, there is evidence that higher moisture content in raw feedstock can lead to more tar formation, since more thermal energy in the gasifier is used to evaporate the water (Stevens 2001). Figure 2-82 summarizes what we have learned about the effects of different feedstock characteristics on the composition of the raw synthesis gas thus far. More studies to determine the effects of moisture content on light gas, tar, and char formation will be conducted at NREL in the coming year.

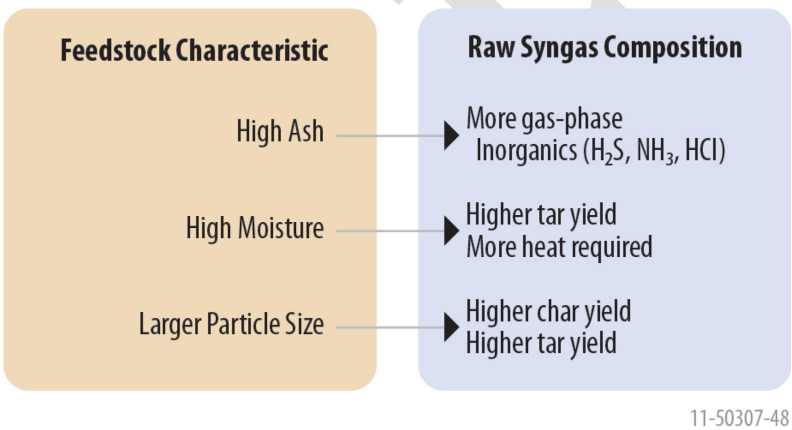

Figure 2-82. Effects of feedstock characteristic on resulting synthesis gas composition out of the gasifier.

2.3.2 Fast Pyrolysis Overview

Pyrolysis is the thermal decomposition of carbonaceous material in the absence of oxygen to produce char, gas, and a liquid product rich in oxygenated hydrocarbons. In general, pyrolysis is performed using a range of temperatures and residence times to optimize the desired product. Figure 2-83 illustrates the approximate yields from different modes of pyrolysis (Bridgwater 2007).

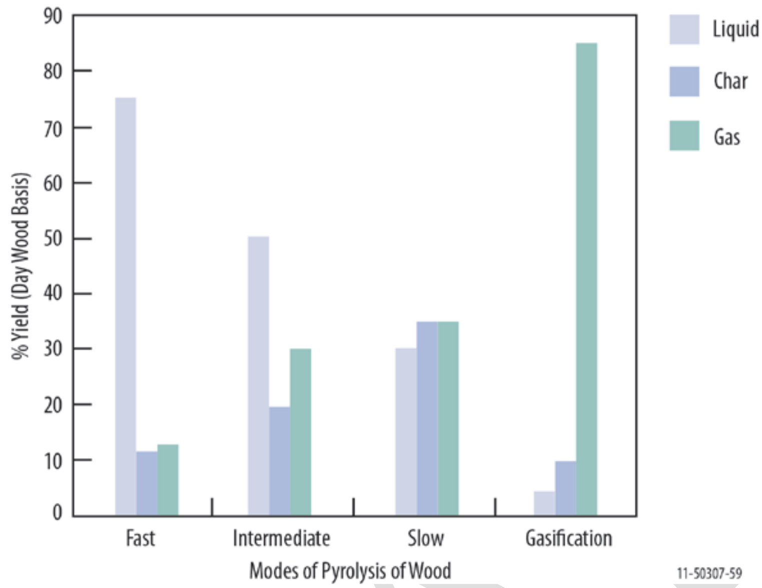

Figure 2-83. Different pyrolysis conversion technologies result in different liquid yield. Fast pyrolysis has a relatively high liquids yield and a low char yield, which is desirable for biofuels production.

Typically in fast pyrolysis, biomass is heated to approximately 500°C in less than 1 second, and then rapidly cooled to stop the reaction. The liquid product, known as bio-oil, is obtained in yields up to 70-80% by weight on a dry feed basis. The bio-oil typically contains 15 to 30% water that cannot be removed by distillation. The oil has a heating value similar to biomass (Oasmaa 2009). The oil can be upgraded by hydrotreating to lower the oxygen content, improve stability and produce a hydrocarbon type fuel. Bio-oil and upgraded oil can be used in applications ranging from value-added chemicals to transportation fuels. An example flowsheet for a circulating fluid bed system is shown in Figure 2-84.

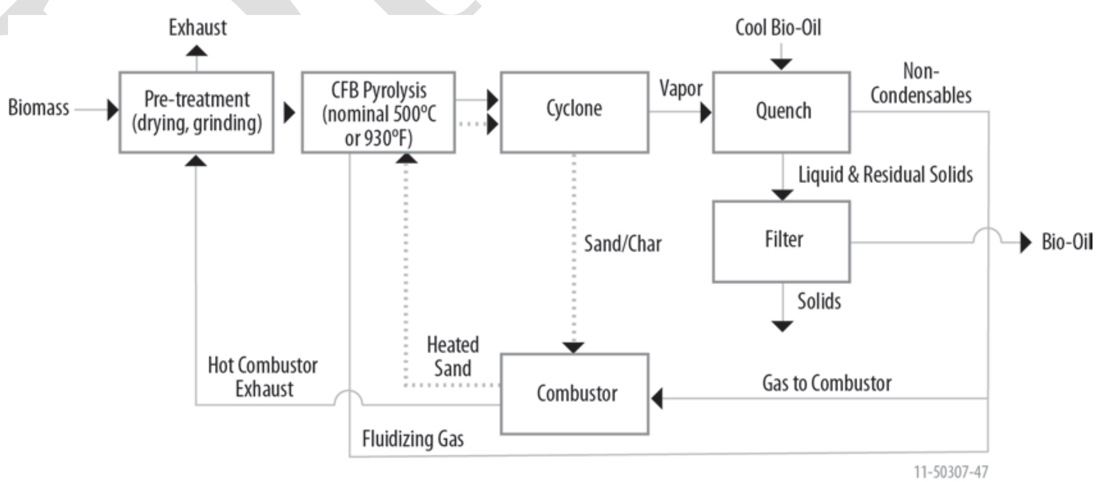

Figure 2-84. An example flowsheet for a circulating fluid bed system for fast pyrolysis.

Feedstock Characteristics for Fast Pyrolysis Systems

Ash content, particle size and moisture level all have important effects on pyrolysis operations and economics.

Ash content affects bio-oil yield as higher ash implies lower organic content in the feed. Inorganic compounds which constitute ash are known to catalyze biomass decomposition and char formation reactions (Agblevor 1994). Solids are separated from the bio-oil by cyclones, where some of the char (which contains the ash) carries over into the liquid and is one of the causes of bio-oil instability upon storage. It may also affect the amount of particulates in the resultant bio-oil which can impact downstream processes such as hydrotreating reactor catalyst life.

Particle size is important as it affects heat transfer in the pyrolysis reactor and liquid yields. The required size is a function of the reactor type. Bubbling and circulating fluidized bed reactors require finely ground material ranging from 2-6 mm. Unconverted biomass solids end up as char or in the bio-oil. Char in the bio-oil has been shown to be a source of instability which causes reactions and phase separation in storage. Filtering reduces bio-oil activity and removes particulates that can plug downstream fixed bed hydrotreaters. Small scale reactors such as ablative and rotating cone reactors can handle larger particle sizes and do not need fluidizing gas. However these reactors do not scale as economically as fluidized beds. Ablative reactors use mechanical pressure to press biomass against a heated reactor wall, causing the biomass in contact with the wall to “melt” and the resultant oil evaporates as pyrolysis vapors. Rotating cone reactors combine biomass and hot sand that are mixed by a rotating cone inside the reactor vessel. Hot pyrolysis oil vapors leave near the bottom of the reactor, while hot sand and char exit the reactor from the bottom of the cone (Bridgewater 2007).

The water in the bio-oil comes from the pyrolysis reaction and from moisture in the feedstock. High feedstock moisture levels can cause liquid phase separation in the bio-oil and increases the heat input requirement to the reactor and the feedstock heating rate may be reduced resulting in a decreased oil yield. On the other hand, higher moisture content left in the feedstock reduces the dryer load. Heat for feed drying can be achieved by using heat from the char combustor or by burning the pyrolysis offgas (Oasmaa 2009).

2.4 Conventional Supply System Summary and Conclusions

The scope of Conventional feedstock supply systems is restricted to currently available technologies and existing infrastructure, regardless of the geographical region in which the biorefinery operates. An important consideration when designing a biomass feedstock supply system is the quality of material that is delivered to the biorefinery. In this design report, two conventional scenarios are presented: the Base Case Conventional scenario and the Low-Ash/Low-Moisture Conventional feedstock supply system. In the Base Case Conventional scenario, no material specification is met. Whole trees are felled, skidded to the landing, where the whole tree is chipped and sent to the biorefinery for storage and eventual conversion. Assuming a southern pine tree as a feedstock, the model revealed a total delivered cost of $53.40/DM ton for the Base Case Conventional system.

In the second design scenario, the Low-Ash/Low-Moisture Conventional feedstock supply system, woody biomass is delivered to the in-feed of the conversion reactor at a specific moisture (10% (wb)), ash content (<1%), and particle size (2 in.). This is a very important characteristic of the system, as conversion efficiencies rely on feedstock that consistently meets their in-feed requirements. For the Low-Ash/Low-Moisture Conventional scenario, a gasification modeled by the National Renewable Energy Laboratory is used to determine the required material spec (Phillips et al. 2007). As an additional constraint, the Low-Ash/Low-Moisture scenario design must meet the DOE cost target of $46.37/DM ton (2007 USD), to meet biofuels production chain cost targets. This was achieved in the Low-Ash/Low-Moisture design by transpirationally drying southern pine trees prior to skidding to the landing, where the trees were delimbed and debarked prior to transport to the biorefinery. At the biorefinery, the material is stored prior to additional drying to bring the material to the required spec. The Low-Ash/Low-Moisture design was subjected to a sensitivity analysis to identify parameters of highest influence on cost, and to see the range of variability in the potential supply system costs for this feedstock.

The Low-Ash/Low-Moisture design meets short term DOE biofuels production goals in terms of quantity, however it relies on a niche resource of southern pine pulpwood. To meet longer term goals, more feedstock will need to be incorporated into designs. This expansion is addressed in the Advanced Uniform Feedstock supply system.

3. ADVANCED UNIFORM-FORMAT FEEDSTOCK SUPPLY SYSTEM

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.

3.1 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. Therefore, conventional biomass supply systems are incapable of meeting these quantity goals required to meet long-term biofuels production goals. Increasing the 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 3-1 shows a schematic of the end-state commodity supply system for all types of lignocellulosic biomass resources.

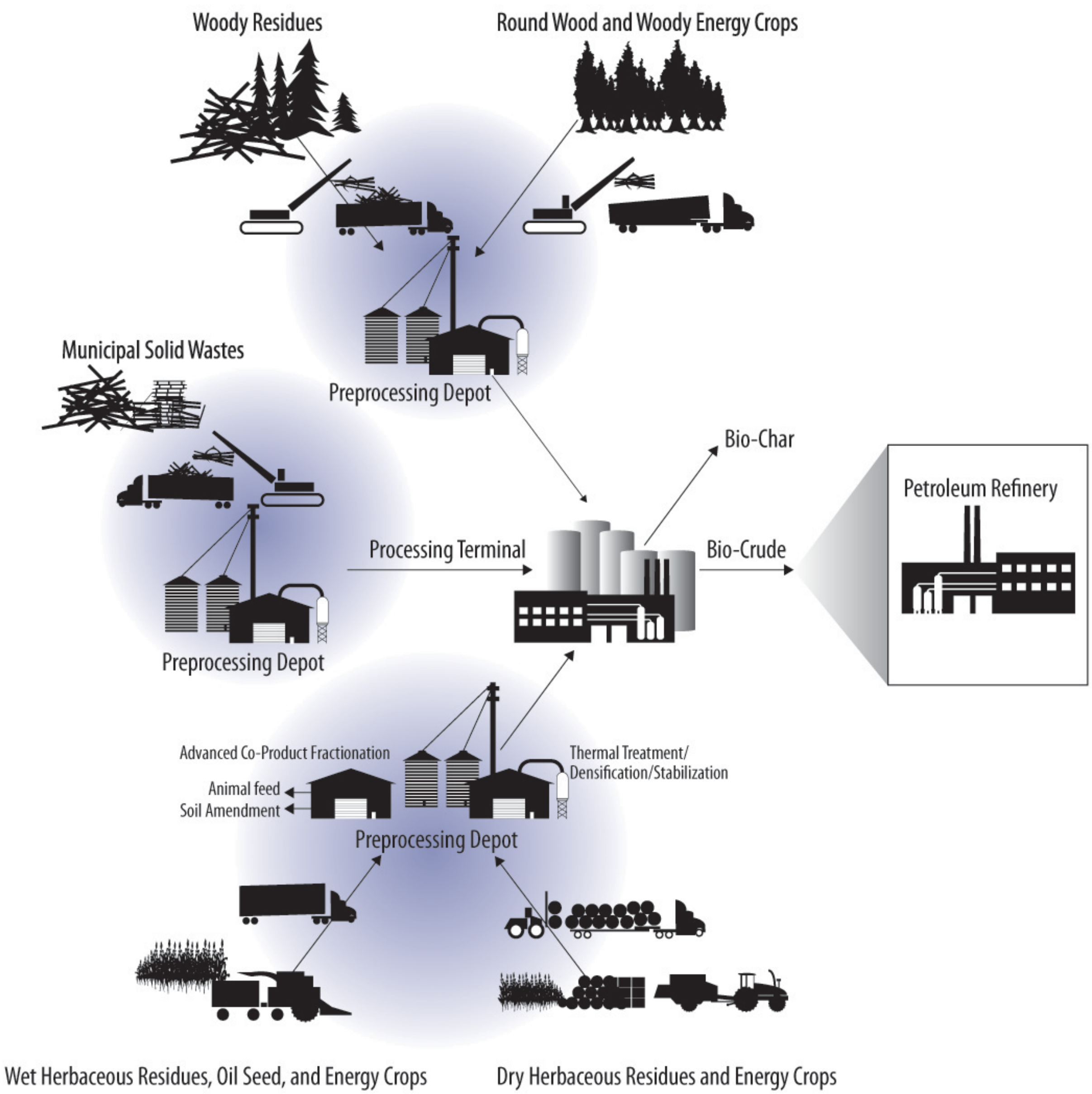

Figure 3-1. The Advanced Uniform-Format feedstock supply system resembles the grain commodity system, which manages crop diversity at the point of harvest and/or the storage elevator, allowing subsequent supply system infrastructure to be similar for all biomass resources.

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 woodchips are flowable, they cannot be handled in existing high-capacity petroleum infrastructure. Also, the existing pulpwood industry moves woody biomass that is not aerobically stable.

3.2 Advanced Uniform Design Performance Targets

The key feature of the Advanced Uniform Design is placing preprocessing operations early in the supply system. Preprocessing depots are central to producing a uniform material that is compatible with the high-capacity handling infrastructure. Figure 3-2 summarizes the Advanced Uniform Design concept.

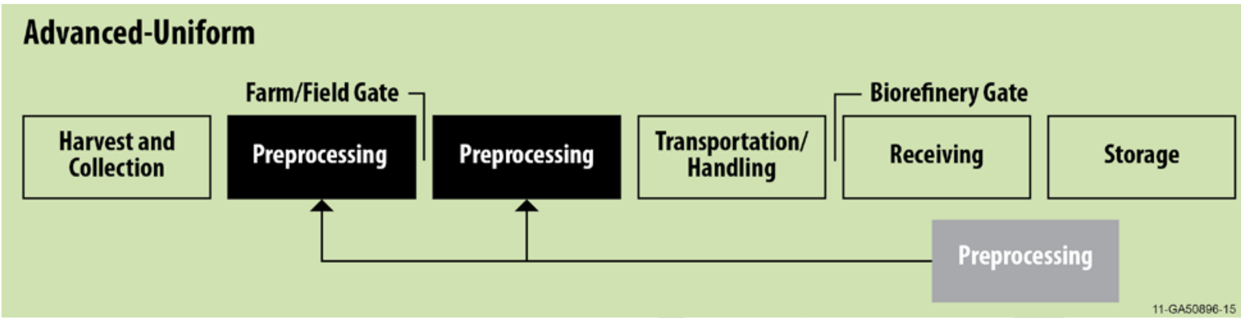

Figure 3-2. The Advanced Uniform Design concept. Advanced preprocessing technologies are incorporated into the harvest/collection and depot operations to make the biomass compatible with existing bulk solid storage, transportation, and handling infrastructures and technologies.

There are six fundamental barriers to implementing these advanced preprocessing concepts. The first three are associated with the physical properties of the biomass:

- Material deconstruction – The feedstock's resistance to deconstruction and drying must be overcome in order to more easily change physical format to progressive/final forms with improved flowability characteristics
- Density – The feedstock's bulk density and energy density must be increased for more efficient handling and transportation
- Moisture – To produce an aerobically stable material, moisture must be removed and managed.
- The last three challenges are related to the supply system equipment:
- Capacity and operational efficiency – Includes overcoming capital and energy costs associated with doing a prescribed amount of work
- Dry matter losses – Includes dust collection/control, field losses, and biological losses
- Operational window – Operations become constrained by harvest windows and other logistic constraints as they move forward in the supply system.

Full implementation of the Advanced Uniform Design overcomes all of these barriers for all biomass resources, regardless of moisture content.

3.3 The Advanced Uniform Supply System Vision

The Advanced Uniform design vision employs preprocessing technology to remedy the density and stability issues that prevent lignocellulosic biomass from being handled in high-efficiency bulk dry solid or liquid logistic systems, which allows the resource to be marketed not only as a local bought-and-sold product but also as an industrial-scale commodity. This design incorporates long-distance transportation (200+ miles), bulk-flowable handling, and feedstock blending to achieve standardized feedstock compositional targets and other properties beneficial to the conversion process. All biomass will be preprocessed into one flowable, aerobically stable format: either a high-density dry solid product (i.e., flour, granules, select pellet concepts) or a high-density liquid product (i.e., pyrolysis oil). Preliminary analytical models indicate that while the Advanced Uniform system can achieve material property targets using existing or near-term equipment, it cannot meet cost targets without incorporating future technologies. The full Advanced Uniform system design case study, to be presented in a later report, will include both liquid and solid format materials as well as existing and future technologies.

High-Efficiency Bulk Solids Handling

Existing grain commodity markets effectively move billions of tons of bulk-solid biomass (corn and cereal grains) around the globe. These products are more naturally formatted for commodity-scale supply system handling infrastructures: particle size is small and fairly uniform, particle density and shape have good flowability characteristics and can be transported cost-effectively, and moisture management is relatively easy and consistent throughout each lot. Similarly, the key to managing biomass resources efficiently at the commodity scale is to preprocess them into a format that shares the same qualities: high dry matter bulk density, good flowability, and aerobic stability. The Advanced Uniform Design vision introduces comprehensive preprocessing that produces lignocellulosic bulk biomass with material properties comparable to those of existing grain commodities. Storage and handling systems for grain are highly replicable, scalable, and optimized for cost-effective performance. These systems are typically constructed and sold as “turnkey” products that are assembled with common interchangeable components to meet each customer’s performance specification. This modular system provides an opportunity for highly efficient and economical implementation.

The equipment used for handling and transporting grain from storage to downstream processes is similarly replicable and interchangeable. Consistent, uniform properties of grain allow trucks and trains to seamlessly move biomass large distances to terminals or destination markets. Another important consequence of grains’ material characteristics is the ability to blend, grade, and efficiently track material throughout trading within the supply system. In the case of corn, distributors employ fast screening methods to test and blend feedstock to stringent specifications of individual biorefineries, while maintaining the integrity of non-genetically modified organism (GMO) food supplies. This is possible by using a uniform-format material with adequate bulk density and flowability performance that allows a common, replicable set of high-capacity bulk-solids handling equipment to be employed throughout the supply system. In the case of lignocellulosic feedstocks, the testing and blending of materials will correspond to biorefinery needs based on characteristics such as sugar, lignin, ash, and energy content. This ability leverages the existing grain commodity markets to provide the basis for the Advanced Uniform system design in terms of material specification and equipment/process design.

On-farm queuing systems, depots or elevators, blending terminals, and biorefineries all work together to create grain commodity markets ranging from the local to the international scale. Commodity markets are highly efficient and effective at connecting the resource to end users within tight specifications. These connections are not limited by distance and, for the case of grain, mitigate local production risks by allowing wider access to resources. The Advanced Uniform design vision establishes material specifications for the corollary of lignocellulosic biomass to existing grain specifications to facilitate commodity-scale markets for this feedstock. Through this specification, efficient and replicable infrastructure and processes can be assembled, connecting resources to biorefineries in a scalable, sustainable way.

3.4 Meeting Targets with the Advanced Uniform Design

Progression to the Uniform-Format system focuses on decreasing the delivered cost of biomass sufficiently to achieve cost targets while increasing supply volume. This will be accomplished by addressing key material property and machine/engineering challenges to increase biomass supply logistics efficiency.

Meeting long-term U.S. DOE biofuels production goals requires the integration of many resources. The diversity of biomass feedstocks, including crop residues, herbaceous energy crops, woody energy crops, and forest resources will be addressed through transition from conventional agriculture and forestry biomass supply systems to advanced systems. Similar to conventional supply systems, the Advanced Uniform system addresses critical logistics challenges, such as efficiency/capacity of equipment, dry matter losses, and the harvest window; however, the Advanced Uniform system also incorporates new considerations such as quality, quantity, stability, and densification. The Advanced Uniform design is a commodity-based, spec-driven system that emphasizes careful engineering of intermediate material formats throughout the supply chain.

3.4.1 National Goals

Both intermediate and long-term DOE biofuel production goals will require biomass supply systems that economically scale beyond the capability of existing systems. Effective scale-up will require feedstocks that use consistent and replicable infrastructure and equipment. Furthermore, the material characteristics of the feedstocks need to allow equipment and infrastructure to operate at their maximum capacity and efficiency. Conventional supply systems do not meet these criteria and can be effectively implemented only at the scale of custom, feedstock-specific supply systems. Only Advanced designs provide the means to overcome material and engineering barriers to economic supply system scale-up. The Advanced Uniform system creates a consistent, uniform material that can exploit existing equipment and infrastructure that has been proven to scale economically. These Advanced Uniform Design characteristics also provide the opportunity to meet cost targets for delivered feedstock price.

3.4.2 Material Properties Barriers

The fundamental material properties that drive supply system performance are moisture content and dry matter bulk density. Moisture content must be low enough for aerobic stability (typically <15–20%) to limit costly material losses within the system. Reduced moisture content has the additional advantage that it often increases downstream performance, such as reduced transportation and handling costs. Another important consideration is that dry matter bulk densities must be greater than 30 lb/ft3 to facilitate efficient transport and storage. Maximizing the load (both weight and volume) not only decreases transportation costs but also reduces the frequency of trucks or trains that arrive at the conversion facility. Decreasing the biomass moisture content directly increases the dry matter density and reduces transportation costs and frequency. Importantly, the Advanced Uniform supply system uses depots to dry the biomass to aerobically stable levels and achieve dry matter bulk densities of 45 lb/ft3.

A final important consideration is biomass deconstruction characteristics. Significant improvements in capacity and efficiency can be achieved by engineering systems to specifically exploit material deconstruction properties and composition. Research at INL studies the impacts of anatomy on the deconstruction behavior of lignocellulosic biomass. Understanding deconstruction material properties is critical to improving equipment performance and may also be applied in fragmentation efforts to separate various components according to their greatest value.

Conventional designs are not capable of taking full advantage of characteristics described above. The Advanced Uniform Design, however, effectively exploits these properties. In an effort to better understand material properties and machine performance, INL has assembled a deployable Process Demonstration Unit (PDU). A list of equipment, specifications, and estimated cost for the baseline (“Pioneer”) configuration is included in Appendix D. The PDU allows observation of a continuous flow of different kinds of biomass through various preprocessing operations. This deployable system greatly improves understanding of preprocessing lignocellulosic materials, and helps to provide information on material properties to modify or design new equipment to meet material targets.

3.4.3 Machine/Engineering Barriers

The key barriers with machines and equipment in the feedstock supply system are associated with efficiency and capacity, cost and energy use, and dry matter losses. Also, for many feedstocks, weather and other constraints leave a short time window available for collecting a majority of the feedstock needed for an entire year's supply. The result of this dynamic is that a large, expensive fleet of equipment is necessary for deployment in a narrow time window. Once the operation is complete, this capital investment is idle. Supply system efficiencies and capacities show steady improvement moving from the Conventional to Advanced Uniform designs. Conventional designs require several custom, application-specific components, which inherently cause inefficiencies. Also, the feedstock formats in Conventional designs are not conducive to maximizing system capacity or throughput. The introduction of biomass depots into Advanced systems moves the system to higher efficiencies and capacities downstream of the preprocessing operation. Higher dry matter bulk density, greater flowability, and a uniform material specification are the contributing factors for these increases. Similarly, the Advanced Uniform Design further increases efficiencies and capacities by advancing these attributes to even more favorable levels. The cost of dry matter loss within the system is directly correlated to the value of the material at the point at which it is lost. Any aggregate loss within the system results in less volume delivered to the biorefinery, but as material moves through the supply system, each operation incurs more cost and energy. One of the key attributes of the Advanced Uniform Design is creating the ability to move the feedstock through proven, standard bulk handling equipment and processes. These systems incorporate dust collection systems to minimize dry matter loss. As such, Advanced systems are capable of total supply chain losses of less than 5%.

Another area that offers room for improvements in cost and efficiency is preprocessing. For example, increasing chipper and grinder efficiency will increase machine throughput and therefore decrease the machine use cost. Finer grinds would reduce the particle size distribution as well. Ongoing research at INL on material deconstruction has increased understanding of how these materials during comminution, and how a variety of pretreatment practices (such as, for example, torrefaction) modify these comminution characteristics.

The deployable PDU also facilitates understanding material properties and machine performance. The PDU allows observation of machine performance in various configurations and with various types of preprocessing operations. Examples of possible preprocessing equipment are retention dryer, pellet mill, hammermill, briquetter, torrefaction unit, and various grinders. This deployable system will greatly improve understanding of the performance of preprocessing equipment using lignocellulosic materials and will provide information to guide the modification and design of new equipment to meet performance targets.

Conventional supply systems address machine performance barriers within the constraint of material properties, including critical logistics challenges such as efficiency/capacity of equipment, dry matter losses, and operational window for gathering material. However, Advanced Uniform systems shift the R&D focus to address material property barriers within the constraint of machine and engineering barriers, building off of improvements gained from Conventional systems and incorporating new considerations such as quality, quantity, stability, and densification. The PDU supports these efforts by providing a controlled environment to study the behavior of many materials under various equipment configurations.

3.4.4 Commodity System Attributes

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. Conventional systems do not produce aerobically stable and flowable materials capable of working with common high-capacity handling equipment that are necessary in regional and national markets. Advanced systems supply a more uniform, flowable material through the implementation of biomass depots, while broadening feedstock accessibility by producing a formatted material that begins to move in common high-capacity handling systems creates new local markets for the feedstock. The Advanced Uniform design meets the requisite material specifications, creating the ability to trade and move material several hundred miles to available markets. Note that the actual commodity employed in the Advanced Uniform system may be either solid or liquid.

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 their 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. The 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 specs in the biomass commodity system is shown in Table 3-1.

Table 3-1. Role of feedstock specifications in a commodity-based biomass system. These specs impact feedstock cost and 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).

3.4.5 Resource Coupling

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 (particularly relevant for herbaceous feedstocks that are harvested annually), (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.

Facilitating diversity in regional cropping options

Particularly relevant for herbaceous feedstocks, expanding regional cropping options requires the supply system to handle diverse material formats, moisture contents, composition, etc. This is attainable only through the Advanced Uniform design, which includes biomass depots that have processes in place to handle the diversity. The benefits of increased cropping options are widely studied, and a few examples include increases soil organic carbon (USDA 2003), increases land productivity (NDSU 1998) by increasing yields (Classen and Kissel 1984), and decreases wind and water erosion when combined with recommended tillage practices (Peterson and Rohweder 1983) and leaving sufficient residue.

Enabling access to remote resources

Biomass distribution in the United States is more concentrated in some regions than in others. An example of such a high-density region is the U.S. Midwest (Figure 3-3), where huge quantities of grains and agricultural residues are produced. Designing biorefineries to depend on local resources strands pockets of high-density production from large areas of dispersed biomass that could greatly increase biomass availability and contribute significantly to national production goals. In fact, relying solely on local resources limits the national biofuels production capability to far below these goals and also promotes construction of smaller-scale facilities that are not optimized for capital economics (Searcy and Flynn 2008). The result of a limited local resource base is that the biorefinery feedstock supply system is much more vulnerable to local weather conditions, diseases, and pests. Figure 3-3 demonstrates how moving to a uniform-format system increases material availability and reliability by expanding the distance over which biomass can be transported economically.

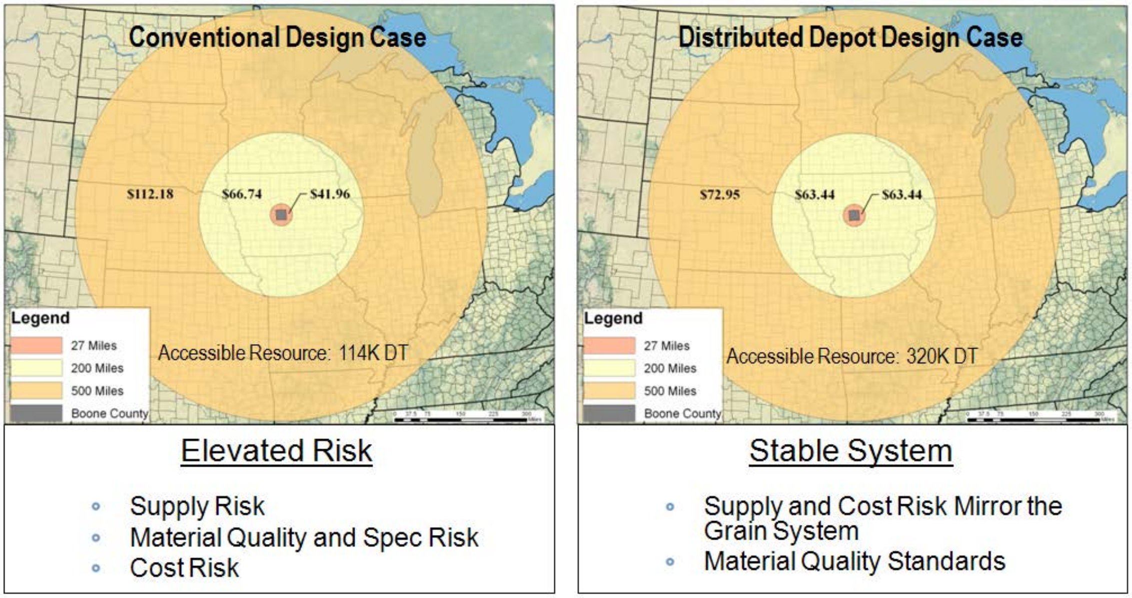

Figure 3-3. Conventional and distributed depot design cases illustrating that the Advanced Uniform Design brings in more resources at a lower cost than Conventional systems (in this case Boone County, Iowa). Transitioning to the Advanced Uniform system increases the distance that biomass can be moved and, unlike Conventional designs, delivers an on-spec material to the biorefinery.

Figure 3-3 is centered on the high corn stover yielding area of Boone County, Iowa. The Conventional scenario (described in Hess et al. 2009) is shown on the left. In this scenario, collecting and delivering baled corn stover from Boone County to a biorefinery located within a 27-mile radius results in a cost of $41.96/DM ton (27 miles approximately marks the county boundary). Relying on another baled corn stover source equal in size to Boone County within a 200-mile radius increases the delivered cost to $66.74/DM ton. Similarly, moving corn stover bales from that county to a biorefinery located 500 miles away increases the cost to $112.18/DM ton. This exercise demonstrates that the baled corn stover (and biomass in general) in that county quickly becomes very expensive and difficult to incorporate into a large biomass supply chain. Under the Conventional system, the 114,000 DM ton/year of material is effectively stranded due to high cost.

Looking at the same county but using the Advanced Uniform system, material is delivered to the biorefinery via a combination of rail and truck in a consistent, dense, uniform format that meets the specification for the modeled conversion process. Collecting the baled corn stover using the Advanced Uniform system from within Boone County for a biorefinery located within Boone county has a higher cost than the Conventional system, $63.44/DM ton. In other words, relying on a local resource to supply a refinery is more cost effective, assuming that one can acquire the material (which, of course, is never the case). This is due to a higher processing cost required to create a stable, flowable material densified to 30 lb/ft3. However, using the Advanced Uniform system, baled corn stover in Boone County can be delivered up to 200 miles at the same delivered cost, and the additional cost to deliver the stover bales as far as 500 miles is less than $10/DM. This is considerably less than the over $70/DM ton incremental amount required to move a bale 500 miles. The reduced transportation cost is a result of having a more dense material, using more efficient transport modes, and achieving higher effective biomass yields. Regarding the latter advantage, the accessible resource in Boone County through the Advanced Uniform system is more than two times what would be available using a Conventional system. Reasons for this increase include an increased operational window as a result of advanced, single-pass harvesting equipment, higher flexibility in material accepted into the system (Conventional systems have much higher material constraints, such as <15% moisture, and are unable to deal with varying material specifications), and climatic restrictions. Importantly, increased biomass availability and more consistent quality greatly reduce the supply risk to biorefineries.

Allowing efficient transport of biomass beyond 200 miles

By formatting the biomass into an aerobically stable, dense material, the Uniform Format system allows for long-distance transport and access to remote resources that cannot be economically accessed in Conventional systems. Long-distance transport also makes higher capacity transport systems, such as rail and ship, more economical per unit distance per ton, and the greater capacity transport systems would decrease truck congestion at large refineries (Searcy et al. 2007). The Advanced Uniform system also formats the feedstock to fit common high-capacity solids handling equipment, which allows the resource to be transported beyond 200 miles.

Addressing supply risks associated with weather, competition, pests, and other local issues

Along with accessing remote resources, the ability to transport the feedstock long distances also mitigates supply risk associated with local issues such as weather, competition, and pests. For example, a 2008 flood (Associated Press 2008) in Iowa ruined the crop on 16% of tillable farmland; surrounding states were impacted as well. In a 1993 flood in the Corn Belt, 9 million acres were submerged (Mattoon 2008). A conversion facility depending exclusively on local resources would be without a feedstock and could therefore not run the plant. As markets become regional and national, local supply shortages can be overcome by compensating with material from farther locations.

3.5 Engineering Approach to Uniform-Format Feedstock Supply System

Current Conventional feedstock supply systems are not capable of supplying the U.S. DOE target of 530 million tons of biomass annually for less than 30% of the biofuel production cost. The proposed Uniform-Format supply system meets the biomass cost, quantity, and quality supply goals. Transitioning from Conventional to an Advanced system, however, presents many challenges, including limitations in existing harvesting and collection equipment and incorporation of biomass depots and blending terminals early in the feedstock supply chain. The transition also imposes many constraints, such as (total delivered) cost targets, machine capacity and efficiency, material losses, and optimization of energy input and machine utilization throughout the operational window. These constraints are the primary drivers of the Conventional system, and they persist in the Advanced Uniform design. Additional considerations in the Advanced Uniform system that are not in the Conventional system include material stability (i.e., shelf life, chemical and biological activity), material specs/quality, and density (bulk, energy).

For maximum supply system efficiency, handling and transportation costs must be minimized by reducing the variety of equipment necessary to move biomass from the field to the biorefinery. Different biomass formats require unique equipment that often cannot be interchanged or used to handle other feedstock formats. Thus, managing feedstock format diversity by increasing feedstock bulk density and flowability (as near to the feedstock production location as is practical) can greatly improve supply logistics efficiency. However, the cost and energy inputs required to reformat biomass and achieve optimum densities and product quality must also be improved.

Supply logistics costs vary substantially between regions and are impacted by weather, biomass species, moisture content, and feedstock types, as well as transportation highway load limits and other regulations. Harvest and storage methods can also change supply logistics costs substantially. It is necessary to manage these inherent complexities and diverse feedstock types to optimize supply logistics and minimize costs in the biofuel production system. However, there exists an industry-wide set of feedstock supply chains; therefore, site-specific logistical solutions are not always preeminent. When considering the development of an entire industry that can be rapidly deployed, a uniform-format feedstock supply system becomes key for both conversion facilities and equipment manufacturers, who require capital assets to be broadly applicable across the industry for optimization on a national scale. Modularized feedstock supply systems, such as the Uniform-Format system, are better suited to handle feedstock diversity than capital-intensive systems located at biorefineries.

Providing a consistent, reliable feedstock to biorefineries is pivotal to creating a sustainable, growing biofuels industry. This can be achieved through a commodity-based biomass feedstock supply system such as the Advanced Uniform-Format system.

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Appendix A

Glossary

Appendix A

Glossary

Bole: The trunk of a tree.

Buck: To cut trees into shorter lengths, such as logs or cordwood.

Cable Skidder: A machine designed to drag cut trees to the yard by attaching cables to the trunks.

Clearcut: The harvest of all the trees in an area.

Commercial treatments: Timber stand improvements, such as thinning, that generate income from the sale of the trees removed.

Coppice: Growth of small stems or suckers from a trunk or roots after the main trunk has been removed.

Coppicing: Pruning trees back to ground level to encourage the regrowth of multiple small stems.

Deck: A pile of logs on a landing.

Delimber: A multifunction machine used to remove limbs from trees and arrange logs in piles on the ground.

Diameter at breast height (dbh): Standard measurement of a tree's diameter, usually taken at 4 1/2 feet above the ground.

Feller Buncher: A self-propelled tracked or tired machine that cuts down (fells) trees and puts them in piles (bunches) without removing the branches.

Felling: The cutting of standing trees.

Fire suppression thinning: Cutting of trees aimed at lowering the volume of wood in a given area to decrease the impact of fire. Usually removes understory and dead wood with few merchandisable trees being cut.

Forwarder: A tracked or tired machine designed to pick up piles of wood that have had the limbs removed and carry them to the road.

Fuel Management: The act or practice of controlling flammability and reducing resistance to control of wildland fuels through mechanical, chemical, biological, or manual means, or by fire (prescribed burns) in support of land management objectives.

Grapple Skidder: A tracked or tired machine designed to drag trees to the road by picking up one end of a pile of trees with a set of pincers (a grapple).

Green Ton: 2,000 lb of woody biomass that has not been dried. Usually ranges from 35% to 55% moisture.

Harvest: The cutting, felling, and gathering of forest timber.

Hog fuel: Comminuted woody material produced from a wood “Hog” or grinder.

Landing: Flat ground where logs are stored prior to transportation; a collection point for logs.

Loader: A machine designed to pick up trees and either put them on or take them off trucks.

Logger: An individual who harvests timber for a living.

Merchantable timber: A stand in which trees are of sufficient size and volume per acre to provide a commercial cut.

Processor: A tree harvester that cuts down trees, takes the limbs off, cuts them into log lengths, and leaves them in piles.

Pulpwood: Wood suitable for use in paper manufacturing.

Roundwood: Sections of tree stems, with or without bark. Includes logs, bolts, posts, and pilings.

Silviculture: The art and science of growing forest trees.

Slash: Branches and other woody material left on a site after logging.

Stumpage: The value of standing trees in a forest.

Stumpage price: The price paid for standing forest trees.

Thinning: A partial cut in an immature, overstocked stand of trees used to increase the stand's value growth by concentrating on individuals with the best potential.

Understory: Vegetation growing under the canopy of larger trees.

Yard: A verb that means to drag a log out of the forest to a *landing* for shipment to a mill.

Appendix B

Additional Conventional Preprocessing Information

Appendix B

Additional Conventional Preprocessing Information

Hogging (Crushing)

Hogs, also known as shredders, grinders, and crushers, are machines that smash, shear, tear, or crush wood and bark using dull plates or hammers to produce particles with rough surfaces and irregular shapes and sizes. They are generally subdivided into either low-speed or high-speed machines, based on the rotational speed of the comminuting device. Hogs are often used to process waste material where the portion of contaminants, such as rock as and metal (from nail, fencing, etc.), is high (Pottie and Guimier 1985, Alakangas et al. 1999). Hogs are not widely used for in-woods comminution of logs, as chippers require less power to process material to a nominal size at a given productivity and whole-tree chippers are generally sufficiently available that portable hogs have not been in high demand (Pottie and Guimier 1985). Hogs are normally big enough to be equipped with their own engines and knuckleboom loaders and can be equipped with a feeding system (Leinonen 2004). However, they are usually very heavy units and, therefore, less portable than chippers (Alakangas et al. 1999). The horizontal feeding system assists whole trees because the table assists in feeding at a constant rate and keeping the trees aligned. The discharge systems of chippers are normally designed so that they can blow the chips directly into a trailer (Figure A-1), while hogs discharge the comminuted material onto a conveyor that may build a pile on the ground or load a truck (Leinonen 2004). Chippers generally allow snow and other debris to fall off and, therefore, crushers that are fed snowy residues have a higher moisture content then chippers fed the same residue (Alakangas 1999). Hogs are more rugged and require less maintenance than chippers (Pottie and Guimier 1985).

A swing-hammer hog (Figure B-1) has multiple rows of hammers attached to a durable horizontal shaft rotor that is capable of reversing the direction of rotation if it gets caught up by metal, rocks, or other potentially damaging objects. The residues are crushed between the hammer and a fixed anvil, and the residues then fall through openings on the bottom half of the hog. The distance between these openings, or the screen size, determines the size of the material coming out of the hog. Although swing-hammer hogs are effective for processing mixed bark or solid wood, they are less effective in grinding long stringy bark such as cedar (Pottie and Guimier 1985). Punch-and-die hogs are better suited for handling long stringy bark as they incorporate a shearing action prior to crushing; however, they are more vulnerable to foreign objects (Pottie and Guimier 1985).

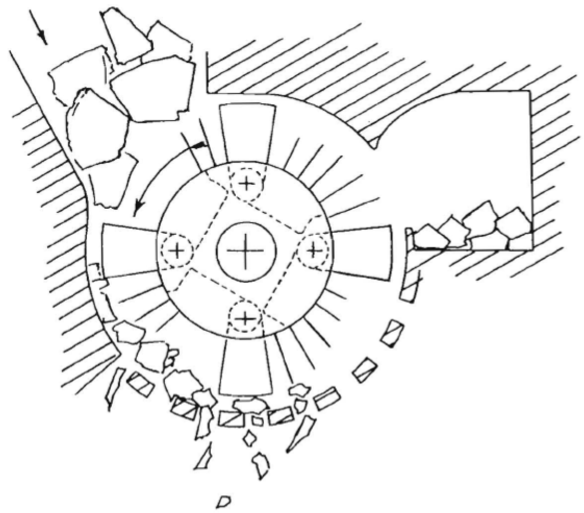

Figure B-1. Schematic of a swing hammer hog (Reprinted with permission from Pottie and Guimier 1985).

Knife hogs have knives mounted on a rotating drum and cut material against an anvil (Figure B-2). A second anvil may be situated after the first on the bottom half of the rotor to create a second surface upon which to further reduce material size. Knife hogs have a lower power requirement then hammer hogs, and they are well suited for stringy material. However, as with any comminuter using knives, they are more sensitive to foreign material (Pottie and Guimier 1985).

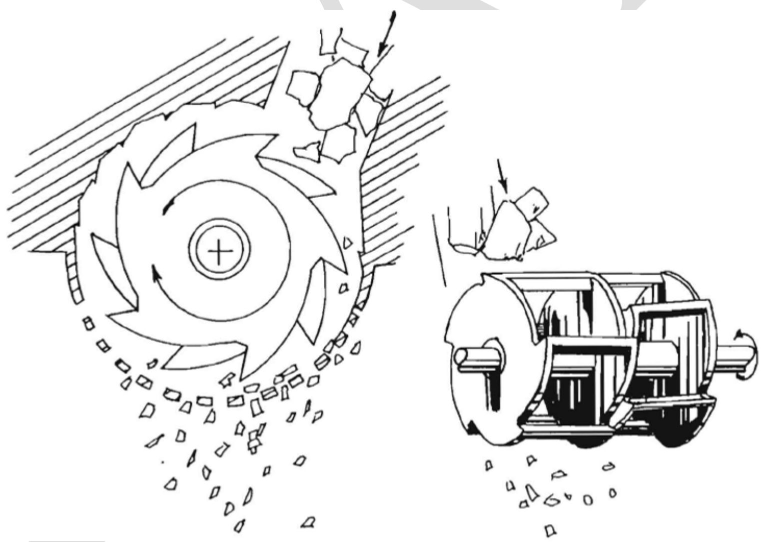

Figure B-2. Schematic of a knife hog (Reprinted with permission from Pottie and Guimier 1985).

Shredders (Figure B-3) have two low-speed counter-rotating shafts with disks that shred material. Material is fed into the shredder through a hopper, and feeding arms are used to push the material through. When a foreign object or excessively large material clogs the shredder, the shafts stop and reverse to remove the object (Pottie and Guimier 1985).

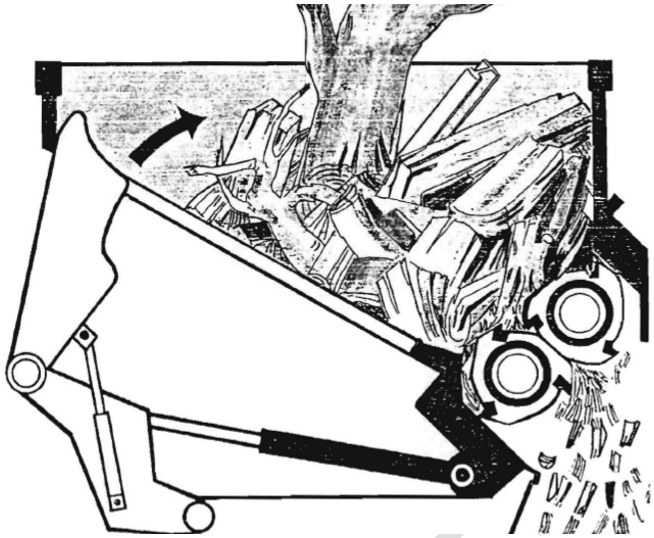

Figure B-3. Schematic of a shredder (Reprinted with permission from Pottie and Guimier 1985).

In a vertical-shaft shredder, a horizontal disk rotor is mounted on a vertical shaft, which is powered by a motor on the base on the machine (Pottie and Guimier 1985). The material is gravity fed and cut between an anvil and rotating knives, which are attached to the rotor and extend radially. As with all shredders, the direction of rotation can be reversed to free foreign material or large objects obstructing rotation. Vertical shaft shredders are well suited for shredding bark. Another variation of the shredder is a multiple-shaft shredder, which is composed of several vertical spiked rollers assembled in a circle, which form what is termed a processing cylinder. Every other roller is powered. The processing cylinder is closed at the bottom by an adjustable sizing screen that rotates freely about the vertical axis. Woody biomass is fed into the top of the processing cylinder, and the biomass is shredded when the material is flung to the side of the processing cylinders by centrifugal force and hits the rollers (Pottie and Guimier 1985).

Chunking

The basic principle of chunking is two parallel counter-rotating discs, each with one curved knife turned inwards. The knives are mounted parallel to the disc radius. The discs are attached to a thick shaft bar, one disc fixed and one mounted on bearings. The chunkwood lengths is determined by the infeed speed, and varies between 3-20 cm. Energy consumption for comminution into chunkwood is only 0.5 – 1 kWh/m^3 of solid wood, or ~ 1.5 – 2 kWh/m^3 lower than for chipping (Danielsson 1989). This results in lower fuel consumption and lower operating costs.

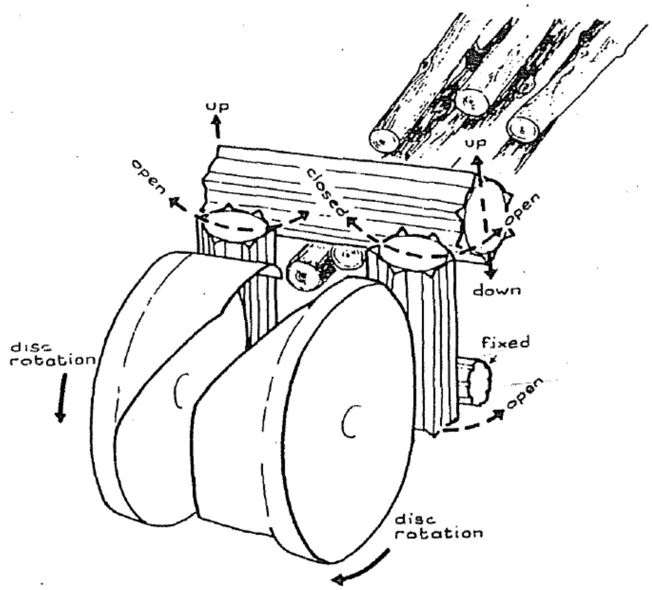

Figure B-4. Schematic of a double-disc chunker (Reprinted with permission from Pottie and Guimier 1984).

Hog Capacity

During hogging, material is randomly fed into the machine and, therefore, determining production capacity is much more challenging then for chippers. As with chippers, the productivity of the hog is impacted by the specific machine, the material being processed, and the screen size used. The material being processed varies by diameter, length, ratio of bark to wood, moisture, species, and bulk density, among other factors. The manufacturer’s rated production increases by a factor of 1.5 to 4 when processing bark as compared to processing wood (Pottie and Guimier 1985), as shown in Figure B-5.

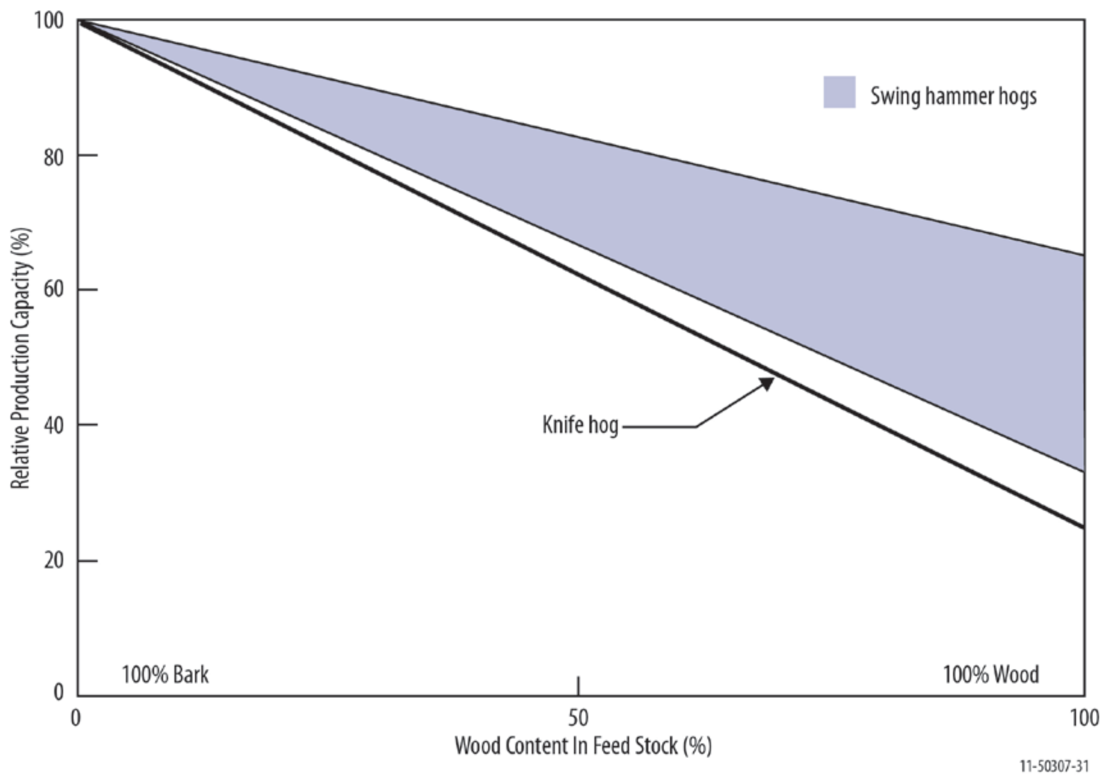

Figure B-5. Impact of changing wood and bark content on production capacity of various grinders (Recreated with permission from Pottie and Guimier 1985). Capacity increases while grinding a higher percentage of bark, and swing-hammer hogs have a higher capacity then knife hogs.

The energy requirement of hogs is impacted by size of the feedstock and size of the resulting hog fuel, density of the wood, sharpness of cutter, wood to bark ratio, temperature, and moisture content (Pottie and Guimier 1985, Arthur et al. 1982). Due to similarities in operating mechanism, knife hogs generally consume the same amount of energy as chippers (Pottie and Guimier 1985, Arthur et al. 1982, Figure B-6). Swing-hammer hogs and punch die hogs smash and cut in a less efficient way, and therefore have higher energy requirements. The hogs also produce a rougher surfaced fuel and more fines than chippers, both increasing the surface area of the fuel and thereby increasing the combustion efficiency (Pottie and Guimier 1985).

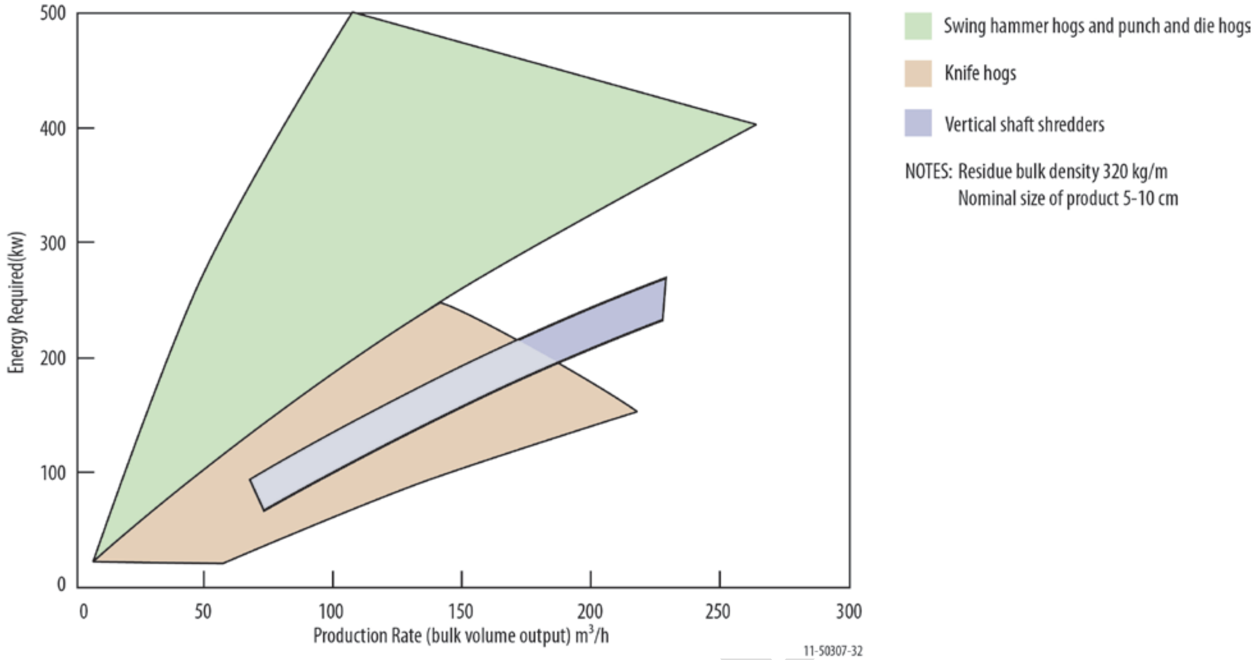

Figure B-6. Energy requirement of various grinder/hog designs (Recreated with permission from Pottie and Guimier 1985).

The energy requirement of vertical shaft shredders falls in the range of that for knife hogs. The scissor-type cutting action of the vertical-shaft shredder is more efficient than the smashing action of swing-hammer hogs and punch-die hogs. Also, vertical-shaft shredders are usually used to process bark rather than wood, the former requiring less comminution energy (Pottie and Guimier 1985).

Decreasing the size of the output material increases the machine's energy draw. Material of higher density requires more energy and, therefore, drier biomass requires less energy. As hammer hogs reduce the size of the material by impact, more brittle material will break more easily (Pottie and Guimier 1985).

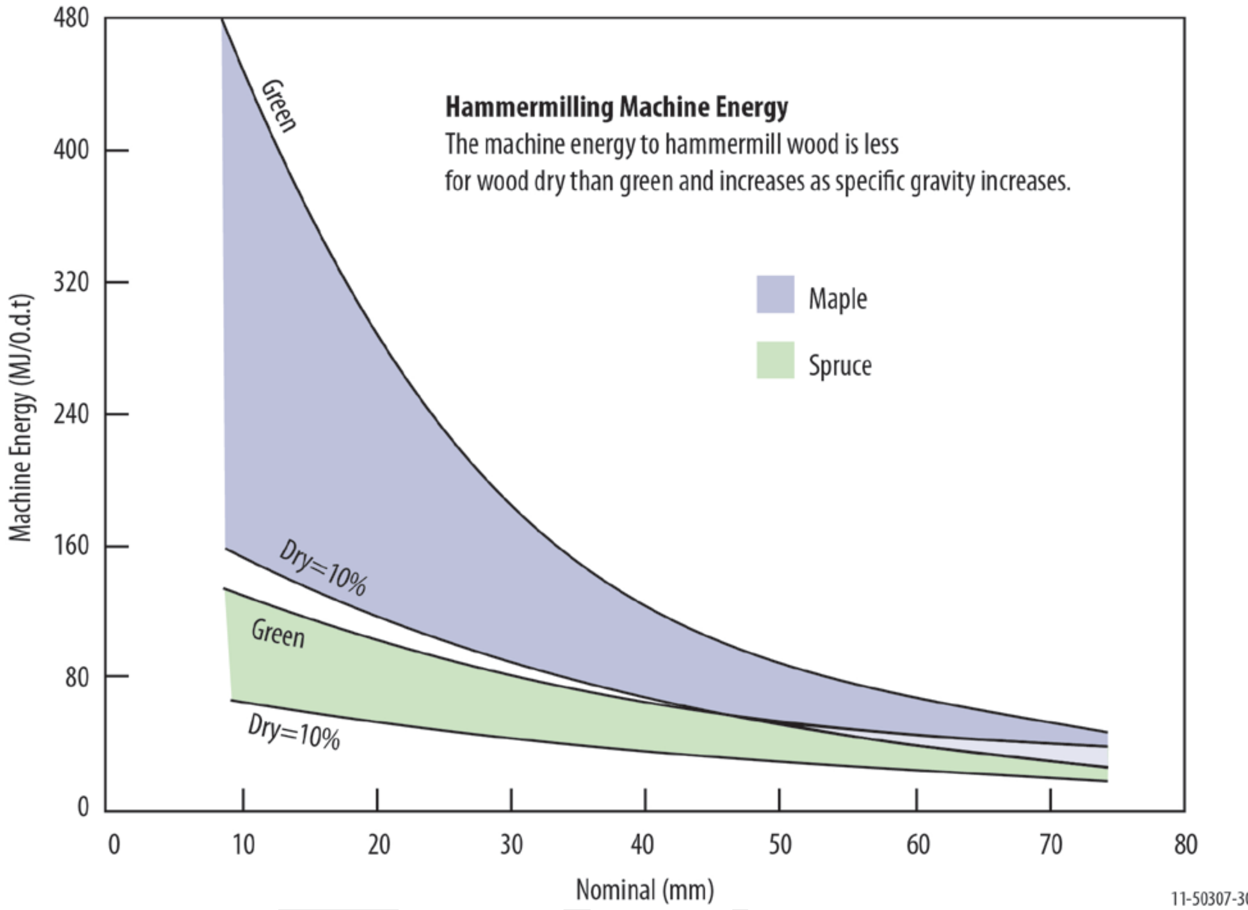

Figure B-7. The relationship between material output length, moisture content, and wood density on energy required for chipping (Recreated with permission from Pottie and Guimier 1985).

The maintenance requirements vary between different hogs and shredders. Swing-hammer hogs and shredders are the most rugged and can withstand high levels of contaminants. These comminutors are even used in the recycling industry to reduce large metal objects, such as cars and large appliances. Vertical-shaft shredders were designed mainly to process bark and are not suitable for materials of high wood content material. They are fairly resistant to damage from contaminants, however, as the rotating knives can swing out of the way if excessive resistance is encountered. Punch-and-die hogs, on the other hand, do not have components that can swing out of the way when damaging contaminants are in the machine, and the machine may have to be shut down to remove blockages, causing excessive downtime. Knife hogs are more affected by contaminants than other hogs. As with chippers, a knife hog's sharp knife cuts material against an anvil, such that even small contaminants (for example, grit and sand) can dull the knives and increase maintenance costs (Pottie and Guimier 1985).

Note that some chippers are mobile enough that comminution can be done at the point of felling rather than at the landing, which would reduce losses during skidding and could potentially reduce handling cost by eliminating the skidding operation. Pottie and Guimier (1985) found that comminution at the landing was twice as productive as comminuting in the field. This emphasizes the importance of optimizing equipment use through thoughtful system configuration.

Chunking

Energy consumption during chunking depends on initial tree size, rotation speed of the cutting head, and final chunk size (Table B-1).

Table B-1. Calculated power requirement at different wood diameters. Energy consumption during chunking increases with increasing wood diameter and increases with increasing rotational speed (Danielsson 1989).

Power required, kW, at different wood diameters					
Rotations/cuts per minute	2 in.	4 in.	6 in.	8 in.	10 in.
400	2	9	25	56	105
445	2	10	28	62	117
650	3	15	41	91	171

The smaller the particle size required, the higher the energy consumption during comminution. Therefore, as chunking generates larger particle sizes, it consumes less energy than chipping or hogging (Table B-2).

Table B-2. Energy consumption for chunking and chipping for various scenarios, kWh/ft^{3}solid (Danielsson 1989).

Material Type	Diameter In.	Machine	Particle Length In.	Energy Consumption kWh/ft^3
Bundles	2-6	Garp chunker	4	15.885
stems	4-8	Garp chunker	4	17.65
logs	1.6-4.3	US chunker	2	24.71-63.54
logs	5.1-8.7	US chunker	3.5	21.18-38.83
bundles	0.8-2	US chunker	3.5	10.59-19.9
stems	2-4	Sasmo HP-30	5.1	35.3-70.6
stems	2-4	Sasmo HP-30	0.8-3.1	70.6-141.2
logs	4	Bruks 722 MT	0.3	91.78
logs	4	Sasmo HP-15L	2.4	42.36

Appendix C

Additional Chip Storage Options

Appendix C

Additional Chip Storage Options

Contact Pile Cover

Laying a tarp or other low-breathing cover directly on top of the pile is generally not recommended for outdoor long-term storage as this can lead to increased dry matter loss, higher MC in upper layers, and decreased heating value (Hall 2009). Larger piles stored without a cover tend to shed precipitation fairly effectively, with moisture often being limited to the top 500 mm (Hall 2009). Placing a cover on the pile, however, limits airflow, which prevents moisture from escaping and promotes self heating. However, short term use on dry materials (<25% MC) can prevent precipitation infiltration, as can using contact covers on smaller piles (<6 m high) as the higher surface area limits the effectiveness of rain shedding (that is, the top layer is a more significant portion of the total volume).

Anaerobic Conditions

Covering a large chip pile with polyethylene film may enable the achievement of anaerobic conditions, which may inhibit microbial growth that increases self heating (Springer 1979). However, with oxygen concentrations as low as 4 – 5 %, deterioration levels have been shown to be the same as open exposure to air (Springer 1979). Achieving oxygen concentrations at or below 1% is very difficult due to tears in the film and wind (Springer 1979).

A-frame Storage

A-frame storage options cover the biomass without contacting the biomass, but air is allowed to flow freely through the structure. The roof is A-shaped so as to prevent moisture/precipitation accumulation on the roof, which could damage the structure, and this promotes moisture run-off away from the biomass. Covering of piles by non-contact cover, such as a roof, (Hall 2009), has been shown to reduce the moisture content of woody biomass from 45 % to 25% in 6 months in certain climates (Springer 2000).

A-frame storage structures should be equipped with temperature and gas detection systems, as well as a sprinkler system or some other fire extinguishing system. Emergency unloading takes place usually from the open side of storage using front-end loaders and, therefore, separate exit doors or gates are unnecessary (NIC 2008). Belt conveyors, electric motors, and static electricity around large amounts of dust pose a risk of ignition and even dust explosions (NIC 2008). A full facility cleaning should take place during shut downs to prevent build up of dust on beams and structures, in corners and on end walls.

Indoor

Indoor storage involves completely enclosing the biomass. It offers a higher level of protection from the elements over open-air storage; however, it is more expensive. Indoor storage protects against exposure to precipitation and other water sources, preventing moisture uptake. The storage space should be well ventilated to avoid CO build up. A CO-sensing system is recommended to alleviate occupational health concerns (NIC 2008).

McDonald and Twaddle (2000) conducted a survey of 191 wood-consuming mills in the U.S. and found that over 97% of the chip piles were stored uncovered, and over 70% were worked using a dozer or loader. Nearly all mills restricted pile height, primarily for safety reasons, but also due to equipment overhanging the pile area or limitations in pile-building capabilities.

Figure C-1. Large-scale enclosed chip fuel storage (Regensw Sustainable Energy Agency 2008).

Silos

Silos are enclosed structures used for bulk storage, preventing exposure of the contents to the elements. The characteristics of the contents and constraints imposed by the shape of the structure and discharge system can prevent steady flow by bridging or rat holing. The particles in most solid biofuels are of varying sizes and shapes, and thus these particles can form a stable bridge (arch) over an opening, even when the opening is large compared to the fuel particles (Mattsson, 2002).

Circular, above-ground silos are the preferred shape due to economy (Gislerud et al. 1988). Common types of dischargers include V-shaped with screw discharge (generally only used for smaller installations), rotor discharge, screw-rotor, wandering screw (for rectangular bins), push-floor discharger, and sliding frame (Gislerud et al.1988). The screw rotor discharge is common for larger round silos.

A screw rotor (center pivot auger) is for unloading a flat-bottomed circular silo (Figure C-2). The auger sweeps the silo base, discharging chips into an opening at the center. These silo unloaders function best when the silo is in a heated space to avoid problems with chips freezing to the walls of the silo (Maker 2004). Frozen chips are also more prone to clogging (Gislerud et al. 1988).

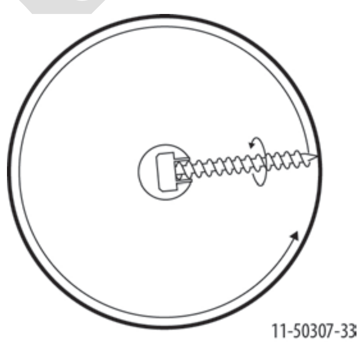

Figure C-2. Center pivot auger (Gislerud et al. 1988).

The push floor dishcarger is frequently used for feeding bark and chips as fuel (Gislerud, Gjolsjo, Thorkildsen 1988) and consists of many elements being pushed back and forth through applied hydraulic force. Some designs allow for wheel loaders to drive into the silo and unload.

To avoid plugs, fuel flow properties should be determined before the fuel is delivered. The flow properties are not always obvious. For example, fuels with a small particle size may have a higher tendency to bridge than fuels with larger particles. As each system for internal handling is more or less unique, it is important to relate the bridging tendency of a new fuel to that of fuels already in use (Mattsson, 2002).

Silos should be equipped with temperature-measurement and gas-detection systems, if technically and economically feasible, and should be prepared for fire extinction and emergency unloading of hot material (NIC 2008). The temperature-measurement system should include heat sensors situated at different heights and horizontal positions and able to measure temperatures at least up to 100°C (NIC 2008). This is often done by mounting the heat sensors on wires that traverse the silo vertically (NIC 2008). The gas-detection system should measure CO and O_2 in the air in the head space of the silo. The CO-concentration can be used as an indicator of oxidation or pyrolysis in the bulk material (NIC 2008), while the O_2 concentration is valuable during an extinguishing operation using inert gas to ensure that an inert atmosphere has been reached in the silo (NIC 2008). Also, the silo should be prepared for emergency unloading in case of a fire; however, it should be noted that normal unloading mechanisms, such as conveyors and elevators, pose a spark hazard (NIC 2008).

Leachate Collection

Piles stored uncovered outdoors will often receive some rainfall, and pile run-off will contain some chemical contamination leached from the wood (Hall 2009). The level of contamination will depend on chip size, moisture content, pile age, and type of material (for example, pure chips of pure wood or with significant bark). The leachate from chip piles will usually contain tannins and will be acidic, especially when significant amounts of bark are present. Depending on the size and location of the storage pile and length of storage, the leachate may need to be collected and treated before being discharged (Hall 2009).

Appendix D

Process Demonstration Unit (PDU) Deployment Plan

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