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Revision 0 DRAFT

Uniform-Format Feedstock Supply System Design for Lignocellulosic Biomass

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March 2009

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March 2009

Idaho National Laboratory
Bioenergy Program
Idaho Falls, Idaho 83415

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ACRONYMS

Uniform-Format Feedstock Supply System Design for Lignocellulosic Biomass

1. INTRODUCTION

The purpose and objective of this 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, and (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 Background

There are no operations in proposed feedstock supply systems 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. As such, there are no shortages of conceptual designs for moving biomass feedstocks from the field 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 lignocellulosic feedstocks to a standardized feedstock supply system infrastructure and biorefinery conversion process.
2. Improving feedstock logistics, specifically the efficiency and capacity of 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).

Lignocellulosic feedstock resources

- Agricultural and processing residues - cereal straws, corn and *Sorghum* stovers, corn cob and cotton gin waste, and distillers dried grain [DDG]
- Dedicated energy crops - switchgrass, *Miscanthus*, sugar cane hybrids, and Conservation Reserve Program [CRP] grasses
- Woody resources - whole wood, wood chips, wood residue bundles, and solid municipal waste [SMW].

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). In fact, estimates based on the 20 in 10 (Bush, 2007) and 30 × 30 (Foust et al., 2008) goals, and the conversion efficiencies of the biochemical and thermochemical technologies (Aden et al., 2002; Phillips et al., 2007), show that an

annual amount of up to 70 million tons of lignocellulosic biomass is needed to meet the yearly ethanol demand within the next 10 years, and between 500 and 700 million tons will be needed annually in 20 years. Given current biorefinery designs, potentially more than 100 biorefinery facilities will need to be constructed within 10 years to process this quantity of lignocellulosic biomass (Aden et al., 2002; Phillips et al., 2007). 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, the subsequent 5 years, 2012 to 2017, will require replicating and scaling these biorefineries 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. Instead, all lignocellulosic facilities, biochemical and thermochemical alike, must operate on a standardized supply system infrastructure, similar to the grain ethanol facilities of today. As such, a critical element needed for rapid biorefinery facility replication is the development of a uniform-format feedstock supply system infrastructure that is tolerant of wide variations in feedstock resources and moisture.

The feedstock supply system encompasses all operations necessary to format and move biomass from the location of production (field) 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, Willhelm, Hess; 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 (Appendix A-1.1). While the actual percentage allocation for lignocellulosic biomass feedstock logistics will depend upon a few factors that are different 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 field to the biorefinery. For example, a conventional bale-based feedstock supply system changes the biomass format at least three times from the field to the biorefinery (e.g., standing crop → bale → shredded bale). 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 bale formats (i.e., round or square in a variety of sizes) with their own respective lines of harvesting and handling equipment. Similar examples can be cited for the woody resources, including equipment for handling round wood, wood chips, and slash bundles. 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 cases in Section 4.

Supply logistics costs vary substantially among regions, depending on weather, crop species, moisture content, and feedstock types, as well as transportation highway load limits and other regulations. Cropping systems and storage methods can also change supply logistics costs substantially. Managing these inherent complexities and diverse feedstock types will be required 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 manufacturers, but also for equipment manufacturers, who require equipment to be broadly applicable

across the industry. Conversion plant and equipment manufacturers must work together, not in a relationship of compromise, but rather through mutual optimization on a national scale.

Achieving national biofuel goals can only be accomplished through 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 the Uniform-Format Feedstock Supply System

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

1. Conventional technology and operation systems that are uniquely designed to integrate with existing agribusiness systems.
2. Pioneer uniform-format systems wherein feedstock supply systems are standardized to two format types, wet or dry (Section 1.2.2), 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 Feedstock Supply System Design

A primary objective that drives the conventional 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 lignocellulosic 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 feedstock supply system designs rely on existing technologies and agribusiness systems to supply biomass 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). 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/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 do work today because they adapt to the local available biomass

resources and facilitate producer participation by minimizing perturbations to their present operations and by reducing the investment risks associated with new and unproven supply system equipment.

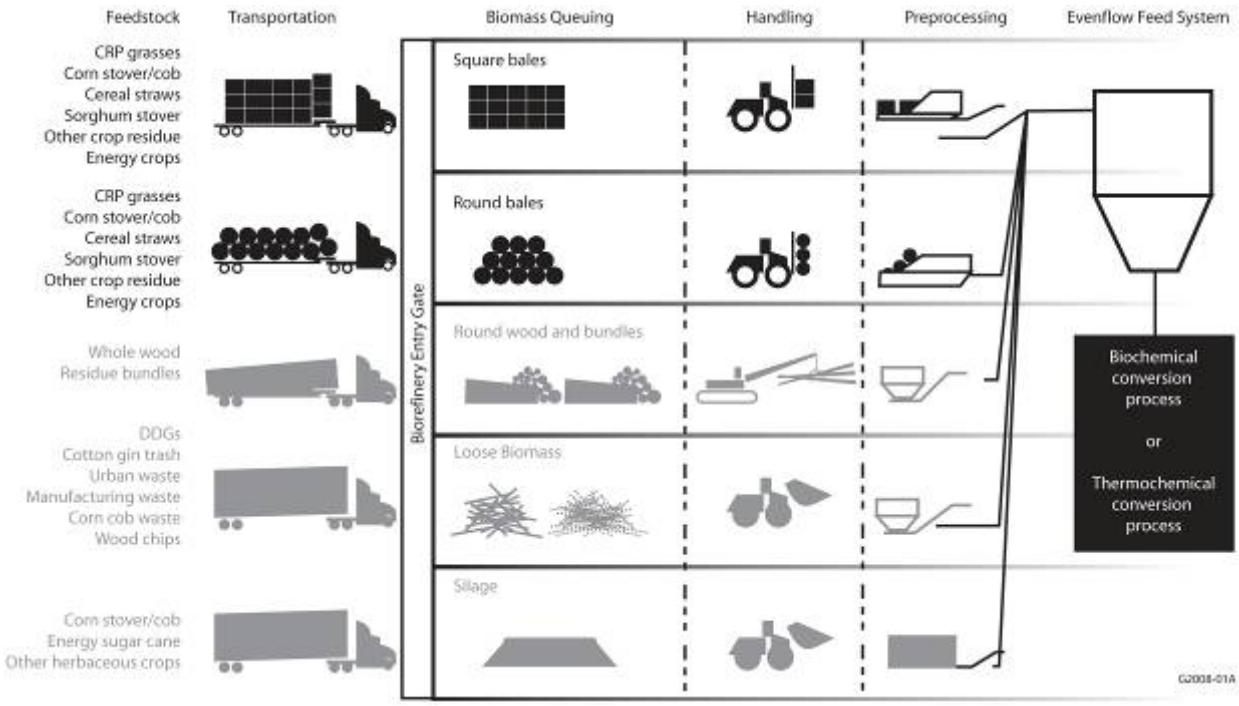


Figure 1-2. Conventional feedstock supply system designs are tailored for each facility and respective feedstock resource. No two are alike, and components are only replicable to the extent that feedstock sources and local conditions are similar. Conventional-bale dry herbaceous systems (in bold) are the focus of Section 2 of this design report.

In conventional designs, the burden of adapting to feedstock resources is assumed primarily by the biorefinery, since each biorefinery is designed for a specific feedstock or set of feedstocks. As conventional-bale designs emerge, supply logistic operations will be performed by a co-op of small-farm operators, large-farm operators, custom operators, and/or, eventually, large commodity-handling agribusinesses. 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, leaving conversion technologies to focus on biomass compositional and recalcitrance diversity, and strive for increasingly greater 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).

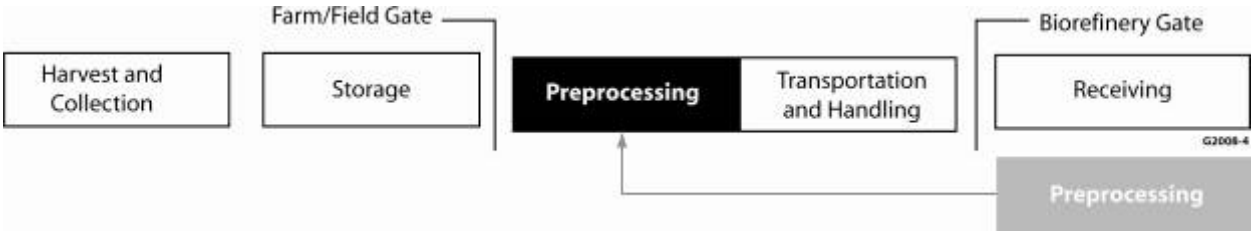


Figure 1-3. Pioneer uniform-format feedstock supply system designs move preprocessing from inside the biorefinery gate to the point of storage, either on-farm or at depot storage.

While the biorefinery feedstock receiving and conversion systems will still be tailored to multiple biomass formats, the pioneer-uniform design concept reduces those formats to two bulk-flowable types, "dry" or "wet," defined by aerobic stability or instability:

- Dry biomass is biomass at a moisture concentration that is aerobically stable. For most biomass, this is typically less than 15 to 20% moisture wet-basis (w.b.). This biomass may be stored and handled without stabilization techniques due to its ambient aerobic stability.
- Wet biomass is biomass at a moisture concentration that is aerobically unstable. For most biomass, this is typically greater than 15 to 20% w.b. Because of the entrained moisture, this biomass requires stabilization techniques to be implemented.

At harvest, most biomass will contain sufficient moisture to be classed as aerobically unstable, or wet, biomass (Hoskinson et al., 2007; Shinners et al., 2007; Pordesimo et al., 2004). If the biomass is in the wet moisture range (i.e., above 15 to 20% w.b.) at any point in the supply system, one of two moisture management strategies must be implemented regardless of the absolute moisture value of the biomass. 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 (e.g., ensiling). Green harvest coupled with timely delivery and conversion could also be an option in some areas for handling aerobically unstable biomass. While the pioneer-uniform design concept includes both aerobically stable and aerobically unstable biomass supply systems, only the aerobically stable, or dry, feedstock supply system designs will be presented in detail within this report.

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, slash piles, processing waste/rubbish piles) that are not optimized for downstream transportation. Pioneer-uniform designs will also overcome the local boutique design approach of pioneer biorefinery and feedstock infrastructures, which will facilitate the more rapid deployment of biorefining facilities across the United States.

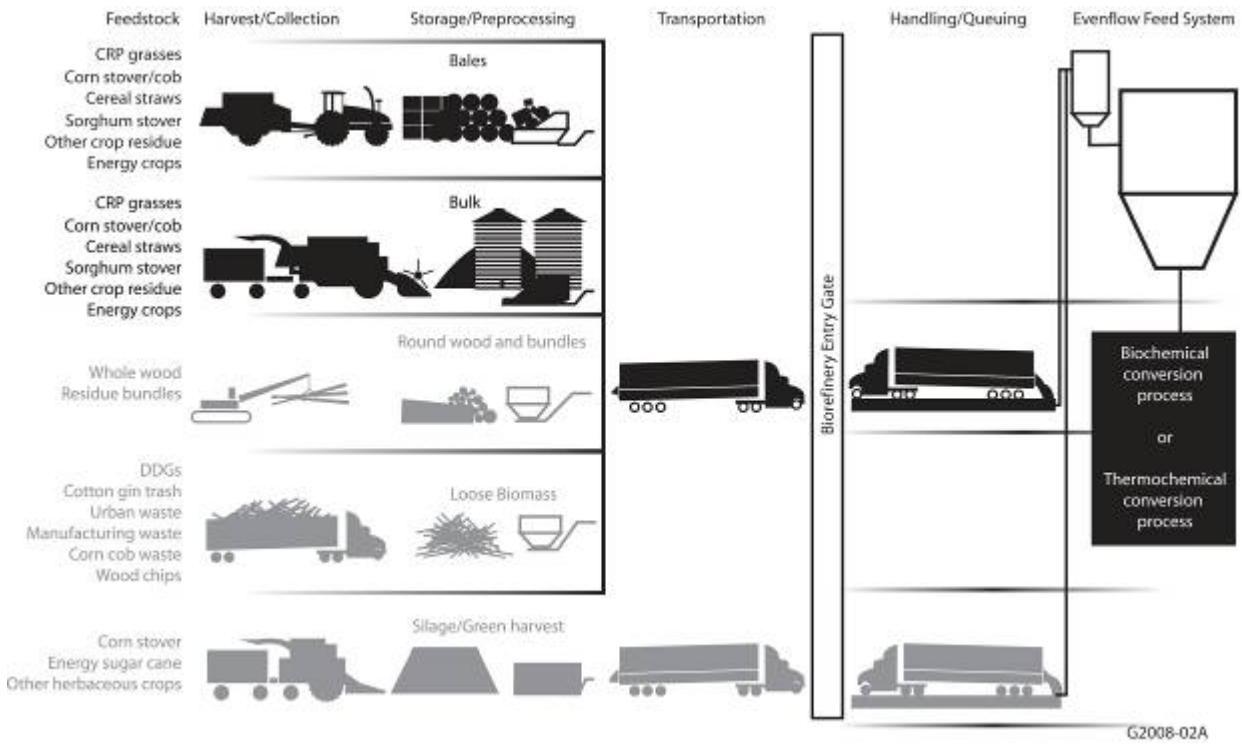


Figure 1-4. Pioneer uniform-format feedstock supply system designs will allow lignocellulosic biomass to arrive at the biorefinery gate in two quality-assured and controlled bulk-flowable formats: wet or dry. Dry herbaceous baled and bulk agricultural resources (in bold) are discussed in detail in Section 3 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 logistic 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 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 will be eliminated as early in the supply system as practically possible through some type of preprocessing. The preprocessing may occur during harvest and collection and/or at centralized preprocessing sites, or feedstock 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 (Figures 1-5 and 1-6).

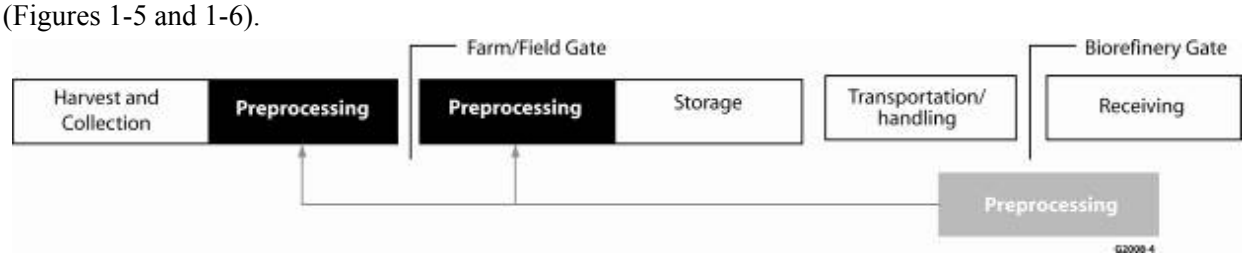


Figure 1-5. Advanced uniform-format feedstock supply system designs adapt lignocellulosic biomass to current high-efficiency logistics systems by preprocessing the biomass into a high-density/aerobically stable material at or near the point of the resource origination.

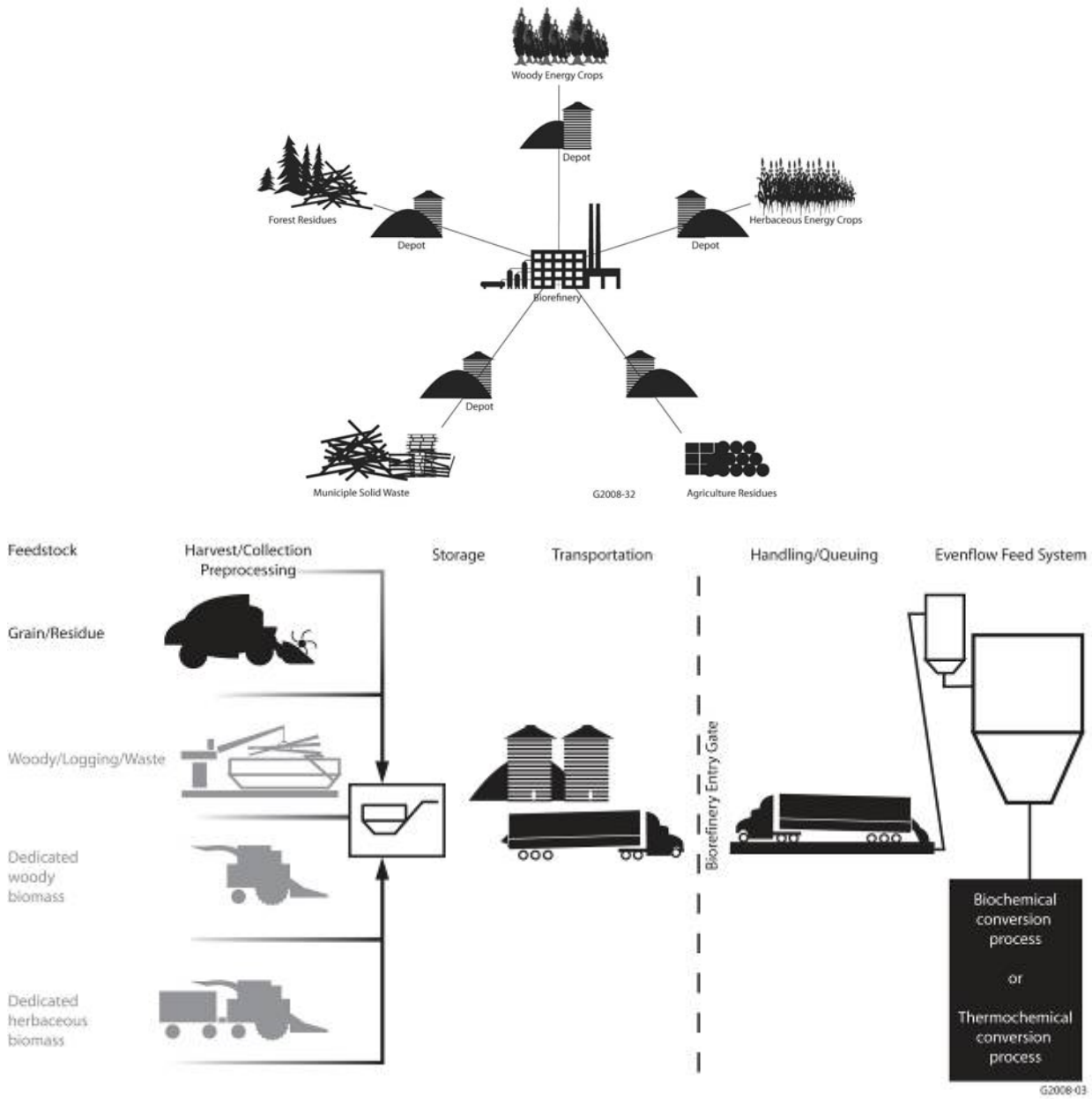


Figure 1-6. Advanced uniform-format feedstock supply system designs follow the model of the current commodity grain supply system, which manages crop diversity at the point of harvest and/or the storage elevator, allowing all subsequent feedstock supply system infrastructure to be similar for all biomass resources. Dry herbaceous uniform-format commodity-scale agricultural resources (in bold) are discussed in detail in Section 4 of this design report.

The advanced-uniform design concept 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). Unlike the conventional-bale and pioneer-uniform design concepts, the advanced-uniform design concept does not have both wet and dry supply delivery lines. Rather, 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) (Figure 1-6). While it is not known at this time whether the mature lignocellulosic biomass industry will implement a bulk solid or liquid feedstock supply system, the high-density granulated product design concept will be the model system presented in this report.

The biomass blending design feature of the advanced-uniform concept precludes the use of high-density unitized 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 advanced-uniform concept for high-density bulk solids is analogous to the current grain supply system. 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 a common-physical-properties format that can be handled by a common supply system infrastructure.

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 the Uniform-Format 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 “farm gate” (point of transition when product is transferred from producer) and “plant gate” (point of transition when product is transferred to biorefinery) boundaries are not supply system design boundaries in this report (Figures 1-1, 1-3, and 1-5). Rather, this design report considers all supply system elements, from the biomass standing in the field (agricultural) or on the stump (forest), to the point of insertion into the biorefinery conversion process reactors.

The content boundaries of this design report are as follows:

- The designs are modeled as dry herbaceous feedstock supply systems, with some inclusion of wet/dry hybrid feedstock systems in the advanced-uniform design. A more detailed feedstock supply system design for herbaceous wet biomass will be prepared as an addendum to this report.
- Woody feedstocks are recognized resource inputs to these designs, but like the wet herbaceous resources, they are not presented in detail or as a modeled scenario resource input. 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. As such, an independent woody resource supply system design is justified.

- 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 but will be covered more thoroughly in a grower payment analysis report (Perlack and Turhollow, in process). 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 is focused 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:

- *Grower Payment.* The cost value assigned to access a given quantity of biomass in the field or forest. (This is not a farm gate or 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.

$$Feedstock\ Cost\,(\$/ton) = \underbrace{Grower\ Payment\,(\$/ton)}_{a} + \underbrace{\left[\frac{Inputs\,(\$/hr)}{Outputs\,(ton/hr)}\right]}_{b} \pm \underbrace{Quality\,(\$/ton)}_{c} \qquad (1\text{-}1)$$

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 *grower payment* (a) or the biomass *quality* (c) elements.

The *grower payment* element (a) is an input into the design models; however, calculations of *grower payment*, 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 *grower payment* 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, agronomic, and production management models may be used to quantify *grower payment* input parameters. The resource assessment tools include POLYSYS as a policy and grower decision modeling framework, and the suite of United States Department of Agriculture (USDA) productivity databases. Modeling the agronomic and production management requires economic and system sustainability assessment tools to identify functionally accessible resource. These tools include, but are not limited to, I-FARM, RUSLE2, CQESTR, SWAT, and EPIC. *Grower payment* element input modeling is not described in this report.

The biomass *quality* element (c) represents the interface with the biorefinery conversion processes. Like *grower payment*, 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., wet herbaceous and woody) 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 storage or queuing location. In addition to obvious operations, such as cutting (i.e., combining, swathing, or logging) and hauling, this often includes some form of densification, such as baling, bundling, or chipping to facilitate handling and storage.
- *Storage and Queuing* are essential operations in the feedstock supply system and are used to accommodate seasonal harvest times, 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.
- *Transportation 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 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.

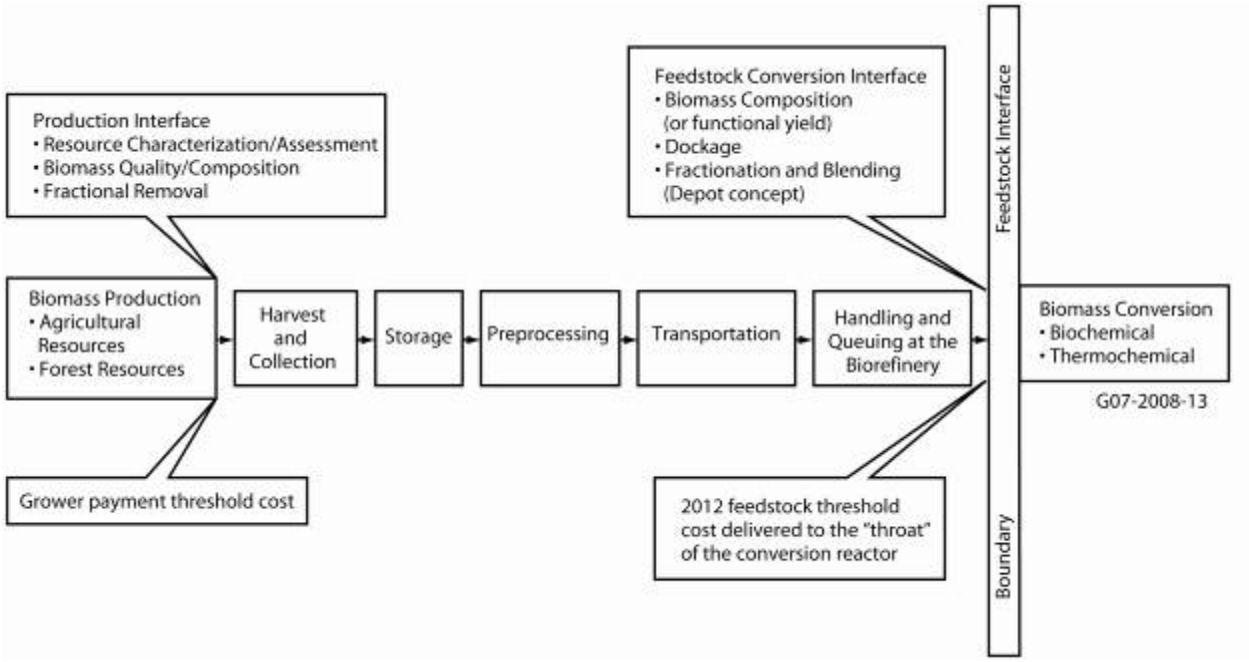


Figure 1-7. Schematic and boundaries for a lignocellulosic feedstock supply system design that allows unit operations to be reordered to achieve optimum supply system performance.

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, farmers are responsible for harvest, collection, and delivery to storage. These assembly functions are integral to production and, thus, remain under the producer's control (even if he chooses to have them performed by others). Often, the farm gate transaction is based on feedstock value in addition to these on-farm operations. The agribusiness is then responsible for feedstock procurement and storage, preprocessing, transportation, and handling. However, if the biorefinery uses a distributed on-farm storage system (or some other on-farm value process), the agribusiness may arrange for the farmer to store the material, which will change the farm gate transaction. The agribusiness may also choose to subcontract feedstock assembly operations before the biomass reaches the plant gate, which would alter plant gate transactions.

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, which makes farm gate and plant gate transactions vary across feedstocks and regions. As such, supply system designs and technology selections are not constrained by farm gate or plant gate boundaries, but they do consider technologies and costs in terms of farm gate and plant gate interface.

1.3.2 Design Cost Targets for the Feedstock Supply System

Feedstock logistics costs associated with the harvest, transportation, and storage of corn grain contribute roughly 7 % to 19% of the total cost of producing a gallon of fuel ethanol (Shapouri and Gallagher, 2002; Duffy and Smith, 2008; Rapier, 2008) (Appendix A-1.1). This example of a commodity feedstock represents the state of technology (SOT) for a mature grain derived liquid transportation fuel production industry. In order for a lignocellulosic based liquid fuel production industry to meet the national target of 40 to 45 billion gallons, it too must be based on a mature commodity feedstock supply system. Thus, feedstock logistics costs associated with lignocellulosic biomass cannot contribute significantly more than 19% of the total production cost of a gallon of lignocellulosic fuel ethanol. Thus, feedstock logistic cost targets (DOE-EERE,OBP, 2007) have been established for the pioneer-uniform and advanced-uniform feedstock supply system designs that are on par with the corn grain supply system, allowing for added costs in the area of preprocessing and storage. These cost targets and the percent of the total cost associated with feedstock logistics for 2012 and 2017 are shown in Table 1-1. The cost target for the pioneer-uniform design, which is based on a dry feedstock, implies advances in supply system unit operations that will sufficiently reduce risk and allow pioneer biorefineries to be established.

Table 1-1. Lignocellulosic ethanol production and feedstock logistics costs for 2007 SOT and 2012 and 2017 targets.

	Pioneer-Uniform 2012 Target	Advanced-Uniform 2017 Target
Ethanol Production Cost ($/gal) ($2007)	$1.33[a]	$1.20[a]
Ethanol Yield (gal/ton)	90[a]	90[a]
Feedstock Logistics Cost ($/ton)	$35.00[b]	$27.00[c]
Feedstock Logistics Cost ($/gal)	$0.39	$0.30
Feedstock Logistics Cost (% of total)	29	25

a. Aden, 2008.
b. Includes dry (< 15% moisture w.b.) herbaceous feedstock only.
c. Includes all feedstock types: dry (< 15% moisture w.b.), wet (> 15% moisture w.b.) and woody.

However, due to constraints on the supply system imposed by feedstock moisture, feedstock bulk density, and feedstock flowability, an advanced-uniform feedstock supply system design must be developed in order to simultaneously meet the 2017 cost target of $27.00 per dry matter (DM) ton (2007$) and the 2030 tonnage target of 600 to 700 million DM tons annually (Foust et al., 2008). The advanced-uniform design is based on its ability to produce a uniformly formatted feedstock that (1) is sufficiently dry to be aerobically stable and minimize the movement of moisture through the system; (2) has a bulk density capable of minimizing long-term storage footprints and maximizing handling/transportation systems capacity; (3) is flowable in typical, perhaps modified, storage containers and conveying/pumping equipment; and (4) significantly reduces the logistics cost of the feedstock supply system. In other words, this uniformly formatted feedstock could be classified as a commodity

product and put into the existing commodity market. The feedstock performance targets for this system are those established by each of the assembly system unit operations (Section 4).

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 4. 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 wet and woody feedstocks as well as dry feedstocks, 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 driving 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, or advanced) to be truly functional, it must demonstrate the ability and flexibility to physically and logistically couple to the resource. The analyses of conventional-bale 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-bale 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-bale and uniform-format designs, demonstrates flexibility in coupling to the resource but diverges from the conventional-bale 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

As explained in Section 1.3, 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 resource cost, quantity (i.e., yield/acre and quantity/square mile), and physical characteristics of the biomass resource, other issues come into play, including merchandizing biomass to multiple markets (i.e., food/feed/lumber/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 the following:

- What are the resources and the associated characteristics of each?
- How much of the resource exists or could potentially exist (i.e., total quantity, yield/acre)?

The Billion Ton Vision 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 minor resources that collectively comprise the major biomass resource for the biofuels market.

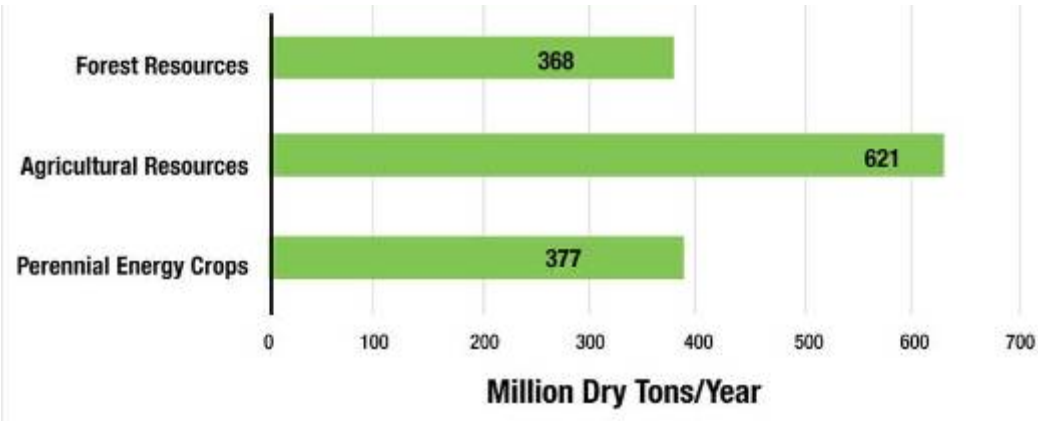


Figure 1-8. The U.S. agricultural and forest lands resource potential as projected by the Billion Ton Vision study (Perlack et al., 2005).

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 herein are limited to corn stover (representing the crop residue resources identified in Perlack et al., 2005) and switchgrass (representing the perennial herbaceous energy crop resources identified in Perlack et al., 2005). Detailed analyses on forest/woody resources are not included in this report.

Finally, supply logistics are highly dependent on biomass quantity per area and biomass yield per acre. For crop residues, biomass yield is estimated from grain yields using the residue-to-grain ratios. Residue-to-grain ratios vary between grain crops as well as with variety, physiological factors such as plant maturity and stress, and planting density (Kemanian et al., 2007). The residue-to-grain ratios used for the designs and analyses in this report are the same as those used in the biomass yield estimates in the Billion Ton Vision study (Perlack et al., 2005). In addition to the residue-to-grain ratios, the estimation of crop residue yields requires the use of standard grain test weights to convert grain yields from bushels per acre (bu/acre) to tons per acre (DM ton/acre). Furthermore, the grain moisture content associated with the

test weight is required to convert grain weights to a dry basis. Estimates of biomass yields of various grain crops based on the 2007 U.S. average grain yield statistics (USDA-NASS, 2008) are shown in Table 1-2., along with the grain test weights, grain moistures, and residue-to-grain ratios used in the yield calculations. The method for estimating biomass yields from grain yields is explained in Turhollow et al., 2008.

Table 1-2. USDA-National Agricultural Statistics Service (NASS) grain production data used to estimate total residue produced.

Crop/Format	Grain Yield[a] (bu/acre)	Grain Test Weight[b] (lb/bu)	Moisture Content of Test Weight (%)	Residue-to-Grain Ratio	Residue Yield (DM ton/acre)
Corn	151.1	56.0	15.5	1.0	3.6
Sorghum	74.2	56.0	14.0	1.0	1.8
Wheat-winter	42.2	60	13.5	1.7	1.9
Wheat-Spring	37.0	60	13.5	1.3	1.2
Barley	63.1	48	14.5	1.5	1.9
Oats	60.9	32	14	2.1	1.7
Soybeans	41.4	60	11	1.5	1.7
Rice	71.9	100	12	1.5	4.7

a. 2007 U.S. average yield (USDA-NASS, 2008)
b. Perlack et al., 2005.

1.4.1.2 Sustainable Biomass Removal

The crop residue yields shown in Table 1-2, as determined from grain production data, represent the total amount of residue if the crop is cut at ground level. However, 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 field 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 field. The harvest efficiencies for crop residues using conventional multi-pass harvesting systems are often much lower than one might expect, with only one-third to two-thirds of the available crop residues actually collected. Harvest efficiency is affected by many variables including the crop condition prior to harvesting (Shinners et al., 2007), weather during harvesting (Shinners et al., 2007), stubble height (the amount of residue left in the field as standing stubble field traffic [Richey et al., 1982]), the ability of machinery to collect biomass from the ground, and the number of passes associated with the harvest process.

The amount of biomass that must be left on the ground following crop harvest to maintain soil health and biomass sustainability is an important consideration of feedstock design. Sustainable residue removal limits depend on soil types, rainfall conditions, crop types and varieties, crop yields, and tillage methods; thus, residue maintenance requirements (RMRs) are highly variable and site-specific (Perlack et al, 2005; Johnson et al, 2006; Wilhelm et al., 2004; Nelson, 2002; Sheehan, et al., 2003), 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 analysis 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.

Because of their effects on net biomass yield and the corresponding feedstock supply radius, residue removal limits have the potential to significantly constrain the supply system design (see Appendix A-1.2) for a description of the supply radius calculation). However, the objective of this report and the feedstock designs herein is to represent the capabilities of the engineering system. Thus, we set the residue 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.

This is not to say that the engineering designs violate basic agronomic limitations. In the conventional-bale and pioneer-uniform corn stover case studies, we assume that existing harvesting equipment is capable of collecting, on average, about 38% of the available above-ground stover (see Section 2.1.2.3 for the discussion of field losses in the conventional-bale design). This is slightly higher than the 33% national-level sustainable removal rate estimated in the Billion Ton Study (Perlack et al., 2005) based on the 2004 tillage practices (20% to 40% no-till), but lower than the 54% and 68% estimated removal rates of the increased no-till and all no-till scenarios, respectively. For the advanced-uniform case study, we have assumed that residue collection technology will be capable of collecting up to 75% of the available residues.

As demonstrated in the projections in the Billion Ton Study (Perlack et al., 2005), residue removal rates are expected to increase as no-till practices, crop yields, and total residue produced increases. However, some residue will always need to be left in the field to maintain soil tilth (a soil's ability to support root growth). Advanced harvesting systems will also play a critical role in future agronomic systems through selective and variable-rate harvest equipment options that optimize residue removal. By selectively removing the biomass fractions that are best suited for biofuels production while leaving the fractions that are best suited for soil health, 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/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 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) 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 is about 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 assumption 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 corn stover and switchgrass feedstocks,

which represent primary resources (i.e, crop residues and herbaceous energy crops). 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 (Section 1.2.2). This typing 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 deal with these biomass feedstocks.

While all supply system design concepts presented herein accommodate both resource types, detailed design analyses and modeling is limited to dry 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" 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 grain markets.
- For the conventional-bale 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 (purchases from the open market at the time of need).

The impact of this assumption on the supply system design is that 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 (the biomass receiving, preprocessing, and storage system) will functionally resemble grain elevators/depots that deliver a standardized product to the biorefinery just as it is needed.

Regardless of the contracting mechanism, feedstock value for the biomass (the price that must be paid to the producer, i.e., a farmer or forester) 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 or energy crops, and values are affected by limited, regional-scale markets, such as fiber, feed, and animal bedding.

The design analyses include feedstock costs as a total grower payment that is added to the summed logistics costs. This grower payment represents all of the complexities of the feedstock interface, and realized costs will be subject to contract arrangements and farm enterprise variables, such as decisions on crop species, rotation, tillage, soil organic matter, and field operations impacts and offsets (Turhollow et al., 2008). It is important to note that grower payment *does not* represent a farm gate or forest landing pricing structure. For these design analyses, grower payment represents the price paid for

the biomass in the field or on the stump, and there are *no* logistic cost assumptions included in the grower payment cost input.

1.4.2 Biorefinery Coupling Analysis

The biorefinery coupling analysis, like the resource coupling analysis, is generally over-simplified. This report assumes that all supply system designs will meet biorefinery quality assurance and quality control specifications without causing cost or logistic perturbations in the supply system. As such, quality credits or debits (dockage) are assumed to cause no logistical impact and to have a $0.00 impact to feedstock costs (Section 1.3, Eq. 1-1). 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 are presented 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. These methods were reviewed and compared by Turhollow and Sokansanj (2007), who compiled from these two methods a recommended standard costing methodology for biomass. While the ASABE and AAEA methods apply specifically to agricultural 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 programmed in an Excel spreadsheet to develop a feedstock cost model. The two-step process for biomass costing includes (1) the calculation of machinery cost (represented in $/hr or $/hr), 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 and discussed in greater detail in Appendix A-1.3.

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 (fixed costs) and operating costs (variable 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 harvest 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. While other variances of this methodology may be used, such as varying ownership cost based upon field speed, 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)

- 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. In order 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[1], the U.S. Department of Labor - Bureau of Labor Statistics[2]; and USDA-NASS[3].

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 Prices Paid by Farmers indexes that are updated monthly. These indexes 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 Repairs Index is used. These USDA-NASS indexes are used for all equipment used in the feedstock supply system analysis, including harvest and collection equipment (combines, 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. For a detailed list of these indexes and a demonstration of their use, see Appendix A-1.4, “Cost Escalation.”

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 $ per ton, $ per item (e.g., bale ft^3), or $/acre (e.g., mowing a field in $/acre, baling in $/bale, and grinding the biomass in $/ton). For calculating these costs, the operating characteristics of the machines are needed, such as speed, efficiency, width of operation, 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 tests, and in other cases it is determined from typical agricultural 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 (tons per hour), and the yearly costs are divided by the annual tons processed to give a cost per 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:

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

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:

$$Q_{eq} = \frac{D_{tons/acres}}{C * t} \tag{1-3}$$

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 per hour or tons per hour

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

Finally, the total annual costs are determined by summing the operating costs ($ per 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 fuel or electricity consumption of the equipment involved.

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

$$Q_{avg} = 0.0438 \times P \tag{1-4}$$

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 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):

- 1 US 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 electric-powered equipment (e.g., conveyors), energy consumption is based on the rated horsepower of the electric motor, according to the following conversion factor (ORNL):

- 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 (i.e., 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 of each of the design scenarios was conducted using @RISK, a commercial simulation software package used to solve Excel spreadsheet models for a probable forecasted scenario. Variables within the model are assigned probability ranges determined from research and documentation. A value is randomly selected from each probability curve and computed as one scenario of the model. Tens of thousands of scenarios are collected, and statistical analysis provides the confidence interval, mean, and standard deviation for the simulation.

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., baling moisture)
  - Biomass Bulk Density (e.g., bale bulk density)
  - Roadsiding Distance
- Storage Variables
  - Dry Matter Loss in Storage
  - Machine (e.g., bale wrapper, loader, etc.) Capacity

- Preprocessing Variables
  - Machine Capacity
  - Biomass Moisture
- Handling and Transportation Variables
  - Transport Distance/Winding Factor
  - Transporter Speed
  - Loader/Unloader Capacity
- Plant Receiving Variables
  - Receiving Hours per Day
  - Feedstock Inventory
  - Feedstock Bulk Density.

For each of the selected input variables, a range and probability distribution of the range was identified. A PERT distribution function was used to describe the probability distribution of most input variables. Defining a PERT distribution requires the following parameters: minimum, mode, and maximum. These parameters are linked in a bell shape, and to the extent that the minimum and maximum values are evenly distributed about the mode, this distribution mimics that of a normal distribution. A PERT distribution is often used when data is sparse. Because we do not yet have large quantities of data, a PERT distribution was used to represent all but two input variables. Two plant receiving variables—Receiving Hours per Day and Feedstock Inventory—were represented by a uniform distribution rather than a PERT distribution. A uniform distribution is defined by two parameters, a minimum and maximum, and assumes that all values between the minimum and maximum are equally likely to occur. A uniform distribution was chosen for these two variables because these parameters are simply a matter of choice.

A Latin Hypercube sampling method was used in the @Risk simulation to generate the input parameter values from the probability distribution functions. Each set of samples represents a possible combination of input parameters which could occur and thus the sampling is the basis of the thousands of "what-if" scenarios used in the sensitivity analysis. Monte-Carlo sampling is the traditional technique to sample from a probability distribution, but because this technique samples randomly from the distribution function, a problem of clustering occurs when low probability values are not sampled due to too few sampling iterations. Thus, Monte-Carlo sampling requires a large number of iterations for adequate coverage over the entire distribution. This problem has led to the development of stratified sampling techniques such as Latin Hypercube sampling that rather than randomly selecting values from the distribution function systematically samples all segments (stratifications) of the distribution. Because each stratification is only sampled once, the reference probability curve can be better represented using this method while needing fewer iterations.

2. CONVENTIONAL-BALE FEEDSTOCK SUPPLY SYSTEM

The scope of the conventional bale feedstock supply system (conventional-bale) design, by definition, is restricted to currently available technologies and existing infrastructure, regardless of the geographical region in which a biorefinery operates. The modeled feedstocks are corn stover (representing a crop residue supply system) and switchgrass (representing an herbaceous energy crop supply system). The conventional-bale design is based on large, square (4×4×8-ft or 3×4×8-ft) bales. Round bales and other biomass collection formats are addressed in the pioneer-uniform design (Section 3). Figure 2-1 shows the process flow and potential waste streams for the conventional-bale system unit operations.

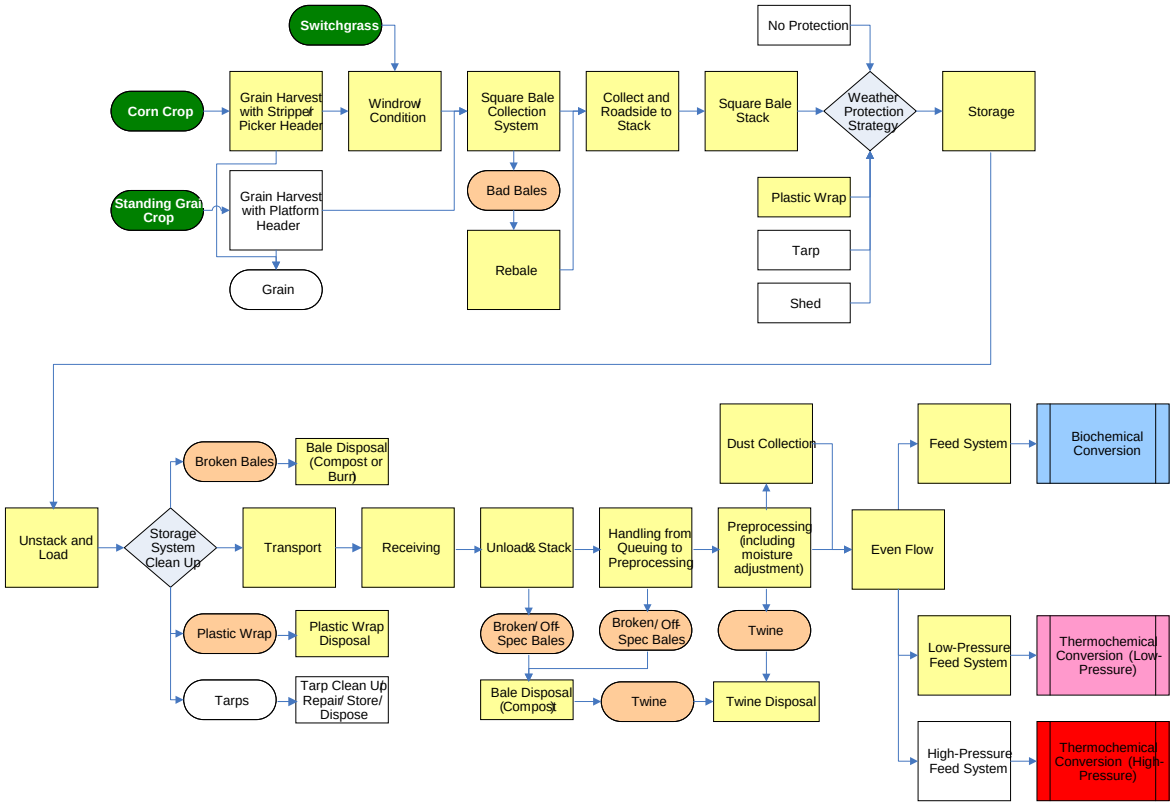


Figure 2-1. Conventional-bale feedstock supply system design process flow. (Green ovals represent format intermediates, tan ovals represent potential waste streams, yellow rectangles represent individual modeled processes, and white rectangles represent alternate processes that were not modeled.)

Even though we have a basic understanding of how current supply system technologies function within existing agricultural operations (i.e., grain harvest for food, feed, and fiber), extending this knowledge to include agricultural residues and dedicated energy crops quickly identifies gaps in the knowledge base. The conventional-bale design is presented by discussing each major supply system unit operation in the respective order of appearance within the design. The order of unit operations in the conventional-bale design are as follows:

- Harvest and collection
- Storage
- Handling and transportation
- Receiving and preprocessing.

The backbone of the 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 in order 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. Additional equipment options are tabulated in Appendix B-1, "Equipment Database."

The modeled conventional-bale 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.

Table 2-1. Conventional-bale supply system design size annual capacity assumptions for corn stover and switchgrass.

	Corn Stover	Switchgrass
Plant Operation Size (delivered tons[a])	800,000 DM tons per year	800,000 DM tons per year
Feedstock Harvested Annually[b]	860,000 DM tons	860,000 DM tons
Acres Harvested Annually	527,000	212,000
Participating Acres	50%	100%
Acres Available for Contract	1,054,000	212,000
Cultivated Acres	2,107,000	4,248,000
Feedstock Draw Radius[c]	45.8 miles	65.0 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 conventional-bale 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. Appendix A-2 provides additional cost and performance detail for each unit operation in the conventional-bale supply system.

2.1 Conventional-Bale Harvest and Collection

Harvest and collection encompasses all processes associated with moving the biomass from the location of production to the storage or queuing location (Figure 2-2). These processes generally consist of cutting, gathering, densifying, and transporting from the field to field-side storage. 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 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. The white ovals and boxes indicate grain harvest operations and material formats that are part of an independent enterprise and are not considered in case studies in this report.

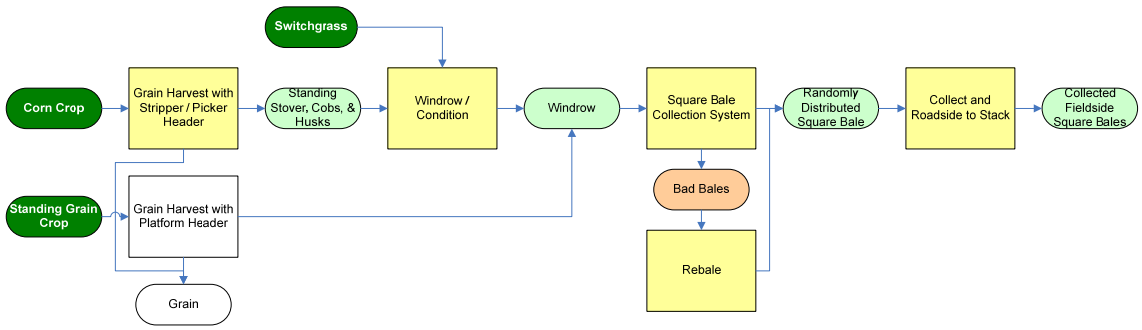


Figure 2-2. Harvest and collection supply logistics processes and format intermediates. (Green ovals represent biomass format intermediates, tan ovals represent potential waste streams, yellow rectangles represent processes modeled in this report, and white shapes indicate alternate process path.)

2.1.1 Conventional-Bale Harvest and Collection Format Intermediates

The type of biomass crop is a significant factor affecting harvest and collection operations. Many systems and operations are used to harvest and collect herbaceous feedstocks. Two typical operations for harvesting and collecting herbaceous feedstocks within the conventional-bale system are collection of the crop residue after grain harvest, or direct harvest, and collection of a dedicated energy crop. The intermediate formats of the feedstock play crucial 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 2-2 identifies the crop residue 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 corn stover crop residue.

	Crop standing in the Field	Grain Harvest	Conditioned/ Windrowed Biomass	Baled Biomass	Collected/ Roadsided Biomass
Biomass Output	Whole Crop (grain and residue)	Stalk, Cob, and Husk (collectively stover)	Stover	Stover	Stover
Yield (DM ton/acre) [a]	8.52 (180 bu/ acre corn)	4.26	3.02	1.63 (2.8 bale/acre)	N/A
Format Output	Standing Crop	Standing Stalk, Cob, and Husk on the Ground	Windrow	Randomly Distributed 4×4×8-ft bales[b]	Collected at Fieldside 4×4×8-ft bales[b]
Bulk DM Density Output	N/A	N/A	1.04 ton/1,000 windrow-ft[c] (~0.8-0.9 lb/ft^3)	9 lb/ft^3 (or 1,150 lb/bale) [d]	9 lb/ft^3 (or 1,150 lb/bale) [d]
Output Moisture (% wet basis [w.b.]) [e]	50%	50%	12%	12%	12%

a. Process output yield calculations based on equipment dry matter loss (Table 2-7).

b. The conventional-bale supply system is based on the 4×4×8-ft bale, though other large square bale formats are available, including the 3×4×8-ft low- and high-density formats.

c. Windrow size is based on a 15-ft swath × yield/acre. (Windrow bulk density is estimated at 10% of bale bulk density; however, biomass material size and weathering can greatly influence windrow volume.)

d. Shinners et al., 2007.

e. Hoskinson et al., 2007.

The corn stover crop residue harvest and collection process begins with the standing corn crop (Figure 2-3a, background). Following grain harvest, the corn stover stubble remains (standing stubble, cob, husk, and some leaves/tops that passed through the harvester and were spread on the ground) are conditioned and windrowed for baling (Figure 2-3b, ahead of tractor). It is possible to use a platform header on the combine, which will cut and pass all of the biomass through the harvester and discharge the residue into a windrow behind the combine (Figure 2-2 alternate process path shown in white). This practice is often used with cereal straws and is not modeled herein as a design option for corn stover. In the conventional-bale design, it is important to note that the moisture of the feedstock is reduced from ~50% to 12% by field drying in the windrow (Table 2-2). Field drying can occur after conditioning and before windrowing if a two-pass operation, commonly referred to as "mow and rake," is employed. This design model uses a single-pass conditioning and windrowing operation that takes standing stubble directly to a windrow.

The size and density of the resulting windrow is an important consideration for baling, field drying, and susceptibility to wind damage. Because this model performs the field-drying operation in the windrow, a relatively small windrow is used (Table 2-2). Doubling windrow size to ~2 ton/ 1,000 windrow-ft can improve the efficiency of the baling operations but may require alternate windrowing methods to ensure adequate and timely field drying of the biomass prior to baling.

The baling operation then drops the bales in the field as they are made (Figure 2-3c). Bale accumulators can be attached to the back of the baler (such as the one shown in Figure 2-3b), allowing the bales to be gathered into rows across the field. However, for this design, a bale accumulator is not used, resulting in a random distribution of bales throughout the field after baling.

Finally, the bales are collected from across the field and transported to the side of the field. The bale collection point is generally placed next to a road that borders the field or is nearby (e.g., less than 5 miles away). This collection operation is often referred to as "roadsiding." Once the bales are roadsided, the harvest and collection unit operation is complete.

(a)

(b)

(c)

Figure 2-3. Corn stover (a) standing in the field (background), and stover stubble after grain harvest (foreground); (b) windrowed with a mower/conditioner (front of tractor) and baled in a 4×4×8-ft format;

and (c) in randomly distributed 4×4×8-ft bales dropped from the baler as they are made, which is the starting configuration for the modeled bale collection process.

The primary feedstock supply system difference between crop residues and energy crops is the initial harvesting process (Figure 2-2). Because dedicated energy crops do not contain a separate grain element (or some other marketable fraction) that must be harvested, they have fewer biomass format intermediates than crop residues (compare Tables 2-2 and 2-3). Biomass attributes of the harvest and collection format intermediates for cornstover and switchgrass are shown in Table 2-3.

Table 2-3. Attributes of harvest and collection format intermediates for switchgrass, a dedicated energy crop.

	Crop in the Field	Conditioned and Windrowed Biomass	Baled Biomass	Collected and Roadsided Biomass
Biomass Output	Whole Crop	Whole crop less stubble (Switchgrass)	Switchgrass	Switchgrass
Yield (DM ton/acre) [a]	5.0	4.50	4.05 (6.3 bale/acre)	N/A
Format Output	Standing Crop	Windrow	Randomly Distributed 4×4×8-ft Bales[b]	Collected at Fieldside 4×4×8-ft Bales[b]
Bulk DM Density Output	N/A	1.4 ton/1,000 windrow-ft (~1.1–1.2 lb/ft^3) [c]	10 lb/ft^3 (or 1,280 lb/bale) [d]	10 lb/ft^3 (or 1,280 lb/bale) [d]
Output Moisture (% w.b.)	34% [e]	12% [a]	12% [a]	12% [a]

a. Process output yield calculations based on equipment dry matter loss (Table 2-7).

b. The conventional-bale supply system is based on the 4×4×8-ft bale, though other large square bale formats are available, including the 4×4×8-ft low- and high-density formats.

c. Windrow size based on a 15-ft swath × yield/acre. (Windrow bulk density estimated at 10% of bale bulk density; however, biomass material size and weathering can greatly influence windrow volume.)

d. INL test data, switchgrass and *Miscanthus* harvest in Illinois, January 2008.

e. Adler et al., 2004.

In the conventional-bale design, the harvesting processes for herbaceous energy crop grasses are similar to those used in forage systems (Rider et al., 1993). For this design, a self-propelled windrower (often referred to as a "swather") is used to cut, condition, and windrow the switchgrass in a single-pass operation (Figure 2-4a). The conditioning process crushes and/or splits the switchgrass stems, which accelerates the field-drying process and conditions the material for subsequent baling operations. To minimize field loss and collect the highest quality biomass possible, the harvesting scenario assumes a fall harvest, which would begin after a killing frost. Due to the higher biomass moisture content of a fall harvest scenario, field drying prior to baling will generally be required (Table 2-3). An alternate approach would be to delay swathing until late fall/winter and allow the grass to dry in the field. This approach greatly expands the harvest window and can minimize storage duration, but the adverse winter weather can cause crop loss and/or crop lodging, making it more difficult to harvest (Adler et al., 2004). Potential crop loss/damage risks from winter weather justify the fall harvest scenario modeled herein. When deciding between a fall or winter harvest, these risks must be considered, but for this modeled scenario, a fall harvest is assumed.

Once the biomass is in the windrow, there is no difference between the crop residue and energy crop harvest and collection unit operation processes in the conventional-bale design model (compare Tables 2-2 and 2-3). The switchgrass is allowed to field dry in the windrow to 12% moisture and is then baled into 4×4×8-ft bales (Figure 2-4).

(a) (b)

Figure 2-4. Switchgrass (a) standing in the field (background, right), and after harvest and windrowed with a mower/conditioner (foreground); and (b) baled in a 4×4×8-ft format.

The conventional-bale design model includes field drying for both the corn stover residue and switchgrass. When field drying is used, the selection of harvest operations must occur with consideration to ambient conditions. During good drying conditions (generally late summer/fall), cutting and windrowing can be performed simultaneously with a single machine, thus eliminating the raking operation (the assumed scenario in Tables 2-2 and 2-3). This can result in reduced harvest cost and time, reduced dirt and debris in the collected biomass, and reduced losses due to breakage. However, if less-than-ideal drying conditions exist, the feedstock might need to be spread thinly in the field with a mow/shred operation and then raked into a windrow prior to baling. In either case, there are significant risks associated with field drying because it increases the chances of precipitation exposure and weather-related harvesting delays, and, in the case of late fall harvests, these delays may altogether prevent drying of the feedstock. As such, environmental factors, farming practices, and crop type all influence harvest and collection scenarios. Depending on the these factors, alternate harvest and collection scenario costs can vary by more than $10/DM ton within the conventional-bale design scenarios due to the different types of harvesting and collection processes required to fit the crop, cropping environment, and farming practices (Table 2-4).

Table 2-4. Windrowing and baling costs for two types of crop residues and perennial grasses (INL Feedstock Model 08-14752).

	Swath	Mow/Shred	Rake	Large Square Bale	Total
Corn Stover ($/DM ton)	—	3.80	6.56	10.82	21.18
Cereal Straws ($/DM ton)	—	—	—	10.82	10.82
Perennial Grasses ($/DM ton)	1.40	—	2.19	13.41	17.00

The three alternate harvest and collection scenarios represented in Table 2-4 are figured according to the following logic:

- *Corn Stover*—Row-crop residues, like corn and *Sorghum* stover, do not pass through the combine during the harvest of the grain and thus require additional operations to cut the remaining stalks. A

flail shredder pulled by a tractor is used to cut and split the stalks open, which accelerates field drying. After the stover has dried to baling moisture (generally <20%), it is gathered into a windrow with a rake and then baled.

- *Cereal Straws*—Wheat, barley, rice, and soybean residues can be harvested and windrowed concurrently with the grain harvest. The entire cut plant passes through the combine harvester, and the straw and chaff are separated from the grain and deposited in a windrow behind the combine. Depending upon the biomass moisture at harvest, the residue windrow can be baled immediately or after adequate field drying.
- *Perennial Grasses*—Switchgrass, rather than being cut with a self-propelled windrower (also known as a swather), may be cut with a tractor-drawn mower/conditioner, field-dried in a wide swath, gathered into a windrow with a tractor-drawn rake, and baled using a large square baler.

2.1.1.1 Biomass Deconstruction, Fractionation, and Yield

Crop physical structure and yield are two biomass material attributes that impact the selection and performance of harvest and collection equipment (Tables 2-2 and 2-3). Cereal straw residues, compared to crops like corn stover and *Sorghum* stover, are generally not harvested or collected in the same fashion. A reason for these differences is the structure of the stem portion of the plant. In the case of cereal straws, the plant's stem diameter, strength, and individual mass is much smaller than corn or *Sorghum* stover, allowing it to pass through harvesting equipment with less reduction in capacity or efficiency than the larger grain crops (Wright et al., 2005). Corn and *Sorghum* stover feedstocks, which typically do not pass though the harvester, require additional equipment to harvest and collect the feedstock. Perennial grasses, such as switchgrass and *Miscanthus*, due to their high yields and thicker stalks, perform differently than traditional forage crops, like alfalfa, in current harvesting equipment. In fact, the specific variety and yield of the feedstock are the primary factors to consider when choosing a particular harvesting technique, such as a self-propelled windrower or a tractor-drawn mower/conditioner. For both crop residues and perennial grasses, the crop/residue yield will significantly impact the selection and efficiency of harvest and collection equipment (Sokhansanj and Pordesimo, 2002).

2.1.1.2 Format and Bulk Density Impact on Supply System Processes

In the conventional-bale harvest and collection design, biomass bale format and bulk density significantly impact the number of bales that must be handled and transported from the field. In this design, collection of crop residues and perennial grasses is accomplished by packaging in large square bales. While the modeled scenario uses 4×4×8-ft bales, these large square bales can be produced in other sizes, including 3×3×8- and 3×4×8-ft bales. An advantage of 3×4×8-ft bales is that they stack more efficiently on the collection/transport equipment; thus, more bales can be moved off the field per collection cycle.

Just as the physical characteristics of the crop can impact harvesting processes, different biomass crops or residues perform differently in baling equipment (Table 2-5). These differences affect bale bulk density, which in turn impacts the number of bales per acre at a respective crop yield for each design scenario (Tables 2-2 and 2-3). Cereal straw residues produce some of the lowest bale densities, resulting in relatively high bale counts per ton of biomass (Table 2-5). The cost to handle each bale is essentially the same, irrespective of bale density or size; thus, plant material or an engineering configuration that produces fewer bales per ton of biomass will improve bale collection and handling efficiencies. For example, a high-density 3×4×8-ft baler producing 1,100- to 1,200-lb stover bales will reduce the bale count from the 3.7 to 4.2 range to the 2.8 to 3.1 range (which is the same as the 4×4×8-ft bale; Table 2-5). As such, handling efficiencies for high-density 3×4×8-ft bales are equivalent to 4×4×8-ft bales, and, as previously mentioned, have the collection/transportation advantage of more bales per collection cycle.

Regardless of the selected biomass handling format, bale density is a key factor in collection and handling efficiencies, capacity, and, ultimately, costs.

Table 2-5. Yield and bulk density data for large square bales of various biomass feedstocks.

		Bale Density	Bale Density	Large Square Bale (4×4×8-ft)	Large Square Bale (3×4×8-ft)
	Crop Yield (baled DM ton/acre)	Wet Bulk Density (lb/ft^3)	DM Bulk Density (lb/ft^3)	Bales/Acre	Bales/Acre
Corn Stover	1.6[a]	10–11[b]	8–9[b]	2.8–3.1	3.7–4.2
Cereal Straw[c]	1.1	8–11	7–9	1.9–2.5	2.6–3.1
Switchgrass[d]	4.0	13–14	11–12	7.0–7.8	9.3–10.4
Miscanthus[d]	5.1	11–13	9–11	8.9–10.0	11.8–13.3

a. INL data, modeled scenario (Table 2-2).
b. Shinners (2007).
c. INL test data, wheat straw harvest in Colorado and Idaho, July to August 2007.
d. INL test data, switchgrass and *Miscanthus* harvest in Illinois, January 2008.

2.1.1.3 Biomass Moisture Impact on Supply System Processes and Material Stability

The moisture content of biomass is a key consideration in the selection of field operations for harvest and collection. The conventional-bale supply system design requires biomass to sufficiently dry so that the material is aerobically stable once it is baled. For most biomass, this is typically less than 15 to 20% moisture w.b. Any biomass above 15 to 20% moisture w.b. will be aerobically unstable and is classed as "wet" biomass (Section 1.2.2). At harvest, most biomass resources can exceed the safe baling and storage moisture limit of 15 to 20% (Table 2-6). In the conventional-bale design, wet aerobically unstable biomass requires field drying prior to baling. If field drying to aerobically stable moisture limits is not possible, alternate supply system strategies must be implemented to stabilize the biomass in the presence of water (e.g., ensiling), remove the water at some later point in the supply system (e.g., Section 4, "Advanced Uniform-Format Supply System"), or provide just-in-time delivery and processing (e.g., year-round green harvest without storage/queuing). Thus, wet biomass that cannot be dried in-field is unsuitable for the conventional-bale design.

Table 2-6. Typical harvest moistures for select crop residues and energy crops.

Corn Stover	Wheat Straw	Switchgrass	*Miscanthus*
20–64%[a]	9–25%[b]	12–15%[c]	16–26%[c]

a. Hoskinson et al., 2007.
b. INL test data, wheat straw harvest in Colorado and Idaho, July to August 2007.
c. INL test data, switchgrass and *Miscanthus* harvest in Illinois, January 2008.

Corn stover is a crop residue that nearly always requires some level of in-field moisture management (Table 2-6). Corn grain is usually harvested between 15 and 30% grain moisture w.b. (Shinners et al., 2007; Hoskinson et al., 2007). Moisture of corn stover at the time of harvest is reported to be roughly twice that of the grain and ranges from 30 to 60% (Shinners et al., 2007). Pordesimo et al. (2004) reported stover moistures ranging from 40 to 66%, while Hoskinson et al. (2007) reported stover moistures as low as 25%. Even at the lowest reported stover moisture, field drying of the biomass prior to baling is required. As an alternative to stover in-field drying, Hoskinson et al. (2007) suggest a fractional harvest of cobs, husks, and upper stalk, which could be within the moisture limit for dry storage at the time of grain harvest.

Cereal grain residues have low plant moisture at the time of harvest, and in many grain-producing regions of the United States fall entirely within the parameters of a dry harvest system (Table 2-6). While national harvest moisture content averages for cereal grains such as wheat and barley range from 10 to 20% w.b. (ASABE, ANSI/ASAE S343.3, 2004), in the arid western United States, moisture content at harvest must be 13% w.b. or less for commodity trade (Rooney, 2008). In these regions cereal straws often get so dry during the heat of the day that it becomes difficult to form a well-packed bale. Consequently, large straw producers in arid regions like Idaho often bale cereal straw residue during the night and early morning hours, when lower temperature and higher humidity produce higher straw moisture (Grant, 2003)

Unlike crop residues, whose harvest time is constrained to the harvest window of the grain, dedicated crops grown for biomass can be scheduled for harvest when crop maturity and moisture are optimal. Moisture levels for green-harvested switchgrass can be in excess of 70% (Venturi et al., 2004; Shinners et al., 2006). Following senescence, or the period after a plant has fully matured, in the fall/winter, switchgrass harvest moisture rapidly drops to the dry biomass range (Table 2-6). Shinners et al. (2006) reported that switchgrass dried considerably faster than typical perennial forage crops (i.e., alfalfa and grass hay) despite the fact that switchgrass yield, and thus the windrow density, was more than double that of typical forage crops. This study reported that switchgrass harvested with a mower/conditioner at 46 to 66% w.b. had dried to a baling moisture of <20% w.b. by the afternoon of the third day of field drying, and when the crop was placed in a wide swath by tedding (spreading and airing), it was possible to achieve baling moisture in a single day. Of course, these times will be longer if weather inhibits the drying process. Nevertheless, the favorable field-drying characteristics of switchgrass make it well suited to a dry-bale harvest system. Conversely, because switchgrass can also be harvested green, it could be incorporated into a wet silage-based supply system, which demonstrates the supply-system flexibility of energy crops.

2.1.2 Conventional-Bale Harvest and Collection Equipment

In the conventional-bale design, the only appreciable difference between corn stover and switchgrass equipment is the additional grain harvest equipment (Table 2-7). For residues, the grain harvest operation precedes residue harvest and substantially alters the crop residue from its original standing position in the field. While some material remains standing in the field, much of the corn stover ends up lying on the ground following the harvest operation (Table 2-2). As a result, equipment selected to windrow corn stover is functionally different from that selected for switchgrass being cut and windrowed (Table 2-7). Once the corn stover and switchgrass are in the windrow, all other harvest and collection unit operation equipment is functionally similar.

Table 2-7. Harvest and collection equipment specifications for the conventional-bale design.

	Grain Harvest Only	Condition/ Windrow Stover Residue	Condition/ Windrow Switchgrass	Baling	Move to Field Side (Roadsiding)
Equipment	JD 9670 STS Combine with JD 608C 8-Row Corn Header	Balzer 15-ft Flail Shredder with windrowing pulled by Case IH Puma 180 Tractor	Agco 9260 Windrower with 9180 disc header	Massey Ferguson 2190 Baler pulled by Case IH Magnum 275 Tractor	Stinger Stacker 5500
Haul Distance	N/A	N/A	N/A	N/A	0.5 miles
Rated Capacity[a]	2000 bu/hr	9.1 ac/hr	12.7 ac/hr	38 bales/hr	90 bales/hr [a]
Field Efficiency (%)[a]	70%	80%	80%	80%	80%
Dry Matter Loss (%)[b]	N/A	29%	10%	Stover=46% Switchgrass=10%	0% (assumed)
Operational Window					
hrs/day	14.0	14.0	14.0	14.0	14.0
days/year	36	36	36	36	36

a. See machinery capacity and efficiency calculations (Table 2-9).

b. Stover based on Richey et al., 1982; Switchgrass based on INL test data, switchgrass, and *Miscanthus* harvest in Illinois, January 2008.

2.1.2.1 Equipment Used in Conventional-Bale Design Model

Grain Harvest

The primary harvesting equipment for grain harvest is the combine (Table 2-7). The basic functions of the combine are to (1) cut the biomass standing in the field, (2) separate the grain from materials other than grain (MOG), and (3) capture the grain while returning the MOG to the field. The combine can use a number of different headers that attach to the front of the combine and interface with the biomass standing in the field. For this design, the John Deere the 9670 STS combine (Figure 2-5a) is selected to be used with the John Deere 608C 8-Row Header (Figure 2-5b). Key distinguishing characteristics of the corn header include a row-crop design developed to harvest corn at the standard 30-in. row spacing and downward-turning snapping rollers at the physical interface of the header and corn stalks. The purpose of these snapping rollers is to pull the corn plant down through the header in order to capture the ears while reducing the amount of MOG that enters the throat of the combine. It is this header design that primarily contributes to the format configuration of the stover prior to windrowing (Table 2-2).

(a)

(b)

Figure 2-5. (a) John Deere 9670 STS combine and (b) John Deere 608C 8-row corn grain header.

Conditioning/Windrowing Stover Residue

In a standard corn grain harvest scenario, a significant amount of stover will remain standing in the field, and the MOG that passes through the combine will be deposited back onto the ground through the combine discharge spreader (assuming the combine is not equipped with a residue discharge chopper). A shredder/windrower follows the combining operation to break down the stover and collect it along with the MOG into a windrow. The basic shredder design has knives mounted on a rotor that is powered by the PTO of the draft tractor. This design uses a Balzer 15-ft flail shredder with windrowing (Figure 2-6a) pulled by a Case IH Puma 180 four-wheel drive tractor, which provides 180 gross hp and 150 PTO hp (Figure 2-6b). The rotating shredder knives cut the standing biomass ~8 to 10 in. above the ground and pull materials resting on the field surface into a windrow. The windrow is formed through collision-induced momentum and a vacuum effect created by the high rotational speed of the rotor and knives. The windrow will field-dry for hours to days and will then be ready for baling.

(a) (b)

Figure 2-6. (a) Balzer 15-ft flail shredder with windrowing which, in the conventional-bale model, is pulled by a (b) Case IH Puma 180 four-wheel drive tractor.

Tractor photo provided courtesy of Case IH (www.caseih.com).

Conditioning/Windrowing Switchgrass

For switchgrass, the windrowing operation begins with the standing crop. The equipment selected in this design is a Hesston 9260 self-propelled windrower (Figure 2-7). The basic functions of the windrower are to (1) cut the biomass standing in the field, (2) condition the biomass by moving it through a set of crimping rollers, and (3) return the cut and conditioned biomass to the field in a windrow. The windrow will field-dry for hours to days and will then be ready for baling.

Figure 2-7. Hesston 9260 self-propelled windrower swathing switchgrass at the University of Illinois Champaign Urbana field trials.

Baling

There are several bale formats that can be selected to collect the field-dried biomass from the windrow. The baler is pulled behind a tractor, and the baler's mechanical systems are powered by the tractor's PTO drive. The baler is equipped with a pick-up system that pulls the biomass from the windrow up into the stuffer, which stuffs the biomass into the compaction chamber. The material is then compacted into a bale, and once the bale has reached the cut-off length, the baler ties the bale together with six poly twine strings. This design uses a Massey Ferguson 2190 4×4×8-ft large square baler pulled/powered by a Case IH Magnum 275 tractor (Figure 2-8). The Magnum 275 has a 275 gross hp tractor with 225 PTO hp.

Figure 2-8. Massey Ferguson 2190 large square baler (4×4×8-ft bales) and Case IH Magnum 275 tractor.

Collection and Roadsiding

The bale accumulator attachment was not used in this design; thus, the tied bale is ejected randomly onto the field surface from the pressure of the next bale being formed. Random bale distribution is acceptable and even desirable for the efficient operation of automated bale collection and stacking equipment. Automated collection and stacking equipment picks up bales on-the-go, and the forward momentum of the stacker is necessary to properly orient and slide the bale into the pickup mechanism (Figure 2-9a).

The Stinger Stacker 5500, a self-propelled bale collection and transport system, is used in this design for bale collection, transport, and stacking. With a full stacking deck that holds eight large square bales (4×4×8-ft), the Stinger can stack bales up to four rows high using hydraulic bale dumps (Figure 2-9b). During standard operation, the Stinger dumps twice to unload. During the first dump, the top four bales are retained on the upper portion of the deck while the bottom four bales are unloaded from the bottom bale deck. The bottom bale deck then resets, and the top four bales slide into the bottom deck position and are placed in the stack.

In this design, the bales are loaded into a bale plastic wrapping system for storage rather than stacked by the stacker. The stacking rack gate is released, and while the machine stays in motion, the bales simply slide off the bale deck onto the ground at the unload point. Because the bales are not being stacked, the stacker can transport nine bales instead of eight to the unload point during each collection cycle. Stacking/wrapping then occurs as part of the storage unit operation.

(a) (b)

Figure 2-9. Stinger Stacker 5500 (a) picking up and (b) stacking bales.

While conventional-bale design harvest and collection processes are functionally simple, specific equipment selection options can be almost limitless. A primary consideration in equipment model selection is the rated machine capacity relative to the number of acres to be harvested within the operational harvest window of the crop and region (Table 2-7). There are other factors to take into account in the equipment selection process, such as user preference, serviceability, and equipment features, which are not included in our analysis. For a list of additional equipment options that could be used in the conventional-bale design scenario, see Appendix B-1.

2.1.2.2 Equipment Capacity and Operational Efficiency

Machine field capacity is a function of field speed, crop yield, field efficiency, and machine working width (ASABE EP496.3, 2006a). Field efficiency 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 (see Section 2.1.2.2, "Operational Dry Matter Losses"). Field speed is difficult to independently quantify because it varies with crop yield (specifically, the amount of materials processed by the machine) and field conditions. Field efficiency is a factor used to account for conditions that cause a machine to operate at less than its theoretical-rated capacity. Time spent unloading, refueling, and in unproductive travel (e.g., turning around at the end of the field) are all events contributing to a reduction of field efficiency. Table 2-8 shows the range and typical values of field speed and field efficiency for different row crops and perennial grass harvest and collection equipment (ASABE D497.5, 2006b). These values were generally used in the modeling of the design scenarios, with the exception of the field speeds noted in the "Model" column of Table 2-8.

Table 2-8. Typical field speeds and field efficiencies for harvesting machines (ASABE D497.5, 2006b).

Machine/Equipment	Field Speed (mph)			Field Efficiency (%)	
	Range	Typical	Model	Range	Typical
Corn Combine	2.0–5.0	3.0	3.8 [a]	65–80	70
Small Grain Combine	2.0–5.0	3.0	3.0	65–80	70
Shredder	3.0–6.0	5.0	5.0	75–85	80
Self-Propelled Rotary Mower Conditioner (Windrower)	5.0–12.0	7.0	7.0	75–90	80
Rake	4.0–8.0	6.0	6.0	70–90	80
Large Square Baler	4.0–8.0	5.0	7.4 [a]	70–90	80
a. Adjustment based on INL 2007 harvest field data.					

Another factor contributing to machine field capacity is the cutting head working width. For the cutting head on a combine, mower, or windrower, the working header width is the percentage of the total width that is actually cutting and gathering the crop. The header working width is assumed to be 100% for row crop machines (i.e., rows guide the head ensuring full usage of the header) and 90% for machines that do not operate in rows (i.e., without rows the header overlaps the previous swath to ensure the entire crop is gathered) (Table 2-9, Footnote d). Field capacities for machinery used in the harvest and collection operation of crop residues and herbaceous energy crops are shown in Table 2-9.

Table 2-9. Field capacities for harvesting machines calculated using the typical field efficiencies and field speeds (ASABE, ASAE EP496.3 2006a; ASAE 497.5 – 2006b).

Machine/Equipment	Yield		Capacity		
	Value	Units per acre	Rated[a]	Field[b]	Units per hour
Corn Combine[c]	180	bushels	2,000	1,400	bushels
Small Grain Combine[d]	60	bushels	550	385	bushels
Corn Stover Shredder[e]	3.02 [f]	DM tons	9.1	7.3	acres
Corn Stover Rake[g]	3.02	DM tons	14.5	11.6	acres
Corn Stover Large Square Baler [h]	1.63 [i]	DM tons	38	30.4	bales
Switchgrass	5	DM tons	12.7	10.2	acres

Windrower[j]					

a. Rated capacities are calculated using the field speed shown in Table 2-8.
b. Field capacities are calculated by de-rating the rated capacity by the "typical" field efficiencies shown in Table 2-8.
c. Corn combine: Class 6 combine with 8-row, 30-in. spacing (24-ft overall with) corn header.
d. Grain combine: Class 6 combine with 25-ft platform header, 85% usage (21.25-ft effective width).
e. Shredder: 15-ft width.
f. Shredder and rake yields are based on 4.26 DM tons/acre production with 71% harvest efficiency.
g. Rake: 25-ft twin rotary.
h. Baler: large square baler, 4×4×8-ft, 9.0 lb/ft^3.
i. Baler yield is based on 3.02 DM ton/acre in the windrow with 54% collection efficiency.
j. Windrower: Rotary mower-conditioner, 15-ft header, 90% header usage.

A key factor for improving the capacity and field efficiency of a given machine is reducing unproductive operational time. In the grain harvest industry, combine field capacity has been greatly improved by using grain carts that virtually eliminate equipment downtime for crop unloading. Equipment service crews working at night can reduce equipment downtime for service and maintenance during hours when machinery should be operating. New GPS-based swath control technology is reducing overlap in non-row crops, such as switchgrass, thereby greatly improving machine working width efficiency. Solutions to improved field capacities and efficiencies are a combination of new technologies, additional pieces of equipment, and management.

2.1.2.3 Operational Dry Matter Losses

Dry matter losses occurring during harvest and collection are generally represented in terms of harvest-efficiency factors, which relate to a machine's ability to harvest or collect the residue, and are represented as the ratio of residue mass actually harvested to the mass available in the field. Dry matter loss is one of the most significant barriers in biomass harvest and collection operations, at over 60% for residues and ~20% for energy crops (Table 2-7). It may be argued that these losses are desirable because biomass left behind will maintain soil sustainability, but uncontrolled loss is never desirable. Biomass will likely need to remain on the field to maintain soil health, but what is left must be a controlled return or omission rather than a machine loss.

Harvest efficiency is affected by several machine and field conditions. For combine harvesters, cut height or the use of stripper/picker headers (e.g., corn headers) affects the amount of biomass left in the field as standing stubble relative to what is returned to the ground in a windrow or distributed through spreaders. Cut height is often dependent on field conditions (e.g., topology and rocks) and, particularly in the case of cereal straws, the tendency of the combine operator to raise the cut height to maximize combine grain capacity. Stripper or picker combine headers are designed to bring the grain into the harvester, leaving behind as much of the crop residue as possible, thereby minimizing the MOG in the harvester separator mechanisms. Multipass operations involving combining, shredding, and raking are particularly prone to field losses. In the case of corn stover, the cobs and husks that pass through the combine and the chopped stover from the shredding operation fall to the ground. The inability to collect these fractions from amidst the standing stubble without collecting excess soil and rocks often results in considerable field losses. Dust generated from the pulverization of dry, friable fractions, such as leaves, may also be a considerable source of field losses, particularly in the harvesting and windrowing operations. Richey et al. (1982) suggest that biomass dust generated during combining, shredding, and windrowing accounts for as high as 20% of the harvest losses. Field traffic in multipass harvest operations is also source of field loss because the stubble gets knocked down by the combine and grain hauling equipment tires (Richey et al., 1982). Field traffic is not as much of a concern for cereal straws that are windrowed behind the combine or energy crops that are directly windrowed, but traffic across the windrows will cause some loss.

Inclement weather that occurs after grain harvest while the crop (residue or energy crop) is in the windrow can also have a significant impact on field losses. Rain causes the biomass to be matted against the ground and, in the extreme case, can lead to microbial degradation. The matted and degraded biomass can be particularly difficult to pick up with a rake or baler. In a 2-year study of corn stover collection, Shinners et al. (2006) note a significant reduction in harvest efficiency due to weather. The harvest efficiency of shredding, raking, and baling was 33% for the year that frequent rain and snow fell during the field-drying period, compared with 41% for the year of better weather.

Baler pickup is also an observable source of field losses and is impacted by travel speed, windrow size, windrow condition, and the orientation of the crop in the windrow. In general, chopped corn stalks are more difficult to pick up with the baler than cereal straws, and cereal straws are more difficult to pick up than grasses. Shinners et al. (2006) report considerable difficulty in picking up chopped corn stover windrows with a square or round baler and forage chopper equipped with a pickup head. Overall, combined stover windrowed by a shredder/windrower demonstrated harvest efficiencies for windrowing ranging from 34 to 82%, depending on the amount of stover trampled by harvest equipment (Richey et al. 1982). Final harvest efficiency after baling was ~34% (Richey et al. 1982). Shinners et al. (2006) conducted a similar study and reported harvest efficiencies of shredding, raking, and baling ranging from 25 to 41%, with the lower value attributed to weather-related issues.

Using a Hesston 9260 windrower, the harvest efficiency for the windrowing switchgrass was 90% (Table 2-7). The baling harvest efficiency was also 90% (Table 2-7). The primary reason for these greatly improved harvested efficiencies relative to crop residues is the simplified harvest and collection processes (i.e., no combine). For crop residues to achieve the harvest efficiencies of energy crops, the combine will ultimately need to become an integral part of the residue harvesting operation.

2.1.2.4 Operational Window

Timeliness is a key attribute in harvest and collection operations. It is impacted by the harvest window (the number of days within which the operation should or can be accomplished), the number of working hours per day, total acres, biomass yield, and machine capacity. The harvest window is generally bound by crop maturity and the arrival of adverse weather, and it varies by crop variety, time of year, and geographic area. Harvesting cannot commence until the crop is mature, and if crop maturity is delayed beyond the optimum harvest window, grain and/or residue yield and quality may be reduced. The fraction of annual crop value lost per day due to harvesting either before or after the optimum harvest window may range from 0.3% to 1%, depending on the crop (ASABE, ASAE D497.5, 2006).

In an extreme case, delayed or prolonged harvest could prevent the completion of harvest before adverse weather destroys the remainder of the crop. Further, a delay between grain and residue harvest, when the residue is laying cut in the field, may also lead to additional dry matter loss that results from microbial degradation and weather-related effects. Shinners et al. (2007) report that these losses increased as the delay between grain harvest and residue collection increased. A delay in harvesting also leads to delays in subsequent field operations, such as fertilizer application and soil preparation, which results in lost opportunity costs and could impact the subsequent season's production and, ultimately, grower participation in residue removal.

The harvest window is estimated using USDA-NASS crop progress data, which show the weekly cumulative progress of crop harvest for each state. A sample of this data is shown in Figure 2-10, which represents a 5-year average of corn harvest progress in Nebraska. Based on this data, the statewide harvest window spanned an 11-week period from week 36 to week 47. The conventional-bale design scenario modeled herein is based on only the most active 6-week period of the harvest window (Table 2-7). In reality, the harvest window within a local production area will be less than the statewide data represents. In addition, weather delays may significantly limit the actual productive days within the harvest window.

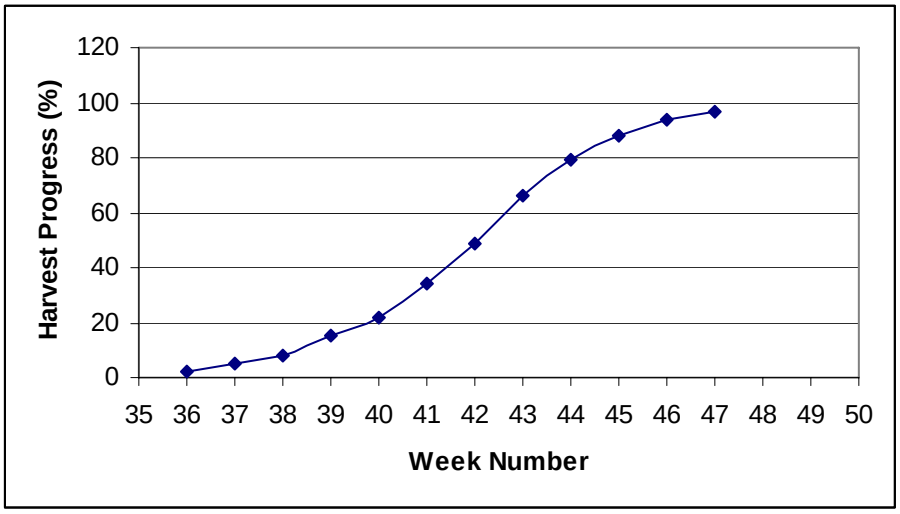


Figure 2-10. Cumulative corn harvest progress for Nebraska (USDA-NASS, 2008).

Baling of crop residues is assumed to occur within the same harvest window as grain harvest, with no more than 7 days' delay for field drying. Consequently, the crop residue harvesting season is shorter than the grain harvesting season but, for the purposes of the conventional-bale scenario model, is well within the 11-week window (Table 2-7).

The daily hours of operation are also subject to ambient conditions. Harvesting operations generally end when the dew sets in and the crops get too tough to thresh or too wet to bale. Similarly, during the heat of the day cereal straws commonly get too dry to make a good bale, limiting daily baling hours. The productive work hours per day is estimated to range from 12 hours/day in wet regions to 14 hours/day in dry regions, assuming the harvest window falls in the August to September time frame. Clearly, the early spring/summer harvest window (e.g., Kansas wheat straw) and late fall/winter harvests (e.g., Tennessee switchgrass) may have much shorter operable hours per day due to weather and/or lower temperatures. Therefore, it is important to have the machine capacity and the number of machines necessary to complete the harvest operations within the harvest window available for each crop/region. Spreading equipment across multiple crops and cropping microclimates, such as using traveling custom harvesters, can greatly expand operational windows for machinery.

2.1.3 Conventional-Bale Harvesting and Collection Cost and Sensitivity Analysis

2.1.3.1 Static Model Cost Summary

A breakout of the costs associated with each piece of equipment used in the harvest and collection unit operation identifies significant cost components that are valuable for making individual comparisons and recognizing areas of research potential (Table 2-10). These costs are reported in terms of DM tons entering each process respectively.

Table 2-10. Static model costs for major harvest and collection equipment in the conventional-bale corn stover scenario.

	Grain Harvest Only[a]	Condition/Windrow Stover Residue	Baling	Move to Field side (Roadsiding)
Equipment	JD 9670 STS combine with JD 608C 8-row corn header	Case IH Puma 180 tractor and a Balzer 15-ft Flail Shredder with windrowing	Case IH Magnum 275 tractor and a Massey Ferguson 2190 baler	Stinger Stacker 5500
Installed Equipment Quantities	N/A	155	105	45
Installed Capital[b]	N/A	12.60	24.11	7.43
Ownership Costs[c]	N/A	1.14	4.00	1.09
Operating Costs[d]	N/A	2.71	6.82	0.92
Labor	N/A	0.60	0.75	0.27
Non-Labor	N/A	2.11	6.07	0.64
Dry Matter Loss Costs	N/A	N/A	3.28	N/A
Energy Use (Mbtu/DM ton)	N/A	91.2	77.3	20.0

a. Grain harvest defines the stover harvest window and stover material input condition (Table 2-1), but in the conventional-bale design, no additional harvesting costs are incurred.

b. Installed capital costs are $ per annual DM ton capacity.

c. Ownership costs include depreciation, interest, taxes, insurance, and housing (Appendix A-2, Table A-7).

d. Operating costs include repairs, maintenance, fuel, lubrication, labor, and consumable materials (Appendix A-2, Table A-7)

Table 2-11. Static model costs for major harvest and collection equipment in the conventional-bale switchgrass scenario.

Equipment	Condition/Windrow Switchgrass	Baling	Move to Field side (Roadsiding)
	Agco 8365 Windrower with 9180 disc header	Case IH Magnum 275 tractor and a Massey Ferguson 2190 baler	Stinger Stacker 5500
Installed Equipment Quantities	60	95	41
Installed Capital[a]	7.84	21.77	6.77
Ownership Costs[b]	1.28	3.60	0.99
Operating Costs[c]	1.89	6.14	0.83
Labor	0.37	0.67	0.25
Non-Labor	1.52	5.47	0.58
Dry Matter Loss Costs	N/A	0.52	N/A
Energy Use (Mbtu/DM ton)	36.1	69.6[d]	18.0

a. Installed capital costs are $ per annual DM ton capacity.

b. Ownership costs include depreciation, interest, taxes, insurance, and housing (Appendix A-2, Table A-7).

c. Operating costs include repairs, maintenance, fuel, lubrication, labor, and consumable materials (Appendix A-2, Table A-7).

d. Energy use of tractor included in the baler value.

2.1.3.2 Cost Sensitivity Analysis

A histogram of the harvest and collection cost (Figure 2-11) for corn stover shows that with 90% confidence the cost of the unit operation ranges between $17.79 and $26.49 per DM ton. Further, the mean and standard deviation of this range is $21.61 ± 2.69 per DM ton. The mode value of the harvest and collection cost is $20.61 per DM ton. This value closely represents the result of the static model, which is $19.96 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

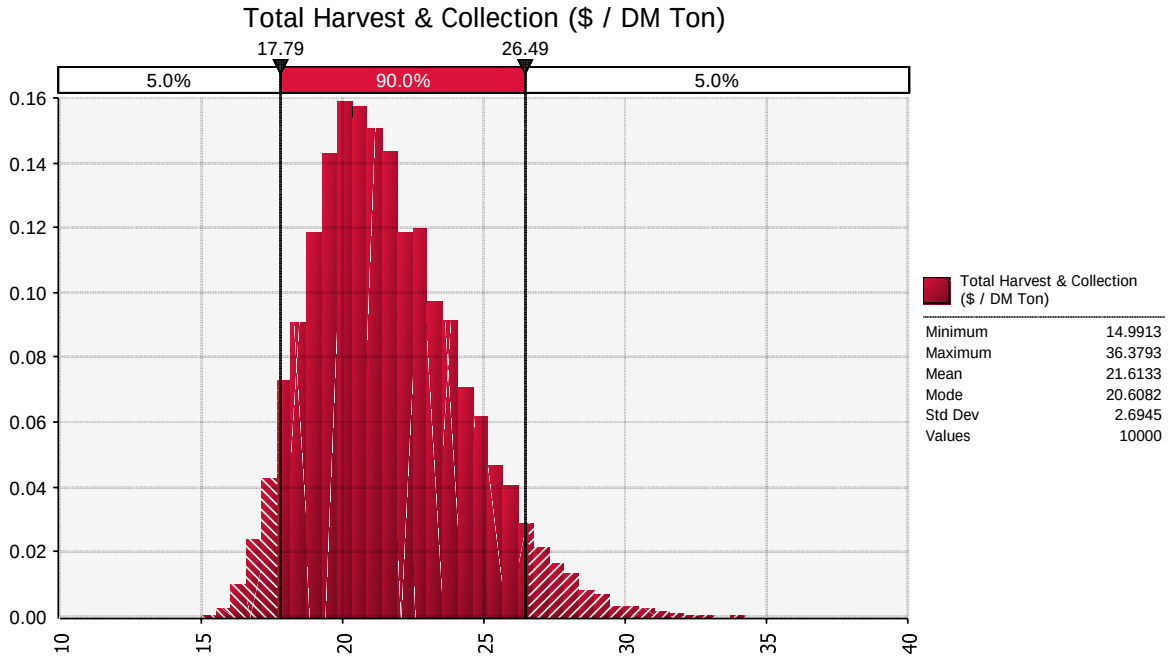


Figure 2-11. Conventional-bale harvest and collection cost distribution histogram from @Risk analysis for corn stover.

Similarly, a histogram of the harvest and collection cost (Figure 2-12) for switchgrass shows that with 90% confidence the cost of the unit operation ranges between $12.69 and $17.45 per DM ton, with the mean and standard deviation of this range being $14.92 ±1.45 per DM ton. The mode value of this cost range is $14.46 per DM ton, which closely represents the result of the static model of $15.25 per DM ton.

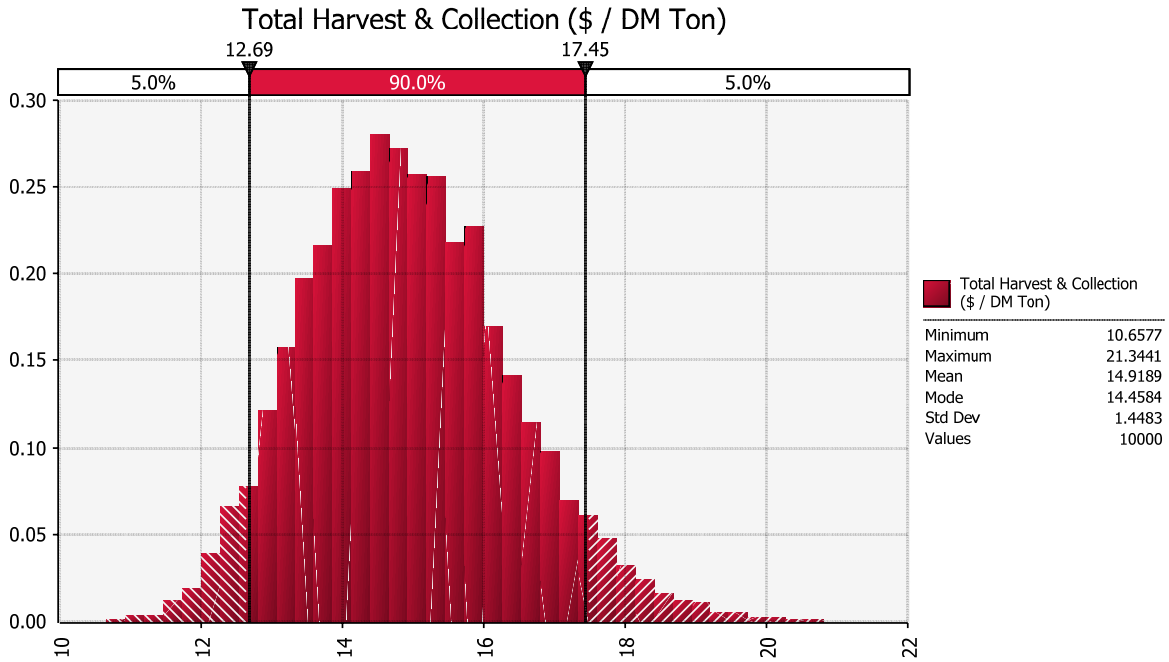


Figure 2-12. Conventional-bale harvest and collection cost distribution histogram from @Risk analysis for switchgrass.

The overall costs associated with the conventional-bale harvest and collection unit operation for both corn stover and switchgrass are provided in Tables 2-12 and 2-13, respectively, on a per DM ton, per bale, and per acre basis. These costs, reported as a mean and standard deviation, come as a result of 10,000 model iterations of the simulated conventional-bale feedstock supply system.

Table 2-12. Harvest and collection cost summary for the conventional-bale corn stover scenario.

	Grain Harvest Only[a]	Condition/ Windrow Stover Residue	Baling	Move to Field side (Roadsiding)	Dry Matter Loss	Total Harvest and Collection
Equipment	JD 9670 STS combine with JD 608C 8-row corn header	Balzer 15-ft Flail Shredder with windrowing pulled by Case IH Puma 180 tractor	Massey Ferguson 2190 baler pulled by Case IH Magnum 275 tractor	Stinger Stacker 5500		
Modeled Cost Totals[b]	No Cost	4.16 ± 0.65 $/DM ton	10.91 ± 1.11 $/DM ton	1.89 ± 0.32 $/DM ton	4.65 ± 1.91 $/DM ton	21.61 ± 2.69 $/DM ton
	No Cost	N/A	6.38 ± 0.54 $/bale	1.10 ± 0.18 $/bale	N/A	7.48 ± 0.60 $/bale
	No Cost	12.27 ± 1.53 $/acre	15.86 ± 3.62 $/acre	2.75 ± 0.75 $/acre	6.26 ± 1.38 $/acre	37.14 ± 4.25 $/acre

a. Harvest costs associated with grain are not included in the cost of the feedstock since they are born by the grain industry.

b. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

Table 2-13. Harvest and collection cost summary for the conventional-bale switchgrass scenario.

	Condition/Windrow Switchgrass	Baling	Move to Field side (Roadsiding)	Dry Matter Loss	Total Harvest and Collection
Equipment	Agco 8365 Windrower with 9180 disc header	Massey Ferguson 2190 baler pulled by Case IH Magnum 275 tractor	Stinger Stacker 5500		
Modeled Cost Totals[a]	3.01 ± 0.77 $/DM ton	9.77 ± 0.96 $/DM ton	1.70 ± 0.28 $/DM ton	0.44 ± 0.21 $/DM ton	14.92 ± 1.45 $/DM ton
	N/A	6.34 ± 0.52 $/bale	1.10 ± 0.17 $/bale	N/A	7.44 ± 0.59 $/bale
	11.58 ± 2.01 $/acre	34.01 ± 7.26 $/acre	5.92 ± 1.51 $/acre	1.45 ± 0.57 $/acre	52.96 ± 8.75 $/acre

a. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

2.2 Conventional-Bale Storage

Storage encompasses all processes associated with stacking, protecting the biomass from weather or other environmental conditions, and storing the biomass in a stable condition until called for by the biorefinery (Figure 2-13). In the conventional-bale design, storage does not include biomass material stabilization (i.e., drying or ensiling) because stabilization of the biomass material occurs with the field drying process in the harvest and collection unit operation. Rather, the conventional-bale storage design employs technologies and methods to protect the bales from both mechanical and biological losses. The storage configuration for the conventional-bale design is on-farm stacks of bales located field-side or near field-side. There are several options that can be used to protect stacks of bales from weather damage, including under-shed storage, tarping, or wrapping in plastic (Figure 2-13). For the conventional-bale design scenario, the plastic wrap storage system was chosen as a universal storage system design that will meet the maximum weather protection requirements and provide a workable biomass storage system for all baled biomass in any environment (Figure 2-13) yellow “Plastic Wrap” box). The selection of the best storage protection strategy depends upon local conditions, including the option of stacks with no protection, which is a common strategy selected in arid regions of the Western United States (Figure 2-14).

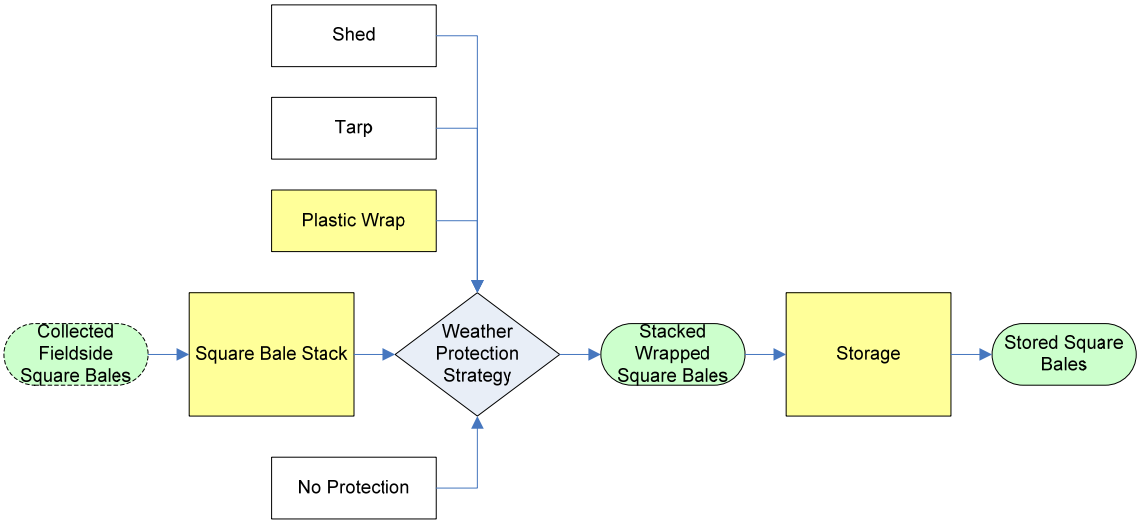


Figure 2-13. Storage supply logistic processes and format intermediates. (Green ovals represent format intermediates, yellow rectangles represent processes modeled in this report, white rectangles represent processes not modeled in this report, and grey diamonds represent multiple process options).

Figure 2-14. Unprotected field-side stack of corn stover bales built with a Stinger 6500 bale handler.

2.2.1 Conventional-Bale Storage Format Intermediates

The conventional-bale storage system design objective is to maintain the original biomass properties throughout the duration of storage, so that when the biomass is retrieved from storage it is as close as possible to its original condition. In practice, however, some changes will always occur, resulting in biomass losses during storage (Figure 2-15). Storage losses are often referred to as "shrinkage." Storage shrinkage and quality degradation factors can include physical loss (e.g., stack wind erosion, handling losses), bulk settling, moisture partitioning, dust accumulation, and some degree of biological impacts. The biological impacts may stem from combinations of filamentous fungi, bacteria, insects, and rodents. Additionally, the moisture content may increase due to precipitation or humidity, or, in arid environments, the moisture content may decrease due to prolonged evaporation. Moisture increases during storage generally accelerate detrimental microbial activity; thus, preventing moisture increases will slow or arrest such microbial activity. Like forage bale storage systems, moisture content of bales going into the storage stack is of particular concern due to the spontaneous combustion risk of high-moisture bales (Gray et al., 1984; Clarke, 1993). The modeled conventional-bale design only accepts bales into storage at or below 12% moisture, which is a safe moisture range for bale stack storage of all biomass. This design also employs a plastic-wrap storage system, which is one of the most aggressive bale protection systems available for field-side storage (Figure 2-16. Even with a bale wrap storage system, there will still be some loss (shrinkage) that occurs during storage, which, for this model, is set at 5% (Table 2-14, yield change). Biomass material properties cause corn stover and switchgrass to be differentially susceptible to physical and biological losses. These potentially off-setting differences would not support the application of different storage loss assumptions based on the biomass material alone, so modeled storage losses of 5% were used for both the corn stover and switchgrass scenarios.

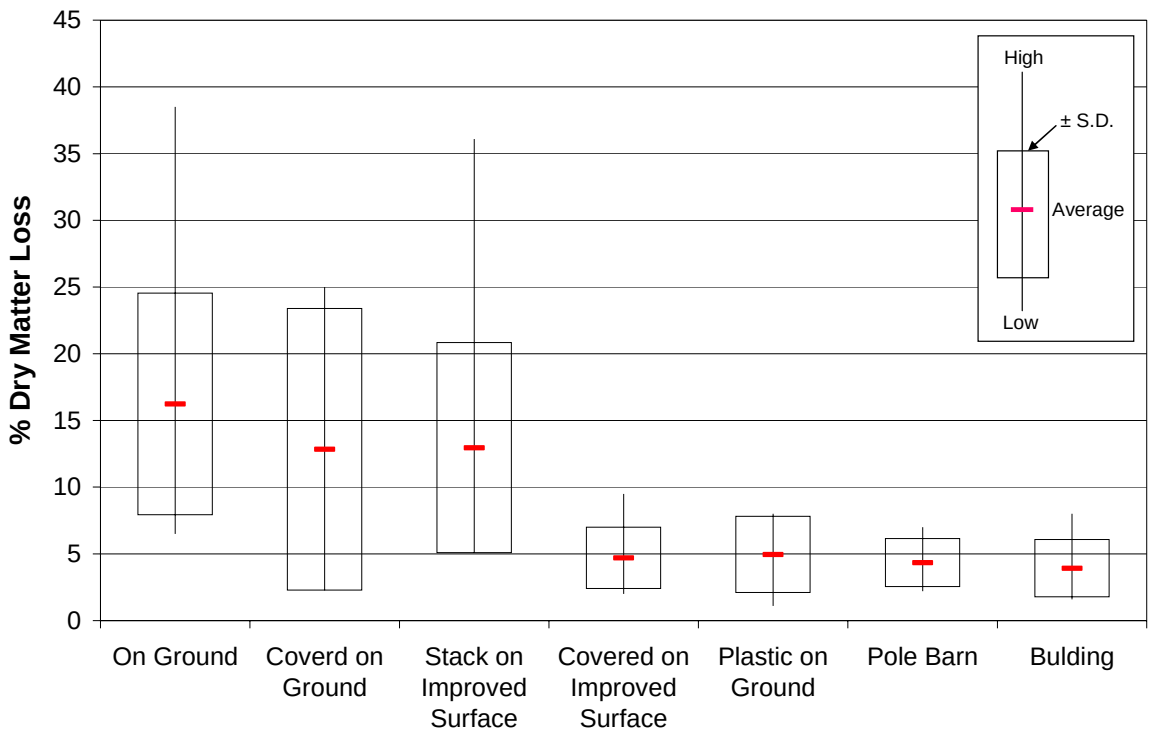


Figure 2-15. Expected range of dry matter loss for different storage configurations in wet climates (Appendix A-2; storage loss data).

Table 2-14. Attributes of storage format intermediates for corn stover crop residue and switchgrass, a dedicated energy crop.

	Stacked Bales	Stored Bales		Stacked Bales	Stored Bales
Biomass Output	Stover	Stover		Switchgrass	Switchgrass
Yield (DM tons/stack) [a]	200 tons/stack (348 bales)	190 tons/stack (348 bales)		200 tons/stack (313 bales)	190 tons/stack (313 bales)
Format Output	Rows of plastic wrapped 4×4×8-ft bales, stacked 1 bale wide and 2 bales high at fieldside	Rows of plastic wrapped 4×4×8-ft bales, stacked 1 bale wide and 2 bales high at fieldside		Rows of plastic wrapped 4×4×8-ft bales, stacked 1 bale wide and 2 bales high at fieldside	Rows of plastic wrapped 4×4×8-ft bales, stacked 1 bale wide and 2 bales high at fieldside
Bulk DM Density Output [b]	9 lb/ft^3 stack (0.13 acres/stack)	9 lb/ft^3 stack (0.13 acres/stack)		10 lb/ft^3 stack (0.11 acres/stack)	10 lb/ft^3 stack (0.11 acres/stack)
Output Moisture (% w.b.)	12%	12%		12%	12%

a. Assume 5% shrinkage of yielding DM tons during storage (i.e., loss of original biomass DM), actual wet tons may be equal to or greater than starting tonnage (Table 2-7).

b. Bale bulk densities as described in Section 2.1, "Harvesting and Collection;" model assumes wrapping results in tight stack with the same bulk density as the bales.

Figure 2-16. Corn stover and/or switchgrass bales stacked in a plastic-wrapped row at field-side.

Storage requirements, such as minimizing mechanical and biological losses, are highly dependent on feedstock variety. For example, small-stem feedstocks, such as cereal straws or perennial grasses, tend to form tighter, more uniform bales than large-stem feedstocks, such as corn and *Sorghum* stover (Table 2-14, stover versus switchgrass bale density). These tighter, more uniform bales handle and stack better and are less prone to breakage. The small-stem feedstocks, due to their size and packing ability, also maintain their natural integrity during the baling process, which decreases the potential of small, broken pieces falling from the bales during handling or blowing away while in storage.

Different feedstock varieties also have varying degrees of available nutrients that significantly affect how they store in terms of biological stability and potential losses. For example, high levels of nitrogen in biomass will facilitate rapid microbial growth and feedstock degradation, which leads to devaluation and increased fire risk. Further, the soluble sugar fraction in the feedstock will act as a pool of nutrient reserves for microbial communities. In comparison, feedstocks that have low available macronutrient levels will require less moisture mitigation and thus pose lower storage risks (Table 2-15).

Table 2-15. Microbial nutrients present in different types of feedstock.

Feedstock Variety	Nitrogen	Soluble Sugars
Corn Stover[a]	0.70%	4–12%
Sorghum Stover	0.8–1.3%	6–26%
Wheat Straw	0.63% [b]	<1%[c]
Switchgrass[c]	0.51%	4–16%

a. Hoskinson et al., 2007.
b. DOE-EERE, 2008.
c. Dien et al., 2006.

Some feedstock varieties contain more antimicrobial compounds than others (De Lucca et al. 2005; Osbourn 1996), which offers the possibility of increased stability in storage at slightly higher moisture contents. Further study is needed to identify and describe these compounds and their effects on biomass stability at varied moisture levels. On the other hand, different feedstock varieties can harbor unwanted microbial communities, causing degradation to occur more rapidly and at lower moisture levels. For example, many yeasts and molds that are commonly associated with various stored forage feedstocks (Roberts 1995) are active at relatively low moisture contents relative to other microbial community members (Beuchat 1983). These organisms are often responsible for dry matter loss and compositional deterioration of low-moisture silages (McDonald et al. 1991; Brady et al. 2005).

Another issue that is often overlooked in biomass storage is that the stored biomass can harbor crop diseases. Certain agricultural diseases target only specific feedstocks, which may influence the amount of feedstock that can be stored in a certain area. For example, the anthracnose lesions caused by *Colletotrichum graminicola*, a filamentous fungus, survives in non-decomposed corn residue, and spores are later spread by windblown rain and rain splash (Vincelli and Hershman 1997). Similarly, *Cercospora zeae-maydis*, which causes gray leaf spots, also survives on non-decomposed corn residue, and its spores are spread by air currents into the following year's growing crop (Vincelli and Hershman 1997). The general overwintering and subsequent spore-spreading mechanism for infection is a common pathway for pathogens that impact many varieties of plants, including corn and *Sorghum*. Therefore, the impact of very-high-volume, field-side, and partially exposed dry storage biomass systems may need to account for the potential for subsequent disease propagation and spreading. The mitigation strategies might prove as simple as plastic bale wrapping or other engineered storage solutions. Alternatively, disease propagation concerns relating to biomass storage might be effectively managed through crop management practices, such as yearly changes in feedstock varieties and crop rotations.

There are environmental and human health implications from the storage of large amounts of biomass. One risk factor in dry storage is fire hazard, which may spread to adjacent facilities and fields and cause releases of airborne particulates containing toxins, including polycyclic aromatic hydrocarbons, heterocyclic amines, and dioxins. Storage of biomass can also attract rodents, which are a human health issue because many rodents are vectors for pathogenic diseases. The variety of feedstock will influence the potential rodent infestation, and some feedstocks may naturally attract rodents more than others.

Mold spores are a human health concern, particularly when inhaled over extended periods of time. With the bale systems, human exposure to molds will initially come from spores released from intact bales. The next key points of exposure are when bales are removed from stacks and when they are processed by a grinding or shredding operation. Dispersed, on-farm hazards will require different mitigation strategies than larger industrial operations, but the best practice for avoiding mold spore inhalation hazards is to prevent the initial mold growth.

Thus, it is important when storing baled feedstocks to understand the impact different varieties have on the storage system. With proper mitigation both small- and large-stem feedstocks with low- or high-macronutrient levels can and are stored effectively as stacked bales.

2.2.1.1 Biomass Deconstruction, Fractionation, and Yield Losses

While the objective of the conventional-bale storage system is to avoid all biomass deconstruction, fractionation, or physical changes causing yield loss, the reality is that such changes will occur. Biomass material changes due to microbial deconstruction, fractionation, and consumption can affect biomass quality and result in significant dry matter losses (shrinkage) in storage (Figure 2-15). Dry matter losses that occur in storage can be due to microbial activity, mechanical loss during handling, or "apparent loss." Apparent loss is loss that occurs due to total mass increases from accumulated foreign material. Microbial actions on biomass can decrease the value of the feedstock because carbohydrate/sugar levels decrease as mass is lost to respired carbon dioxide or converted to microbial cells and byproducts. Environmental challenges on stored biomass can accelerate or arrest microbial activity that degrades and/or consumes biomass structural sugars.

Specifically, storage systems that do not protect the biomass from prolonged contact with moisture will result in significant structural sugar loss and reduced estimated biomass value (Table 2-16). A study investigating the effect of storage on a chopped pile of wheat straw points to moisture exposure as a key factor in the reduction of structural sugars (Radtke et al. 2005). The chopped pile contained 38 tons dry basis (d.b.) of wheat straw and was stored uncovered in Idaho for one year. Sampling after one year revealed that varied levels of darkening of the straw occurred due to moisture exposure. The top of the pile had been transiently wet and was visibly water stained, and the center of the pile contained both a dry section and a wet section. Analysis of the total structural sugar levels in the dry, transiently wet, and continually wet sections of the pile indicate that the biomass structural levels decrease substantially upon temporary or prolonged moisture exposure (Table 2-16). For biochemical conversion refineries, a reduction in structural sugar content devalues the feedstock. The allowable feedstock price that could be paid for the transiently wet and continually wet straw would be $9.29 and $22.89/DM ton less than the pre-stored material, respectively.

Table 2-16. Effects of various environmental conditions on baled wheat straw stored outdoors without protection for one year (Radtke et al., 2005).

Stack Material Storage Condition	Storage Duration	Sample Description	Total Structural Sugars (% of dry wt)[a]	Estimated change in feedstock value (year 2000 $US)[b] ($/DM ton)
Pre-storage	Zero	Straw going into storage	64.7	$0
Dry	1-year	Visibly undamaged	65.4	$0.90
Transiently Wet	1-year	Visibly water stained, dry when sampled in spring	58.2	-$9.29
Continually Wet	1-year	Dark brown, wet straw when sampled in spring	49.3	-$22.89

a. INL data, wheat straw Idaho storage study, 2004-2005.

b. Based on minimum ethanol selling price (MESP) of $1.07 per gallon (year 2000 $US). Calculations derived from Ruth and Thomas, 2003.

In contrast to microbial dry matter losses, mechanical dry matter losses occur when bales fall from stacks or fall apart and when loose material is scattered. These losses are relatively easily recognized and mitigated and will decrease as operators make minor adjustments to their storage practices. Additionally, economic depreciation during storage of biomass can also occur with the accumulation of foreign material. In this situation, the relative concentration of biomass decreases per ton of material that has to be handled. Causes include windblown dust and soil sticking to the biomass upon removal. In some regions, mitigation for windblown dust may need to be considered as much as mitigation for problems involving moisture.

2.2.1.2 Format and Bulk Density Impact on Supply System Processes

Large 4×4×8-ft square bales are the storage format for the conventional-bale design. Other formats, including different sizes of square bales, round bales, and loose-stacked bales, can all have significant positive and negative impacts on storage systems. However, since only one bale format is considered in this design, the bulk density of bales becomes the significant consideration in assessing storage costs (Table 2-11). Even with just one bale size, another format consideration that can contribute to cost is the stack configuration. Bale bulk density can significantly impact the number of bales per stack, and both stack configuration and bale bulk density can impact the area of land required for a given storage stack configuration (Table 2-11).

This conventional-bale design uses a stack configuration of 1 bale wide and 2 bales high (Table 2-11 and Figure 2-16). While this configuration is necessary for the chosen plastic-wrap process, it is fairly inefficient in terms of land area use. If land use is inexpensive and available, as this design assumes, this configuration is a cost-effective solution. If land area is expensive (e.g., improved storage site, summer storage that idles cropping acres, etc. [Table 2-15]), the two-bale-high stack configuration may not be feasible due to inefficient land area use of this configuration. A more efficient land-area-usage stack configuration for 4×4×8-ft bales is 4 bales high either in single or multiple adjacent rows (stack configuration in Figure 2-41). In an enclosed structure, the stack might be 6 to 8 bales high to achieve the highest possible land area usage efficiency. Determining the best storage configuration is a “balancing act” between the storage system/configuration costs and the potential biomass dry matter losses of a particular configuration (Table 2-17). Notice that cost of dry matter loss exceeds the cost of storage structures or improvements for wrapped bales in wet climates and for stacks, regardless of site preparation and climate. Using storage structures or wrapping bales costs more but has the potential to save significantly on dry matter loss.

Table 2-17. Modeled comparison of typical storage improvements and structure costs compared to dry matter loss and its impact on feedstock costs.

	% Dry Matter		Ownership Cost of Structure or Improvements ($/DM ton) [c]	Cost of Dry Matter Loss ($/DM ton), at Feedstock Cost of $22.19/DM Ton [d]	
	Dry Climate Loss, Range	Wet Climate Loss, Range[b]		Dry Climate	Wet Climate
Stack on ground	1–9	7–39	0.07 (taxes)	1.20	4.30
Stack on improved ground surface	4–18 [a]	7–36	0.40–1.60 [e]	1.50	3.30
Covered stack on ground	3–13 [a]	6–25	1.50	1.50	3.30
Covered stack on improved surface	1–5 [a]	2–10	1.80–3.02	0.50	1.10
Bale wrap on ground	1–4 [a]	1–8	6.20	0.60	1.20
Pole barn	1–4 [a]	2–7	12.30	0.50	1.00
Totally enclosed shed/building	1–4 [a]	2–8	14.10	0.40	0.90

a. Due to the lack of data on dry matter loss in dry climates, dry matter loss values in dry climates are calculated based on a relationship illustrative by Holmes, (2004) as 0.5 × wet climate values (Appendix A-2).

b. Multiple data sources; Appendix A-2.

c. Ownership costs are based on a structure to accommodate 100 DM tons, property tax of $300 per acre (Bruynis and Hudson, 1998) (Edwards and Hofstrand, 2005), improvement tax rate of 2%, maintenance cost of 2% per year. Details of construction costs are available in the works cited.

d. Cost of dry matter loss in the delivery chain from harvest up to the point of discharge from storage is: (delivered cost) ÷ (1-$dry matter loss) – (delivered cost), where "delivered cost" is the cost of feedstock delivered to storage.

e. Range of site preparations is between grading with packed gravel at $0.60/ft^2 and concrete hardstand at $3.00/ft^2. (Low and high values from a telephone survey of eight paving contractors in five midwestern states). Only gravel improvement is used in this comparison (Cromwell, 2002. Dhuyvetter et al., 2005. Groover, 2003. Shinners et al., 2007.).

The field-side storage used in this conventional-bale design is inherently a distributed storage system. Even with the higher-yielding switchgrass, individual scenario model stacks do not exceed 200 tons of biomass (Table 2-11). While fire, including arson, is a concern in distributed storage systems, the losses from fire will never cause a catastrophic failure to the biomass supply, since the loss will be isolated to the effected stack. However, if dry biomass is stored in a more central location, fire and fire codes can become a significant consideration in stack configuration and land area requirements for storage. If local fire codes follow the International Fire Code recommendations, individual stack size would be limited to 100 tons of biomass with a fire lane between each stack (ICC, 2003). Another concern with the centralized storage configuration for dry biomass is the potential for loss of property due to fire (Figure 2-17).

Figure 2-17. An example of property damage resulting from a biomass fire at a commercial baled hay handling facility.

2.2.1.3 Biomass Moisture Impact on Supply System Process and Material Stability

Large rectangular bales are generally transported and stacked at the side of the field. To maintain high-quality bales, these stacks are typically stored in a well-drained, protected environment. In most regions, this requires covering the stacks (e.g., traps, pole barns, plastic wrap, etc.) to prevent weather damage. In some cases, the top row of bales on the stack is manually arranged to minimize water penetration into the stack core. However, large square bales are prone to water penetration because of the way they are formed. During baling, layers of biomass are pressed together creating what are typically termed "flakes." Round bales are not compressed into flakes, so the water absorption characteristics of round bales are different that square bales. In general, round bales tend to resist water penetration better than square bales. However, for square bales, these flakes tend to allow water to channel into the bales and stacks. This channeling can be observed even in very low precipitation areas (<10 in. annually) of the arid western U.S. (Figure 2-18). More precipitation would cause even greater infiltration and subsequent moisture damage. The total dry matter loss for the wheat straw bales shown in Figure 2-18 was below 1%, due to the low precipitation and favorable drying conditions between weather events. However, in wetter climates, the storage of large square bales would necessitate the use of tarps, wraps, or pole-barn-like structures due to moisture channeling through the bales.

Figure 2-18. Large square wheat straw bales from the top of a stack stored field-side in Idaho. Note that water channeling, shown by the dark blue food dye, extends well past the region of damaged straw (dark brown straw) that is visible.

Buckmaster et al. (1989) investigated the storage stability of baled, shed-stored alfalfa hay in Michigan. They monitored the dry matter loss, ash content, fiber content (acid detergent fiber [ADF]), crude protein (CP), and the development of insoluble proteins in the bales of alfalfa with varying moisture content (11.5 to 48%) and density. Table 2-18 shows part of the results published by Buckmaster et al. (1989). Each moisture range includes at least two moisture points. The bales were stacked in five rows and three columns. The columns were separated by Styrofoam-type insulation board. The stack number identifies the location of the tested bale in the stack.

Table 2-18. Partial results of storage stability of baled alfalfa (Buckmaster et al. 1989).

Moisture Content Range	10 to 15%		15 to 20%		20 to 25%		25 to 30%	
Number of Stacks Monitored	1	2	5	3	3	2	1	2
Moisture Content (% w.b.)	11.5	14.4	17.7	16.8	24.0	22.4	27.7	26.4
Density, lb/ft^3	6.9	10.8	5.4	11.7	6.3	14.2	6.6	14.4
Dry Matter Loss %	2.1	2.5	3.1	3.0	4.4	4.4	5.8	9.4
Maximum Temp., °F	79	77	79	99	84	109	81	117
Average Temp., °F	63	64	70	77	64	84	70	93

Buckmaster et al. (1989) found that dry matter loss was directly correlated to the moisture content of the bales but could be considered independent of the bale density. However, the dense bales showed a higher temperature during storage than the loose hay. Increased moisture content at the time of baling resulted in an increase in the concentration of CP, ash, and ADF when the bale was removed from storage. Quality retention ratios indicated that ash and ADF did not change, but the amount of insoluble protein increased with the increased moisture content.

The quality of stored hay (alfalfa, clover, or grasses) is impacted by a number of factors: the higher the relative humidity, the moisture content of the hay, and the ambient temperature of storage are, the greater the dry matter and nutrient losses Ullrey (1997). For properly field-cured and barn-dried hay, the moisture content of the hay is low (less than 14 to 15%), and even relatively high humidity and temperatures are unlikely to cause the growth of molds and bacteria. In temperate regions in North America and Europe, hay can be stored in the field at a moisture content of 20 to 25% without molding during winter months, due to a combination of temperature (lower than 20°C for the greater part of the storage period) and storage conditions that allow for free air circulation (Wilcke et al.). However, most hay that is stored at 20 to 25% moisture will require a chemical preservative, such as propionic acid, to protect the hay from the dry matter losses associated with mold and bacteria growth (Knapp et al. 1974; 1975; 1976).

The amount of moisture that can be allowed into the biomass before substantial damage occurs is case-specific and subject to debate; however, the underlying principles are relatively consistent. Microbes react more to an index termed “water activity” (a_w) than they react to the bulk percentage of moisture in the biomass. This water activity represents the equilibrium amount of water available to microorganisms and enzymes, and it corresponds to the equilibrium relative humidity divided by 100 (Troller and Christian 1978). The a_w measurement of 1.0 represents pure water that is unbound, while an a_w value of 0 would indicate no water available and completely dry material. Molds and filamentous fungi will grow at a water activity of 0.7 to 0.9, and only a select number of organisms grow below the 0.7 level (Figure 2-19). Figure 2-19 indicates that dry storage should be designed to keep the water activity of the biomass at 0.7 or below to prevent the degradation of biomass by most filamentous fungi and bacteria, which will in turn reduce dry matter losses in the feedstock.

Different feedstocks can be at a water activity of 0.7 with more or less total water (% moisture) in the system. This is dependent on many factors in the feedstock, including the relative amounts of salts, free sugars and sugar polymers, as well as the plant's tissue structure and substructures. Three feedstocks were compared in Figure 2-19 for their moisture content/water activity relationship. While some variation is seen due to changes in harvest time and variety, all three feedstocks require that the moisture content be below 15% for the water activity to be 0.7 or less. This suggests that biomass being stored dry should be kept at moistures of 15% or less for dry storage, which is consistent with the recommendations of Rotz (Rotz 2003, 2004).

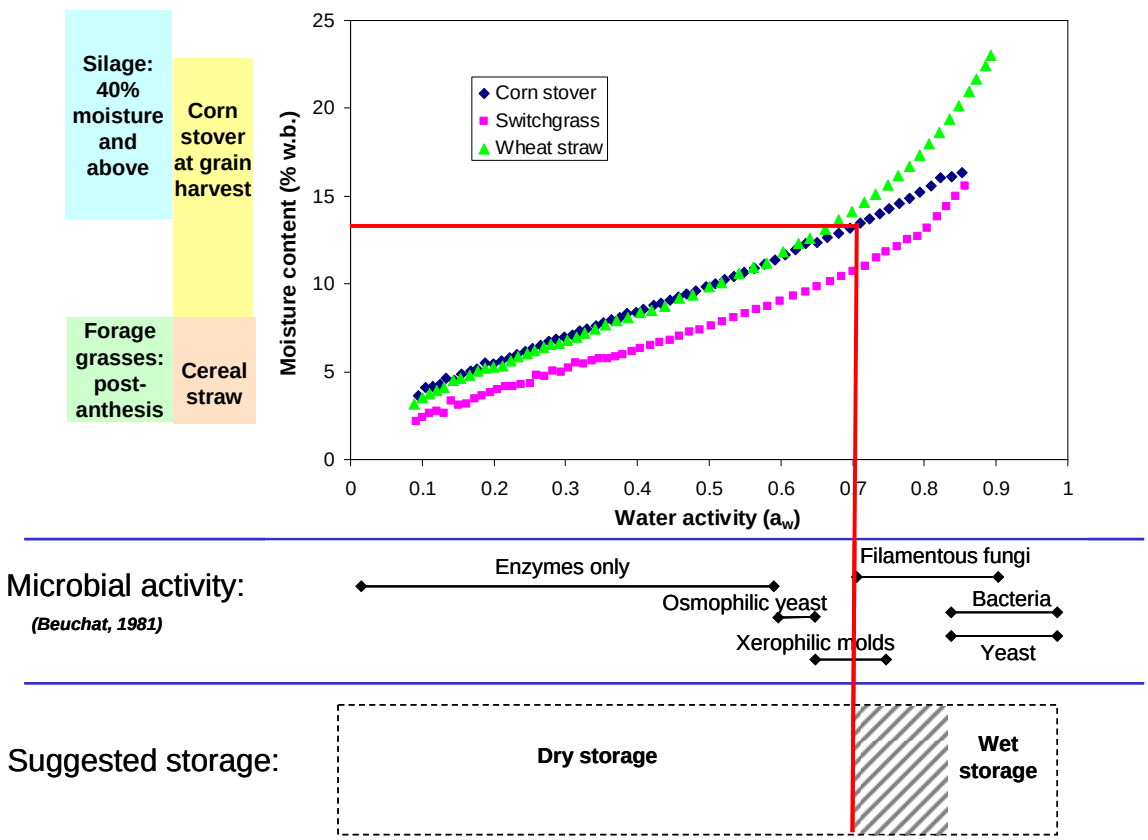


Figure 2-19. The relationship of moisture content and water activity and the impact of water activity on storage of harvested material.

Relative humidity and, thus, water activity can be used to predict if high dry matter losses will occur in storage systems that have high air/biomass contact surface areas. The relationship of water and temperature together largely determine the damage of relatively exposed biomass. For example, during the period of the storage study shown in Figure 2-20, there was very little damage to the biomass due to humidity. We observed that when the temperature was high enough to support microbial activity (approximately 40ºF) relative humidity, or water activity, was too low to allow microbial damage to the biomass. Similarly, when the relative humidity, or water activity, was high enough to support microbial activity ($a_w > 0.7$), air temperature was too low to support microbial growth. This is why there was no outer layer of damaged biomass due to contact with humid air in this study. However, in regions where relative humidity is high (generally more than 75% humidity or a water activity of 0.75) and temperatures are high (generally more than 40ºF), there will likely be an outer region of microbial damage to the biomass.

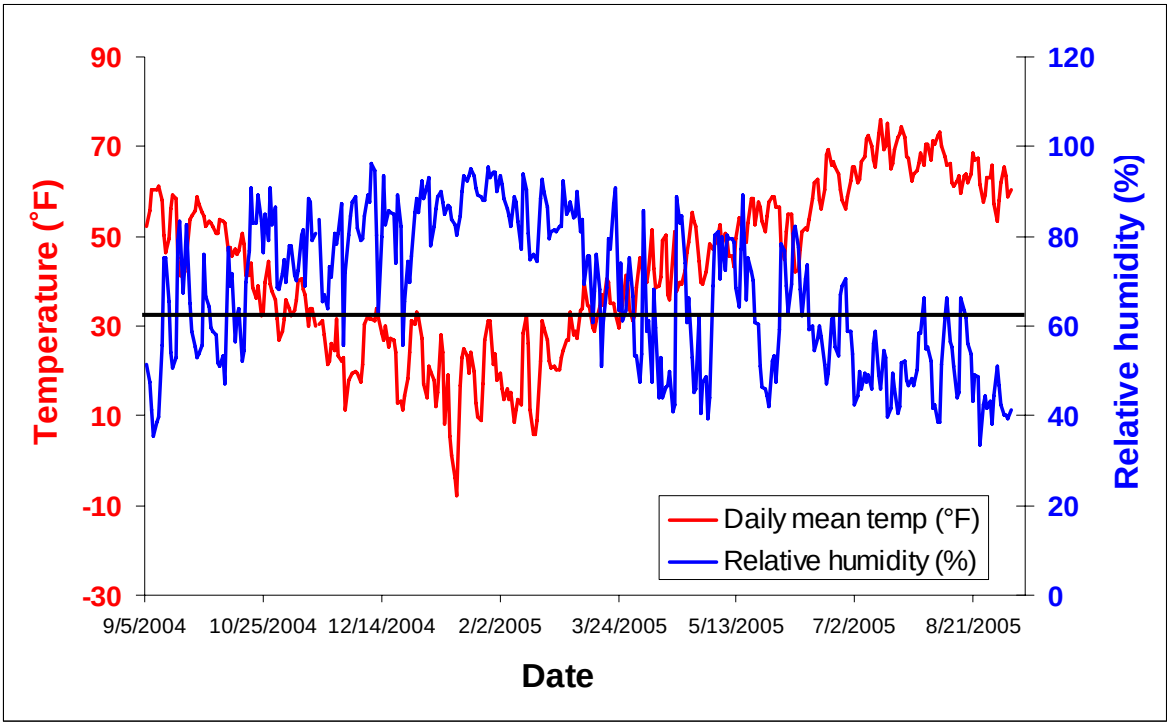


Figure 2-20. The relationship of temperature and humidity over one year in a climate with cold winters and warm, dry summers. The black horizontal line represents a rough cutoff point where if both temperature and relative humidity fall above the line, conditions for rotting are prominent.

2.2.2 Conventional-Bale Storage Equipment

The conventional-bale design storage equipment is the same for both the corn stover and switchgrass designs (Table 2-19). The stacking and weather protection processes (i.e., plastic bale wrapping) are operationally coupled to the roadsiding process in harvest and collection. The bale collecting equipment brings the biomass to the field-side storage site and simply drops the bales on the ground beside the stack (Table 2-6).

Table 2-19. Storage equipment specifications for the conventional-bale design.

	Stacking	Weather Protection	Storage
Equipment	Caterpillar TH220B Telehandler	Stinger 4000 Cube-Line Wrapper	None
Haul Distance	N/A	N/A	N/A
Rated Capacity[a]	120 bales/hr	120 bales/hr	200 tons/site
Operational Efficiency (%)[b]	67%	67%	N/A
Dry Matter Loss (%)	0%	0%	5%[c]
Operational Window			
hrs/day	14.0	14.0	24[d]
days/year	36	36	365[d]

a. Estimate of the operating time that is actually spent working and the amount of capacity used.
b. Published efficiency input into the analysis model (Appendix B-2).
c. Dry matter loss for wrapped bale storage (Table 2-11).
d. Assumes that all biomass is wrapped and held in storage for 1 full year, which is a recognizably conservative assumption.

A telehandler is then used to make a two-high bale stack by picking up one dropped bale and stacking it upon another dropped bale. The telehandler then picks up the two-high bale stack and loads it into the wrapper. The Caterpillar TH220B telehandler is the self-propelled loader used for bale handling in this design scenario (Figure 2-21). As demonstrated in the picture, this machine has a rated load capacity of 7,000 lb and can be outfitted with a fork system appropriate for moving bales two at a time. The loader arm is telescoping, and with the four-wheel drive steering, the TH220B can be used to move bales into the stack needed for the bale wrapping system.

Figure 2-21. Caterpillar TH220B Telehandler.

Bale wrapping is performed with the Stinger 4000 Cube-Line Wrapper (Figure 2-22). The Cube-Line 4000 will wrap 4×4×8-ft bales stacked two high (conventional-bale design scenario), 3×3×8-ft/3×4×8-ft bales stacked three high, or single rows of round bales. The bales are loaded onto the Cube-Line platform in two-high stacks, and the wrapper pulls the stack through the wrapping hoop. The hoop rotates around the stack, using rolls of the wrapping plastic to completely encompass the bale stacks. With continuous supplying of the two-high bale stacks on the Cube-Line platform, the result is a row of fully wrapped bales (one-bale-wide by two-bales-high) as shown in Figure 2-16.

Figure 2-22. Stinger 4000 Cube-line Wrapper.

In the conventional-bale design scenario, no equipment or capital assets are assumed for the storage site. Rather, the storage site is assumed to be an unimproved field-side location that is naturally well-drained and adjacent to a road.

2.2.2.1 Equipment Capacity and Operational Efficiency

Upon being moved to the side of the field with the Stinger Stacker, a telehandler system is used to move the bales into the wrapper system, which then wraps and places the bales in a one-bale-wide, two-bale-high, in-line stack. The rated capacity of the bale wrapper is 120 bales per hour (Table 2-17). Based on manufacturer data, the field efficiency of the bale wrapper is modeled at 67%, leading to an operational capacity of 80 bales per hour, or 52.4 tons per hour. The telehandler system is capacity limited by the bale wrapper, and the stacking costs represent that drop in the telehandler's operational efficiency.

The stack capacity is limited by international fire code which requires no more than 100 tons per stack with a minimum of 10 ft between adjacent stacks. The field stack costs are an aggregate of land rent, insurance, and land preparation costs. Land preparation costs are modeled at \$0.69/ft^2 and depreciated over 20 years with a repair and maintenance factor of 2% of initial costs annually.

2.2.2.2 Operational Dry Matter Losses (Shrinkage)

The storage dry matter loss data presented in Table 2-15 shows that wrapping does not entirely prevent dry matter loss. Water can still get in under the plastic, especially if it is allowed to pool around the stack. Placing wrapped bales on an improved surface (e.g., gravel) that facilitates drainage away from the bales helps to reduce losses. We evaluated the cost of building a gravel pad at the storage site, and at a cost of \$0.69 per ft^3 (includes excavation and gravel), storage loss would need to exceed 16% to cover the cost of the site improvement. Further, considering that storage in the conventional-bale and pioneer-uniform designs occur at the side of the field, having a gravel pad at the edge of the field is not practical, especially considering that the field in which the stover is stored will change with the corn rotation.

Since baled corn stover in the conventional-bale and pioneer-uniform designs will be most prevalent in dryer climates, a 5% dry matter loss in storage is assumed for the conventional-bale design, based on the data in Table 2-15. The resulting cost of a 5% dry matter loss in storage is \$2.08 per DM ton (Table 2--28).

2.2.2.3 Operational Window

As described in the previous roadsiding discussion, the Stinger Stacker costs are based on slide-off unloading. The implication of this assumption is that the bale wrapping operations are coupled with the roadsiding operations, and the operation window assumptions for wrapping follow this dynamic.

2.2.3 Conventional-Bale Storage Cost and Sensitivity Analysis

2.2.3.1 Static Model Cost Summary

A breakout of the costs associated with each piece of equipment used in the storage unit operation identifies significant cost components that are valuable for making individual comparisons and recognizing areas of research potential (Table 2-20). These costs are reported in terms of DM tons entering the storage process.

Table 2-20. Static model costs for major storage equipment in the conventional-bale corn stover and switchgrass scenarios.

	Equipment	Stacking	Weather Protection	Storage
		Caterpillar TH220B Telehandler	Stinger 4000 Cub-line Wrapper	Insurance, Land Rent, Stack Maintenance
Corn Stover	Installed Equipment Quantity	43	43	N/A
	Installed Capital[a]	3.55	2.04	N/A
	Ownership Costs[b]	0.47	0.30	0.10
	Operating Costs[c]	0.41	5.40	N/A
	Labor	0.29	0.29	N/A
	Non-Labor	0.12	5.11	N/A
	Dry Matter Loss Costs	N/A	N/A	1.40
	Energy Use (Mbtu/DM ton)	4.5	3.0	N/A
Switchgrass	Installed Equipment Quantity	39	39	N/A
	Installed Capital[a]	3.22	1.85	N/A
	Ownership Costs[b]	0.42	0.27	0.10
	Operating Costs[c]	0.37	4.86	N/A
	Labor	0.26	0.26	N/A
	Non-Labor	0.11	4.60	N/A
	Dry Matter Loss Costs	N/A	N/A	1.12
	Energy Use (Mbtu/DM ton)	4.0	2.7	N/A

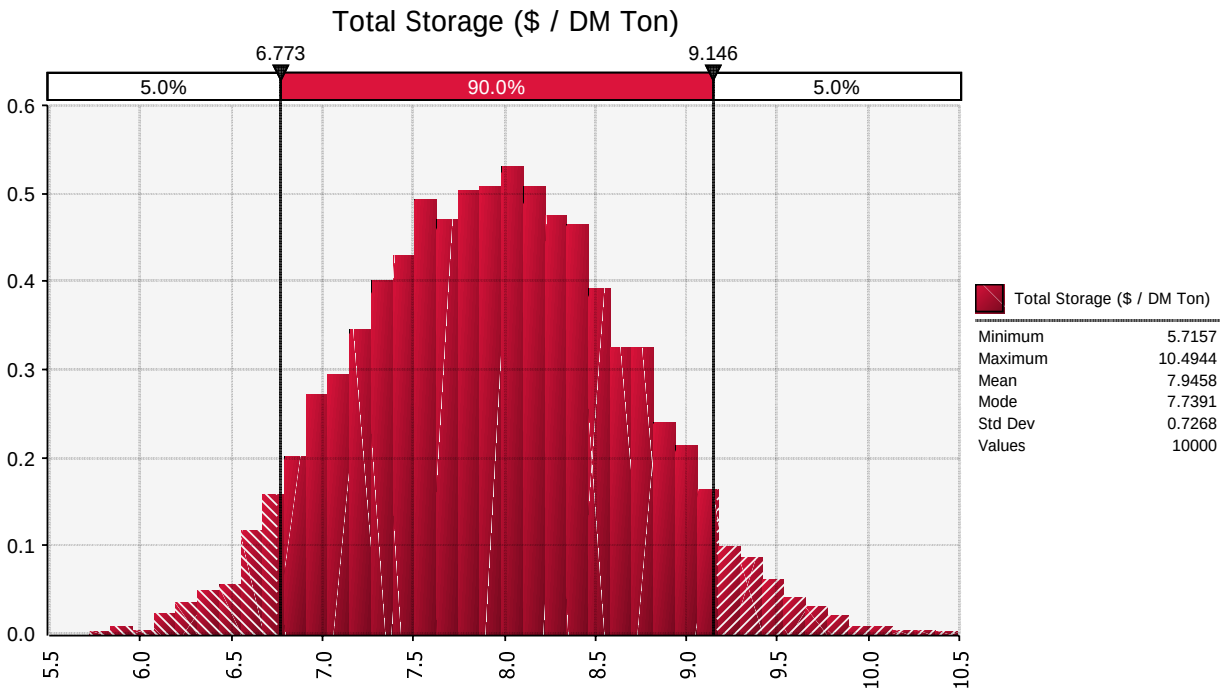
a. Installed capital costs are $ per annual DM ton capacity.

b. Ownership costs include depreciation, interest, taxes, insurance, and housing (Appendix A-2, Table A-7).

c. Operating costs include repairs, maintenance, fuel, lubrication labor, and consumable materials (Appendix A-2, Table A-7).

2.2.3.2 Cost Sensitivity Analysis

A histogram of the storage cost for corn stover (Figure 2-23) shows that with 90% confidence the cost of the unit operation ranges between $7.07 and $9.24 per DM ton. Further, the mean and standard deviation of this range is $8.11 ± 0.66 per DM ton. The mode value of the storage cost is $7.97 per DM ton. This value closely represents the result of the static model, which is $8.08 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.



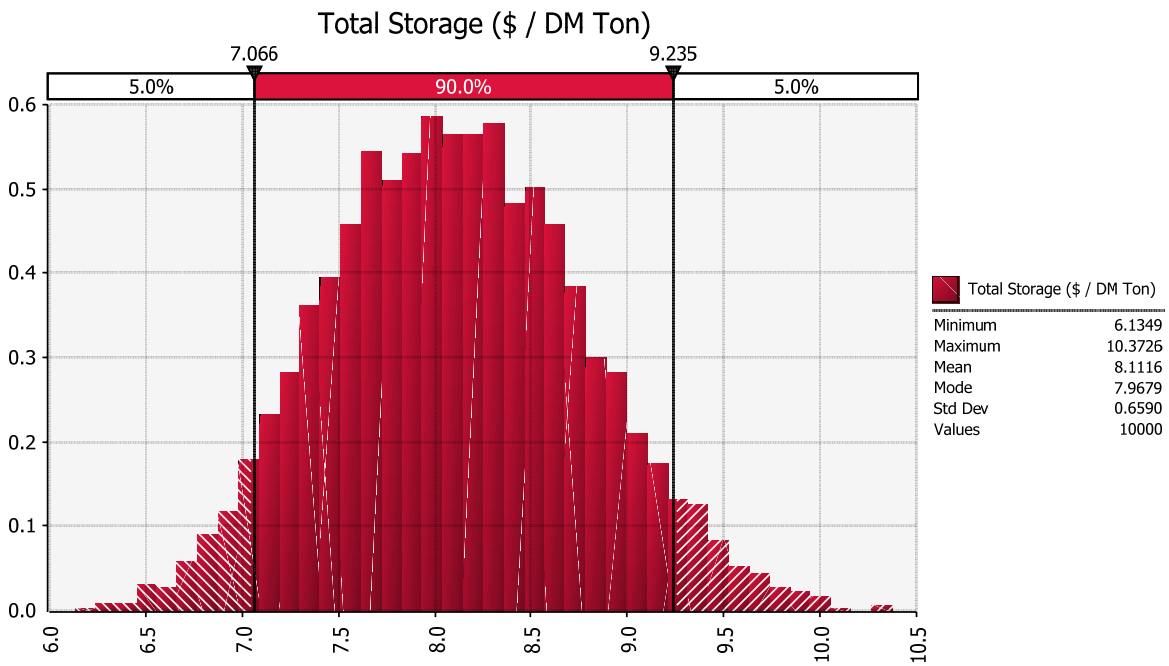
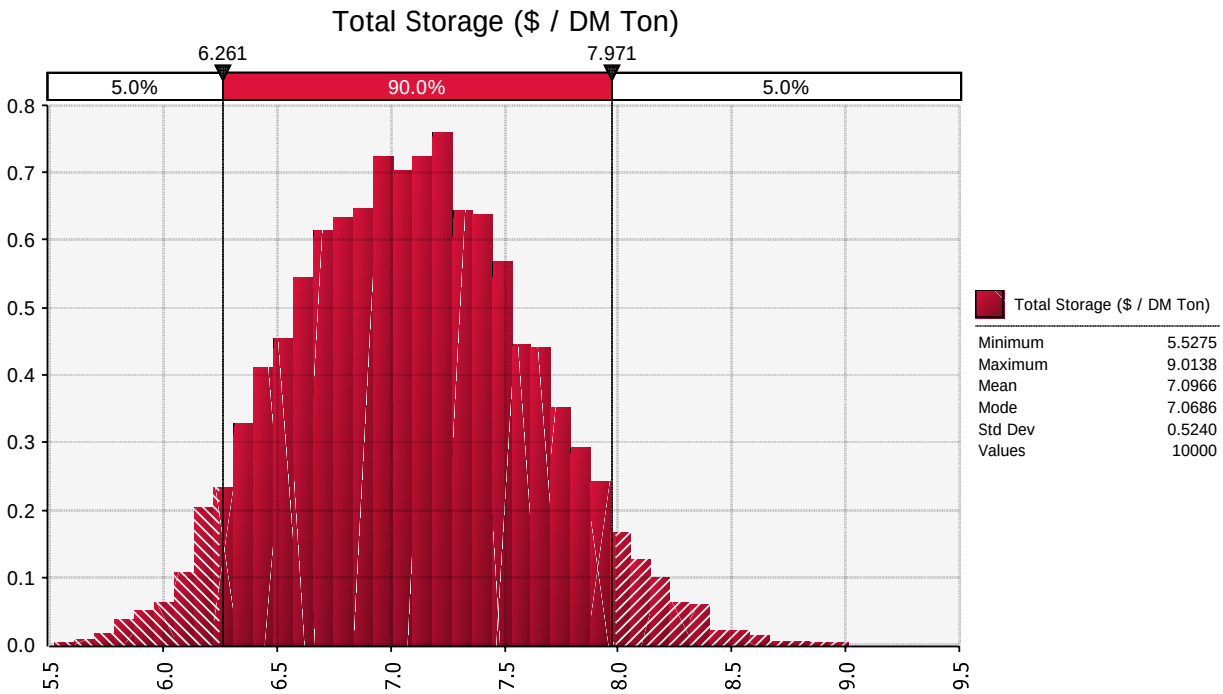


Figure 2-23. Conventional-bale storage cost distribution histogram from @Risk analysis for corn stover.

Similarly, a histogram of the storage cost for switchgrass (Figure 2-24) shows that with 90% confidence the cost of the unit operation ranges between $6.25 and $7.95 per DM ton with the mean and standard deviation of this range being $7.08 ±0.52 per DM ton. The mode value of this cost range is $7.09 per DM ton, which closely represents the result of the static model of $7.14 per DM ton.



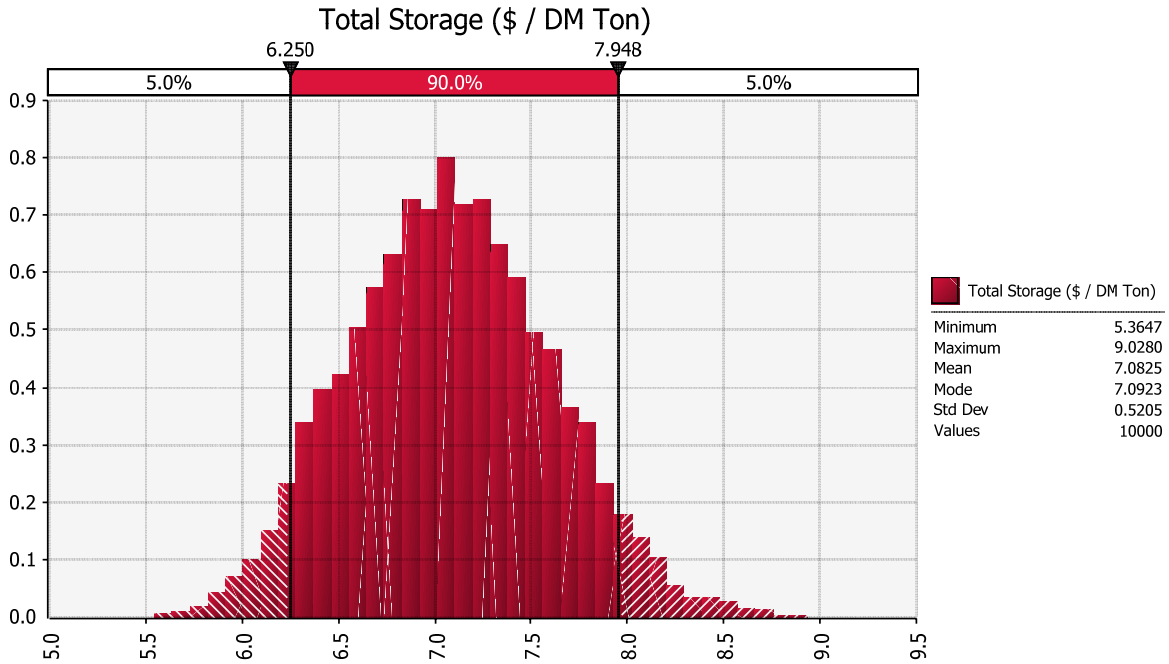


Figure 2-24. Conventional bale storage cost distribution histogram from @Risk analysis for switchgrass.

The overall costs associated with the conventional-bale storage unit operation for both corn stover and switchgrass are provided in Table 2-21 on a per-DM-ton and per-bale basis. These costs, reported as a mean and standard deviation, come as a result of 10,000 model iterations of the simulated conventional-bale feedstock supply system.

Table 2-21. Storage cost summary for the conventional-bale corn stover and switchgrass scenarios.

Equipment		Stacking	Weather Protection	Storage	Dry Matter Loss	Total Storage
		Caterpillar TH220B Telehandler	Stinger 4000 Cub-line Wrapper	Insurance, Land Rent, Stack Maintenance		
Corn Stover	Modeled Cost Totals[a]	0.91 ± 0.13 $/DM ton	5.66 ± 0.34 $/DM ton	0.10 ± 0.01 $/DM ton	1.44 ± 0.44 $/DM ton	8.11 ± 0.66 $/DM ton
		0.53 ± 0.07 $/bale	3.30 ± 0.04 $/bale	0.06 ± 0.01 $/bale	0.84 ± 0.25 $/bale	4.73 ± 0.28 $/bale
Switchgrass	Modeled Cost Totals[a]	0.82 ± 0.12 $/DM ton	5.09 ± 0.28 $/DM ton	0.10 ± 0.01 $/DM ton	1.07 ± 0.32 $/DM ton	7.08 ± 0.52 $/DM ton
		0.53 ± 0.07 $/bale	3.30 ± 0.04 $/bale	0.06 ± 0.01 $/bale	0.69 ± 0.20 $/bale	4.58 ± 0.24 $/bale

a. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

2.3 Conventional-Bale Handling and Transportation

The handling and transportation unit operation within the conventional-bale design centers around the movement of baled material from long-term, field-side storage to shorter-term, bale-yard storage at the biorefinery (Figure 2-25). These processes involve the use of self-propelled loaders and semi-tractor trailers. The modeled conventional-bale design calculates a mean transportation distance to the biorefinery based on a supply radius of 45.8 miles (Table 2-1). Using the combined variables of feedstock yield, total cultivated acres, acres of desired feedstock in production, and acres of feedstock in contract with the biorefinery, the mean transportation distance for this design is calculated to be 32.4 miles. Taking into account a 0.5 mile roadside distance and a winding factor of 1.2 for the haul distance to the biorefinery, the final transportation distance for the conventional-bale design is 38.2 miles (Appendix A--1.2.*)*

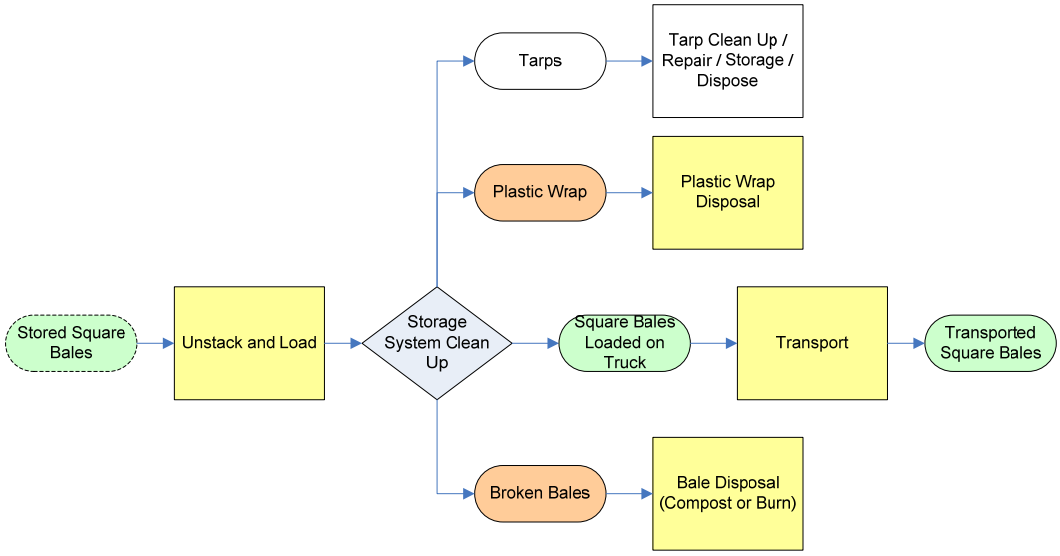


Figure 2-25. Handling and transportation supply logistic processes and format intermediates. (Green ovals represent format intermediates, tan ovals represent potential waste streams, yellow rectangles represent processes modeled in this report, white rectangles represent processes not modeled in this report, and grey diamonds represent decision points).

Estimating the cost of the handling and transportation unit operation often focuses on just the transportation distance part of the system in terms of a dollar per mile quote from a local trucking company. Though this method of estimating costs may yield accurate values, it erroneously suggests that transportation distance is the most important parameter impacting the total handling and transportation cost. While transportation distance is, without question, an important parameter that represents the variable cost component of the total cost, the fixed costs associated with loading and unloading the transport container (semi-tractor trailer, rail car, etc.) can be more significant. The relative contribution of both the fixed and variable cost components is illustrated in a typical handling and transportation operation where 26 large square bales (4×4×8-ft) of corn stover are transported on a standard 8-ft-wide × 53-ft-long semi-tractor trailer with a payload of 34,000 lb (~15 DM tons). In this example, bales are loaded and unloaded two at a time at a rate of 80 bales per hour using a self-propelled loader (Section 2.2.2.1, Figure 2-20). As shown in Figure 2-23, the fixed costs, totaling about $55 per load, exceed mileage costs up to a hauling distance of about 18 miles. Note that the dollar per DM ton-mile cost rises sharply within this 18-mile haul distance due to the high fixed cost. The total cost per DM ton increases linearly with transportation distance where the fixed costs alone account for $4.20 per DM ton.

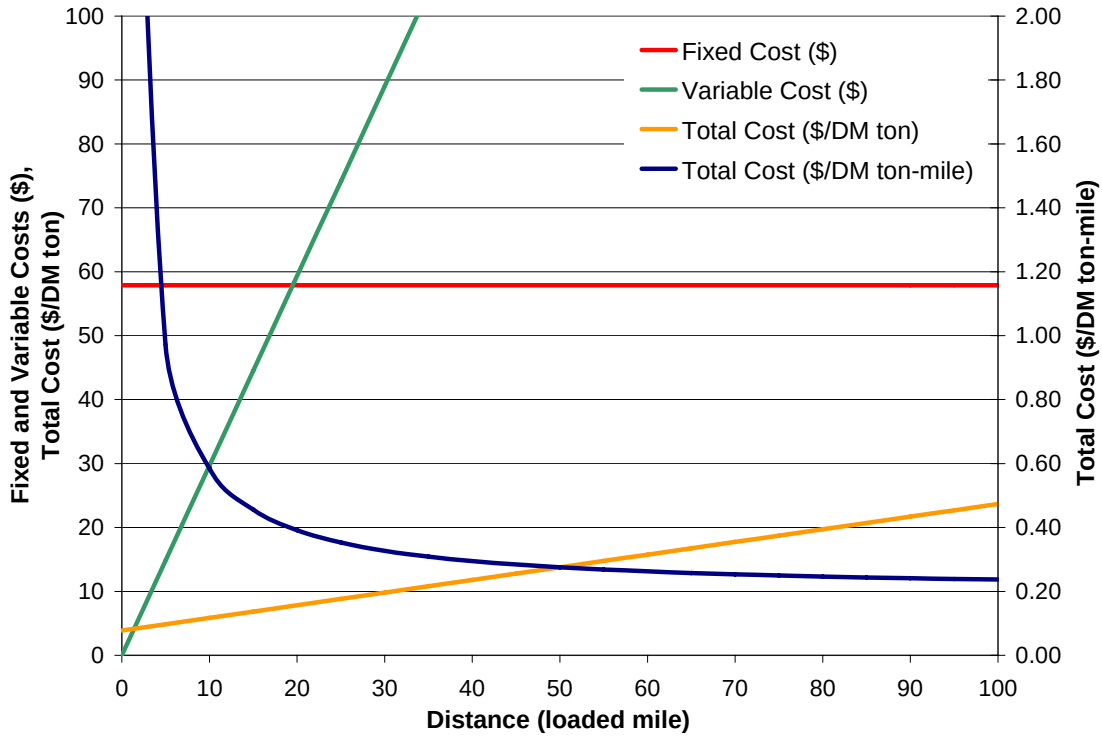


Figure 2-26. Transportation costs for hauling larger square bales of corn stover with a semi-tractor trailer.

The fixed and variable costs of transportation are subject to the same prevailing constraints affecting all supply system operations: capacity and efficiency. Within the diversity of the conventional-bale supply system, these constraints are impacted by a number of feedstock, equipment, and infrastructure attributes, including feedstock format, feedstock bulk density, moisture content, transportation distance, load capacity and weight limits, and dry matter losses. These attributes and their impacts on handling and transportation are discussed in the following subsections.

2.3.1 Conventional-Bale Handling and Transportation Format Intermediates

The conventional-bale handling and transportation unit operation interfaces only with 4×4×8-ft bale formatted feedstock from the time it loads out of the long-term, field-side storage stacks to the time it unloads into the bale-yard queuing stacks. The equipment used to perform these operations does not directly impact the format of the material through this process. As such, the only changes in the format intermediate within the handling and transportation operations come as a result of feedstock variety, which for the modeled conventional-bale design, are captured only in the dry matter bulk density (Tables 2-22 and 2-23).

Table 2-22. Attributes of handling and transportation format intermediates for corn stover (a crop residue) and switchgrass (a dedicated energy crop).

Biomass Output	Corn Stover	Corn Stover		Switchgrass	Switchgrass
Operation	Loading	Transport		Loading	Transport
Yield	26 bales	26 bales, 34,000 lbs.		26 bales	26 bales, 37,800 lbs.
Format Output	Unwrapped 4×4×8-ft bales loaded on flatbed trailer	4×4×8-ft bales delivered to plant		Unwrapped 4×4×8-ft bales loaded on flatbed trailer	4×4×8-ft bales delivered to plant
Bulk DM Density Output	9 lb/ft^3	9 lb/ft^3		10 lb/ft^3	10 lb/ft^3
Output Moisture (% w.b.)	12	12		12	12

2.3.1.1 Biomass Deconstruction, Fractionation, and Physical Property Changes

The conventional-bale handling and transportation processes do not alter the physical characteristics of the baled feedstock, and it is transported from the long-term storage stack and unloaded into the bale-yard queuing stack at the biorefinery in the same baled configuration.

2.3.1.2 Format and Bulk Density Impact on Supply System Processes

The square-bale feedstock format is the most significant variable impacting handling and transportation processes in the conventional-bale design. This format dictates the use of a self-propelled loader and a flatbed trailer to load, transport, and unload the feedstock from long-term storage to the queuing stack at the biorefinery. Large square bales are often handled two at a time with a standard bale spear, although as many as four bales can be handled together using available grapple attachments (e.g., Roadrunner). Handling and transportation costs are directly impacted by the relatively low bulk density of the baled feedstock, typically around 6 to 10 lb/ft^3 when dry (Table 2-19). This relatively low bulk density format makes it difficult to load enough bales on a truck to reach the gross vehicle weight (GVW) limit required for optimizing delivery systems. The bulk density required to maximize various truck configurations to accommodate a range of load limits is shown in Table 2-23 and the load configurations are shown in Figure 2-27. Again, as a reference, large 4×4×8-ft square bales of corn stover at 12% moisture typically weigh ~1,300 pounds or have a DM bulk density of 9 lb/ft^3 (Table 2-22). Thus, baled corn stover almost maximizes the load capacity of the third truck configuration (Table 2-23), which is allowed in some western and mid-western states.

Table 2-23. Bulk density required to maximize various load capacity configurations to accommodate a range of load limits.

Truck Configurations[a]	Load Limits		Payload		Maximum Load DM Bulk Density (lb/ft^3)
	Length (ft)	GVW (lb)	Max (lb)	Bale Count	
(1) 48-ft Flatbed Trailer	48[b]	80,000[b]	51,100	24 – 4×4×8-ft 36 – 3×4×8-ft	16.6 – 4×4×8-ft 14.8 – 3×4×8-ft
(2) 53-ft Flatbed Trailer	53[c]	80,000[b]	50,800	26 – 4×4×8-ft 39 – 3×4×8-ft	15.3 – 4×4×8-ft 13.6 – 3×4×8-ft
(3) 24-ft Flatbed Tractor pulling two 30-ft Flatbed Trailers	105[d]	105,500[d]	59,500	44 – 4×4×8-ft 66 – 3×4×8-ft	10.6 – 4×4×8-ft 9.4 – 3×4×8-ft

a. Impacts on transportation costs for these configurations are discussed in greater detail in Section 2.3.2.2.
b. Federal limits.
c. Common state maximum on National Network (NN) highways.
d. Allowable common limits in CO, ID, KS, ND, NE, OK, and SD for two trailing units on non-NN highways.

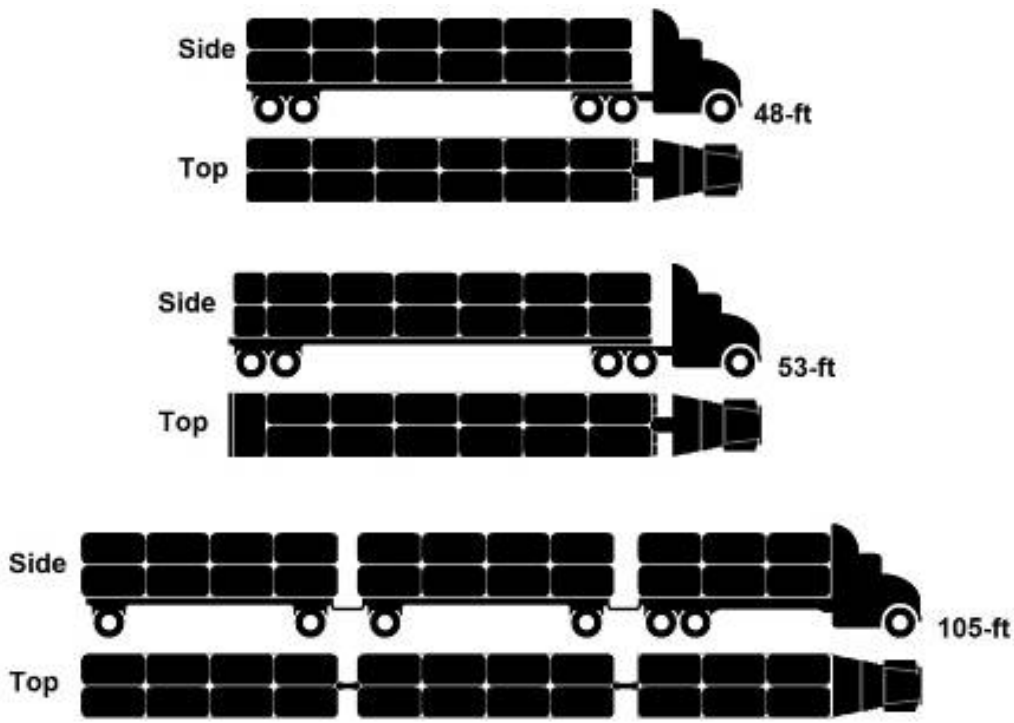


Figure 2-27. Truck configurations for a 48-ft trailer, a 53-ft trailer, and a 24-ft flatbed tractor with two 30-ft trailers.

2.3.1.3 Biomass Moisture Impact on Supply System Process and Material Stability

Material moisture is generally an important factor impacting transportation costs, but considering the relatively low bulk densities of baled feedstocks, moisture only becomes a significant attribute when it begins to limit the payload. Consider the example shown in Figure 2-28 for a 53-ft flatbed tractor-trailer unit hauling 26 4×4×8-ft bales. According to Table 2-23, a dry matter bulk density of 15.3 lb/ft^3 would maximize the payload of this vehicle. If the biomass dry matter density is 7.6 lb/ft^3, bale moisture would have to be over 50% in order for it to limit the total payload. On the other hand, if the bales have a dry matter bulk density of 11.4 lb/ft^3, bale moisture above 25% would exceed the payload limit of the vehicle. For the conventional-bale design, which assumes the use of a 53-ft semi trailer, 4×4×8-ft bales, and an

80,000 lb. GVW limit, the bale moisture of corn stover and switchgrass would have to be higher than 42% and 34%, respectively, in order to significantly impact transportation costs, except for some nominal cost associated with higher truck weights, such as increased fuel consumption and maintenance costs.

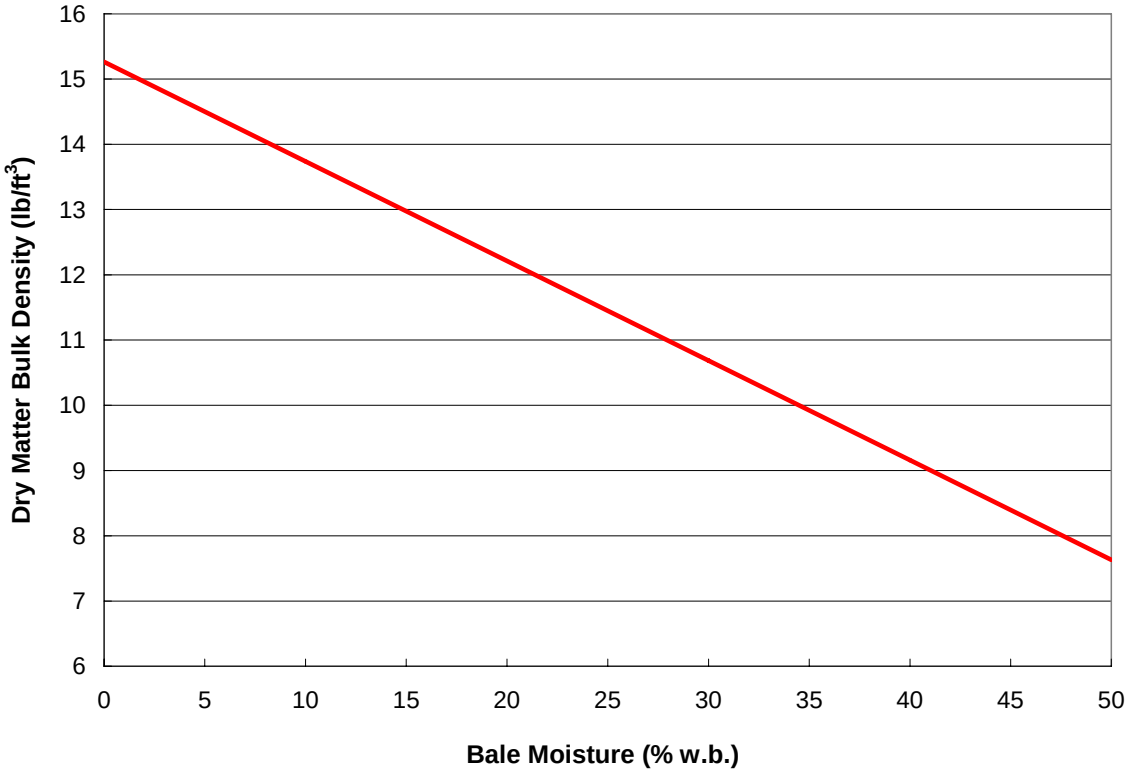


Figure 2-28. Effect of moisture on the bulk density of a 4×4×8-ft square bale needed to maximize truck load capacity. Example bale has a dry matter bulk density of 15.3 lb/ft3, representative of a 53-ft flatbed tractor-trailer unit hauling 26 bales (Table 2-23).

2.3.2 Conventional-Bale Handling and Transportation Equipment

Transportation from field-side storage to the biorefinery is most often accomplished with a self-propelled loader and semi-tractor trailer, as modeled in this conventional-bale design. This option is chosen since it is capable of accessing the various on-farm storage locations, provides a reasonable transportation cost, and is widely used for this purpose. Moving baled feedstock from fieldside storage to the biorefinery will first require removing the plastic wrap from the bales. Based on manufacturer input for wrap removal, it is generally regarded as a low-labor item, which can be handled by simply cutting the wrap along the side of the stack and allowing the self-propelled loader to pull the bales away from the wrap as it loads the truck. The conventional-bale design assumes that unoccupied labor is available onsite in the form of truck drivers to perform this task. Therefore, the labor costs associated with removing the wrap are absorbed in the transportation costs (Table 2-24).

Table 2-24. Handling and transportation equipment specifications for the conventional-bale design.

	Unstack/Unwrap, Load, and Clean-up	Transport
Equipment	Caterpillar TH220B Telehandler	Kenworth T800 3-axle Day Cab with Fontaine Phantom 53-ft Flat Bed Trailer
Rated Capacity	100 bales/hr	N/A
Field Capacity	80 bales/hr	6.4 tons/hr [a]
Operational Efficiency (%) [b]	80% [c]	46% [d]
Dry Matter Loss (%)	0%	0%
Operational Window		
hrs/day	14.0	14.0
days/week	6	6
weeks/year	50	50

a. Assumes a 38.2 mile haul distance at 50 mph and a 28-minute strap time.

b. Estimate of the operating time that is actually spent working and the amount of capacity used.

c. Ratio of field capacity to rated capacity.

d. Calculated efficiency from the analysis model based on the operating time that is actually spent hauling and the amount of capacity used.

2.3.2.1 Equipment

Unstack/Unwrap, Load, and Site Clean-up: Telehandler

A Caterpillar TH220B Telehandler is used to unstack the bales, load the semi-trailer, and clean-up the storage site. This piece of equipment is described in Section 2.2.2.1 and shown in Figure 2-21. In addition to a telehandler, a standard dump truck will haul the waste plastic wrap to a disposal site (i.e., landfill). The process of site clean up, including the use of a dump truck, is not modeled individually, but instead is included in the cost of the bale wrap process. Disposal costs are based on the following assumptions: 2 lb of plastic wrap per bale, a landfill charge of $35 per ton, and a handling and transport cost of $35 per ton, for a total disposal cost of $0.07 per bale.

Transport: Semi-Tractor and Trailer

The semi-tractor used in this design scenario is the Kenworth T800 3-axle day cab. It is configured with a 450 hp caterpillar engine satisfactory for pulling a bale-loaded Fontaine Phantom 53-ft flat bed trailer (Figure 2-29). The trailer is 102 in. wide and supports six rows (positioned lengthwise with the trailer) of two-high and two-across bale stacks with a seventh row of two-high bales stacked on the back of the trailer perpendicular to its length. This configuration allows for a total of 26 4×4×8-ft bales per load. At 53-ft in length, the trailer pulled with the T800 will function within all U.S. federal and state vehicle length road limits.

Figure 2-29. Kenworth T800 3-axle semi-tractor and the Fontaine Phantom 53-ft flat bed trailer used to transport 26 4×4×8-ft square bales.

2.3.2.2 Equipment Capacity and Operational Efficiency

Handling and transport of baled feedstock from field-side storage to the biorefinery is accomplished with a self-propelled loader and semi-tractor trailer. The self-propelled loader's capacity is modeled as 80 bales per hour, with an operational efficiency of 80% (Table 2-24). The semi-tractor trailer is a three-axle day cab pulling a 53-ft flatbed trailer. The bales are stacked two high and two across on the trailer allowing for 26 bales per load. The average haul distance, defined as the distance from the feedstock production or on-field storage site to the biorefinery, is modeled at 38.2 miles and the average truck speed is 50 mph.

Based on the distance between field-side stacks and the bale-yard at the biorefinery, different methods of transportation can be more or less cost effective than others. The option of using a self-propelled loader and semi-tractor trailer is chosen since this system can access the various on-farm storage locations and is widely used for moving square-baled material. However, a comparison of semi-tractor trailer and rail car transport options, hauling large square 4×4×8-ft bales is provided to show their respective advantages and identify the variables that influence when to chose one system over the other (Figure 2-30). This comparison uses a linear relationship between cost per DM ton of transported feedstock and transportation distance, given by:

$$T_{cost} = R_{cost} \times T_{dist} + H_{cost} \tag{2-1}$$

where

T_{cost} = total transportation cost, ($/DM ton)

R_{cost} = variable rolling cost, ($/DM ton/loaded mile)

T_{dist} = transportation distance from production site or storage stack to biorefinery (loaded mile)

H_{cost} = fixed handling cost for loading and unloading the transportation equipment ($/DM ton).

The variable rolling costs (R_{cost}) and fixed handling costs (H_{cost}) are represented in Figure 2-30 by the slope of the lines and the value at the intersection with the y-axis, respectively. The "trans-load" curve represents moving baled feedstock by truck for the first 20 miles and then loading it from truck to rail for an additional haul beyond 20 miles. In general, this would be done when rail lines are not close to the storage stack, but the final transport distance is beyond ~100 miles, the distance at which the truck transport curve intersects with the trans-load curve in Figure 2-30. The required 100-mile haul distance is due to the additional fixed cost ($12.84 per DM ton) incurred by loading the rail cars with the baled

feedstock, represented by the vertical part of the trans-load curve. If the transport distance is known to be beyond ~52 miles prior to loading a truck, and rail transport is close enough to load from the field, then moving the feedstock by rail alone would then be the best option.

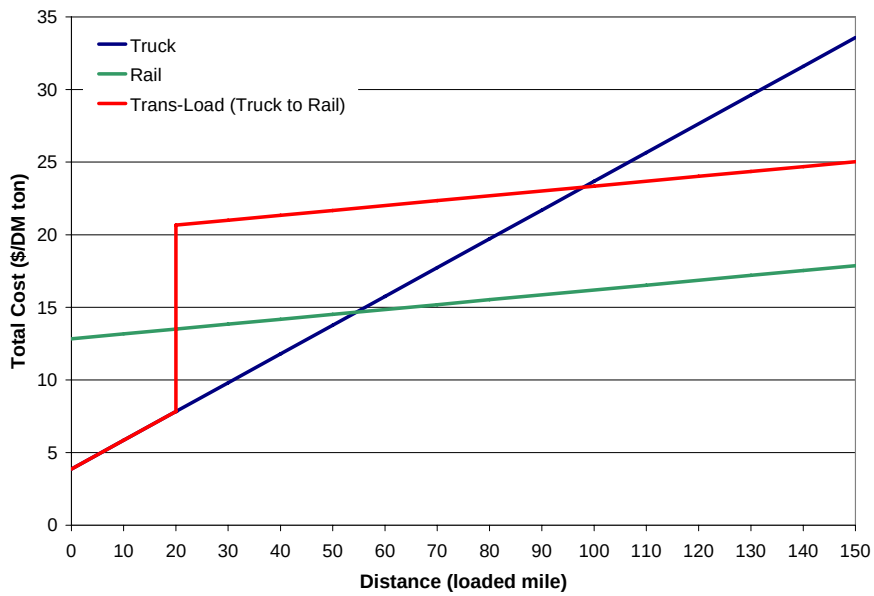


Figure 2-30. Transportation cost comparison for truck and rail.

The variables used in Eq. 2-1 for each transportation option are identified in Table 2-25. These variables are directly affected by the capacity of the transport container (variable cost contributor) and the efficiency of the handling equipment (fixed cost contributor) used to load the containers. Thus, trucking biomass has the lowest fixed costs but the highest variable costs of the two systems.

Table 2-25. Transportation costs.

Transportation Method	Cost ($/DM ton)
Truck	Cost = 0.196 × Dist + 4.33
Rail[a]	Cost = 0.034 × Dist + 12.84
a. Searcy et al., 2007.	

Capacity limits of a semi-tractor trailer, quantified by total vehicle size and GVW, are set at the state level. However, federal law mandates that states meet certain federal limits (Harwood et al., 2003):

- States may not set maximum weight limits on the Interstate System at less than 80,000 lb GVW
- States must permit tractor-trailer combination trucks with trailer lengths up to 48 ft in length to operate on the National Network (NN)
- States must permit trucks within the length limits given above with widths up to 8.5 ft to operate on the NN.

The NN is a network of routes designated by the federal government in consultation with the states. The non-interstate routes within the NN vary by region and are generally more extensive in western states compared to eastern states. A few states have increased the GVW limit on interstates above the 80,000-lb federal mandate, and most allow semi-tractor trailer lengths up to 53 ft, with some allowing as long as 59.5 ft. For state highways not in the NN, some states allow higher weights, some eliminate the semi-

tractor trailer length limit, and some reduce the semi-tractor trailer length limit (few less than 48 ft) compared to the NN within the state. For exceptions to these limits, most states allow trucks with weights and trailer lengths exceeding state limits to operate under a "routine" permit on specified highways and/or under specific conditions. Overall, federally mandated road limits provide uniformity to the transportation system; however, states exercise their rights to change these limits, sometimes significantly, especially with the use of over-legal permits.

Because truck size and weight limits often differ by state, the transportation costs may vary considerably as well. Table 2-26 illustrates the impacts on transportation cost for several truck configurations that accommodate different load limits. These same truck configurations are illustrated in Figure 2-27 for a visual comparison of their stacking arrangements.

Table 2-26. Impacts on transportation cost for several truck configurations that accommodate different load limits.

Truck Configuration	Load Limits		Bale Count	Payload (lb)[a]	Transport Cost ($/loaded mile)	Transport Cost ($/DM ton)
	Length (ft)	GVW (lb)				
48-ft Trailer	48[b]	80,000[b]	24	31,400	3.84	10.62
53-ft Trailer	53[c]	80,000[c]	26	34,000	3.96	10.12
24-ft Flatbed Tractor, two 30-ft Trailers	105[d]	105,500[d]	44	57,600	4.73	7.14

a. 4×4×8-ft square bales, 1,309 lb each.

b. Federal limits.

c. Common state maximum on National Network (NN) highways.

d. Allowable limits in CO, ID, KS, ND, NE, OK, and SD for two trailing units on non-NN highways.

2.3.2.3 Dry Matter Losses (Shrinkage)

Handling and transportation operations, like other operations in the supply system, are subject to dry matter losses. In many cases, mitigation strategies exist to limit these losses. However, in the case of loading and unloading bales within the transportation system, small losses are considered more or less inevitable with few mitigation options available, and as such, these losses are not accounted for in the cost analyses. On the other hand, dry matter losses occurring during transportation can be significant in terms of environmental and social impacts. For example, loose material blowing off of bales and collecting along common routes approaching the biorefinery may prove to be significant enough to require bale loads to be covered, particularly if these routes are within populated areas. Furthermore, the combined dry matter losses occurring during transport, if not controlled, could become an environmental issue subject to regulatory control. Nevertheless, for the purpose of this conventional-bale design, losses occurring during transport from the field to the biorefinery are considered to be negligible; loads are modeled uncovered and minor losses are not considered in the model.

2.3.2.4 Operational Window

The schedule for handling and transporting baled feedstock to the biorefinery is directly tied to the receiving schedule at the plant gate. This schedule is dependent on maintaining a 72-hour reserve supply in the bale yard as well as meeting the 24-hour a day supply demand of the preprocessing operation. With these constraints, the handling and transportation operations will run on an extended regular schedule of 14 hours per day, 6 days per week, for a total of 350 days per year. Based on the capacity of a semi-tractor trailer hauling 26 bales, a truck will, on average, roll through the plant gate about every

8 minutes during the 14-hour work day. Also, based on this operating schedule, truck traffic could be an issue that, at the very least, becomes a topic of discontent within the community. The issue of having trucks entering the plant gate every 8 minutes throughout each work day will need to be addressed as part of the plant site selection.

2.3.3 Conventional-Bale Handling and Transportation Cost and Sensitivity Analysis

2.3.3.1 Static Model Cost Summary

A breakout of the costs associated with each piece of equipment used in the storage unit operation identifies significant cost components that are valuable for making individual comparisons and recognizing areas of research potential (Table 2-27). These costs are reported in terms of DM tons entering the storage process.

Table 2-27. Static model costs for major handling and transportation equipment in the conventional-bale corn stover and switchgrass scenarios.

		Unstack/Unwrap, Load, and Clean-up	Transport
	Equipment	Caterpillar TH220B Telehandler	Kenworth T800 3-axle Day Cab with a Fontaine Phantom 53-ft Flat Bed Trailer
Corn Stover	Installed Equipment Quantity	5	34
	Installed Capital[a]	0.41	6.01
	Ownership Costs[b]	0.14	1.21
	Operating Costs[c]	0.65	8.89
	Labor	0.53	5.28
	Non-Labor	0.12	3.62
	Dry Matter Loss Costs	N/A	N/A
	Energy Use (Mbtu/DM ton)	4.2	110
Switchgrass	Installed Equipment Quantity	4	41
	Installed Capital[a]	0.33	7.25
	Ownership Costs[b]	0.12	1.55
	Operating Costs[c]	0.59	11.45
	Labor	0.48	6.31
	Non-Labor	0.11	5.14

Table 2-27. (continued).

	Unstack/Unwrap, Load, and Clean-up	Transport
Equipment	Caterpillar TH220B Telehandler	Kenworth T800 3-axle Day Cab with a Fontaine Phantom 53-ft Flat Bed Trailer
Dry Matter Loss Costs	N/A	N/A
Energy Use (Mbtu/DM ton)	3.8	156

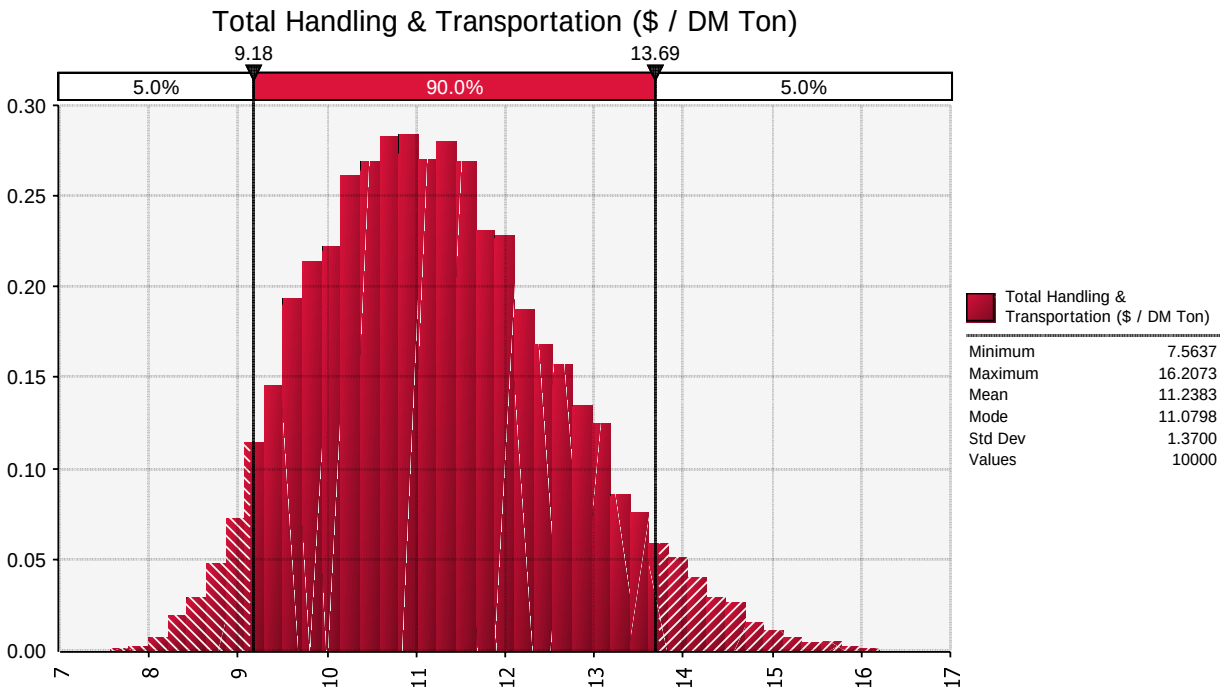
a. Installed capital costs are $ per annual DM ton capacity.

b. Ownership costs include depreciation, interest, taxes, insurance, and housing (Appendix A-2, Table A-7).

c. Operating costs include repairs, maintenance, fuel, lubrication labor, and consumable materials (Appendix A-2, Table A-7).

2.3.3.2 Cost Sensitivity Analysis

A histogram of the handling and transportation cost (Figure 2-31) for corn stover shows that with 90% confidence the cost of the unit operation ranges between $10.03 and $14.16 per DM ton. Further, the mean and standard deviation of this range is $11.93 ±1.25 per DM ton. The mode value of the handling and transportation cost is $11.95 per DM ton. This value closely represents the result of the static model, which is $10.90 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.



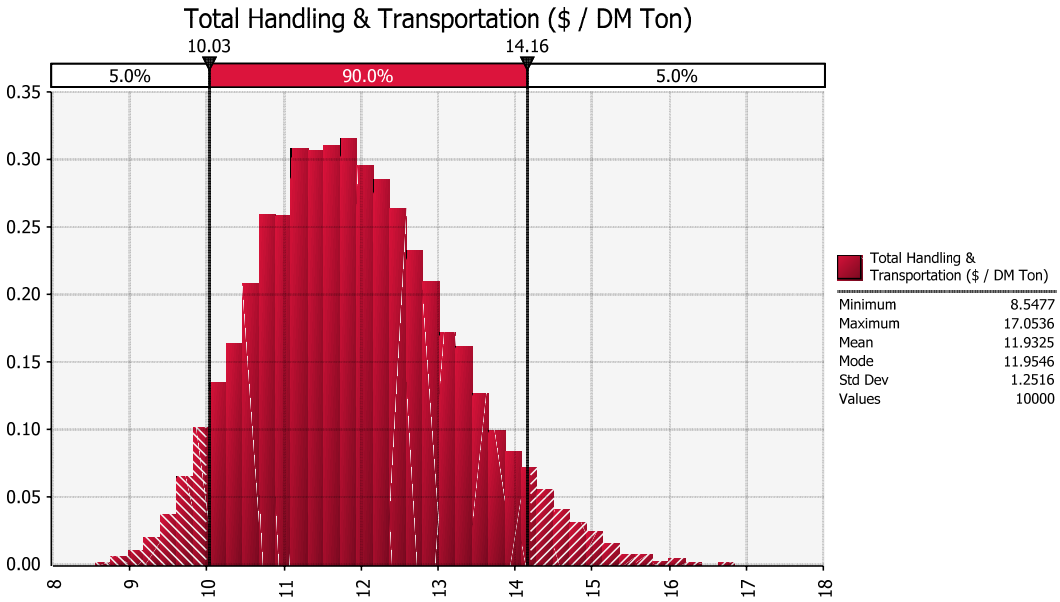
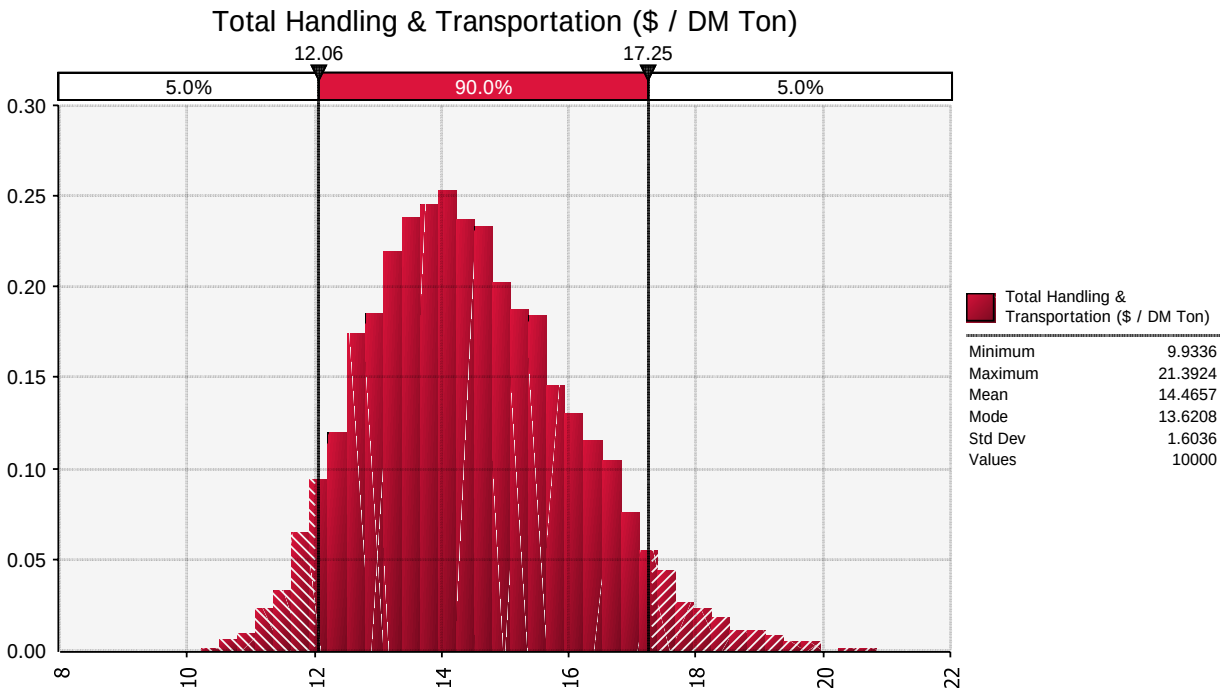


Figure 2-31. Conventional-bale handling and transportation cost distribution histogram from @Risk analysis for corn stover.

Similarly, a histogram of the handling and transportation cost (Figure 2-32) for switchgrass shows that with 90% confidence the cost of the unit operation ranges between $11.96 and $16.61 per DM ton, with the mean and standard deviation of this range being $14.14 ±1.43 per DM ton. The mode value of this cost range is $13.51 per DM ton, which closely represents the result of the static model of $13.71 per DM ton.



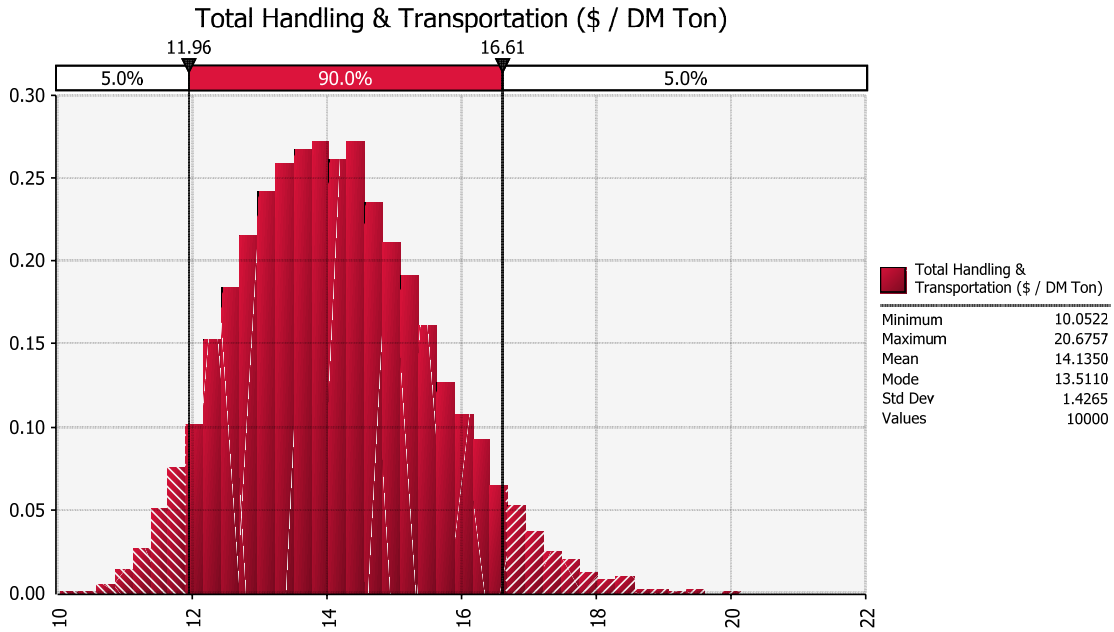


Figure 2-32. Conventional-bale handling and transportation cost distribution histogram from @Risk analysis for switchgrass.

The overall costs associated with the conventional-bale handling and transportation unit operation for both corn stover and switchgrass are provided in Table 2-28 on a per-DM-ton, per-bale, and per-mile basis. These costs, reported as a mean and standard deviation, come as a result of 10,000 model iterations of the simulated conventional-bale feedstock supply system.

Table 2-28. Handling and transportation cost summary for the conventional-bale corn stover and switchgrass scenarios.

Equipment		Stacking	Transport	Total Handling and Transportation
		Caterpillar TH220B Telehandler	Kenworth T800 3-axle Day Cab with a Fontaine Phantom 53-ft Flat Bed Trailer	
Corn Stover	Modeled Cost Totals[a]	0.84 ± 0.09 $/DM ton	11.09 ± 1.22 $/DM ton	11.93 ± 1.25 $/DM ton
		0.49 ± 0.04 $/bale	6.48 ± 0.60 $/bale	6.97 ± 0.60 $/bale
		2.54 ± 0.15 $/mile	3.99 ± 0.15 $/mile	6.53 ± 0.30 $/mile
Switchgrass	Modeled Cost Totals[a]	0.76 ± 0.08 $/DM ton	13.37 ± 1.40 $/DM ton	14.13 ± 1.43 $/DM ton
		0.49 ± 0.04 $/bale	8.68 ± 0.77 $/bale	9.17 ± 0.78 $/bale
		2.21 ± 0.12 $/mile	3.68 ± 0.12 $/mile	5.89 ± 0.23 $/mile

a. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

2.4 Conventional-Bale Receiving and Preprocessing

Biorefinery receiving and preprocessing encompasses all processes associated with weighing and unloading incoming trucks, moving baled feedstock into short-term storage (queuing), moving bales from queuing into the preprocessing system for grinding, and feeding the ground feedstock into the conversion process (Figure 2-33). The primary objective of the conventional-bale supply logistics system is to get the biomass from the field to the biorefinery. Biomass quality control, if any, will be done by bale sorting. Ideally, unacceptable bales will never be transported from storage to the biorefinery. If unacceptable bales do arrive at the biorefinery, these bales can be rejected when they are unloaded and/or handled into the preprocessing mills (Figure 2-33); however, the conventional-bale design assumes all bales are transported to the biorefinery.

The conventional-bale preprocessing design requirement is to simply shred the bale and sufficiently size-reduce the biomass sufficiently to move it through the feed system and into the conversion reactors. Multistage fractional milling preprocessing systems that produce biomass particles and particle-size distributions to optimize material handling and conversion are not modeled in the conventional-bale design, but more advanced milling options are considered in the pioneer-uniform and advanced-uniform supply logistic designs (Sections 3 and 4). In reality, such a simplified preprocessing system may not be adequate for some conversion processes, and additional or alternate preprocessing systems may be required for the conversion system to function properly.

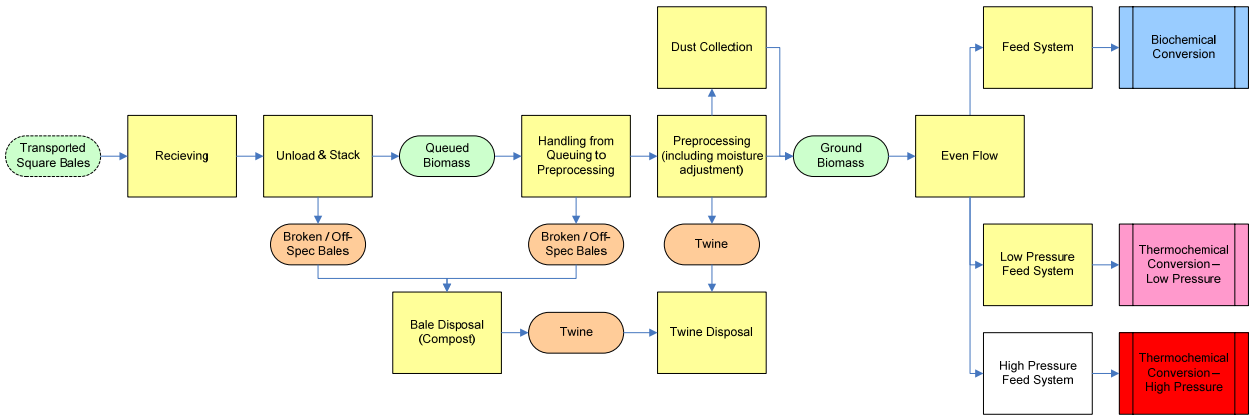


Figure 2-33. Receiving and preprocessing supply logistic processes and biomass format intermediates. (Green ovals represent biomass format intermediates, tan ovals represent potential waste streams, yellow rectangles represent processes modeled in this report, and white rectangles represent processes not modeled in this report. The blue, pink, and red rectangles represent different conversion processes.)

2.4.1 Conventional-Bale Receiving and Preprocessing Format Intermediates

Bale format (e.g., large square bales) plays a crucial role in determining both the type and size of equipment used to receive, handle, queue, and preprocess the feedstock at the biorefinery. The variables that impact the selection of equipment for conventional-bale receiving and preprocessing modeled in this report are based on the 4×4×8-ft square bale format (Table 2-29). The design of the receiving operation is largely impacted by the size of the feedstock inventory that must be maintained in queue to supply the plant. Although just-in-time delivery minimizes the queuing capacity, a queuing system is, nonetheless, needed to prevent costly disruptions to the conversion operation due to delays in feedstock delivery. The conventional-bale design only receives biomass 14 hours each day, while the biorefinery operates 24 hours each day. Therefore, between 162 and 180 truck loads of 26 bales each will be received daily within a 14-hour operating window, and over the full 24-hour period, 4,000 to 5,000 bales will be removed from the bale yard queue and preprocessed for conversion (Table 2-29). As such, a feedstock inventory will be maintained for immediate access while feedstock delivery is suspended during off-shift hours or during weather delays. In this design, the queuing bale yard will hold a 72-hour feedstock inventory; however, depending on the receiving schedule and the probability of weather events that could halt delivery operations, a larger storage queue may be required. The queuing bale yard is intended to be a first-in-first-out queue; thus, feedstock inventory is rotated at a regular interval.

Table 2-29. Attributes of receiving and preprocessing format intermediates for corn stover, a crop residue.

	Receiving and Queuing	Preprocessing		Receiving and Queuing	Preprocessing
Biomass Output	Stover	Stover		Switchgrass	Switchgrass
Yield (DM tons/day)	2,600 (4,640 bales)[a]	2,600		2,600 (4,160 bales)[a]	2,600
Format Output	4×4×8-ft bales stacked in bale yard	Bulk (1-½-in. minus)		4×4×8-ft bales stacked in bale yard	Bulk (1-½-in. minus)
Bulk DM Density Output	9 lb/ft^3	7.4 lb/ft^3		10 lb/ft^3	10.3 lb/ft^3
Output Moisture (%	12	12		12	12

w.b.)					

a. Total tonnage and bale number for the bale yard queue is the daily (24-hour period) 2,600 DM tons multiplied by 3 days (72-hour queuing period) equals 7,800 DM tons queue yard capacity, or about 14,000 bales.

After the trucks arrive at the bale yard and are weighed, they are unloaded directly into a queue yard stack (Figure 2-34a). The integrity/durability of received bales has a significant impact on the efficiency of the bale handling equipment. In the conventional-bale design, bales arriving at the biorefinery have already been handled at least three times (e.g., collection, stacking, transport), and because the receiving operation must handle the bales two additional times, bale integrity/durability is critical to the receiving equipment's ability to move the feedstock without breaking bales. Bales that break during handling basically explode into a pile of unmanageable biomass that must be pushed out of the way or recovered with a large volume bucket loader. Broken bales result in operational inefficiencies and can cause product losses.

The size of bale queue yard stacks is limited to 100 tons (as received), and each stack is separated by a 20-ft clearance, as required by the International Fire Code (ICC, 2003) (Figure 2-34b). The large 4×4×8-ft square bales are stacked 4 high × 5 wide, and depending on the bale density, from 6 to 10 bales long for a 100-ton stack. Because of bulk density differences between corn stover and switchgrass bales, and adjustments for the moisture of as-received tons, individual queue yard stacks have a total of 170 stover bales or 150 switchgrass bales. The queue yard stack tonnage is actually less than 100 tons because stacks are built in multiples of 10 or 20 bales. (Note the difference in corn stover and switchgrass bale counts in Table 2-29).

(a)

(b)

Figure 2-34. Receiving and cueing processes within the conventional-bale receiving and preprocessing unit operation: (a) Bale handling and truck unloading and (b) lane separating two stacks of 4×4×8-ft bales in a bale yard.

Following the same schedule as the conversion facility, stacked bales are moved from the bale queue yard to the grinder, and the bales are preprocessed into a bulk format for insertion into the feed systems of the conversion process (Figure 2-35). The bulk density of the material at this point is approximately 7.4 lb/ft^3 for corn stover and 10.3 lb/ft^3 for switchgrass, with similar moisture content as the pre-ground, baled material (12% w.b.) (Table 2-29).

Figure 2-35. Images of corn stover and switchgrass feedstocks preprocessed through a nominal 1-1/2 in. minus grinder screen.

Each biomass feedstock has distinct physical characteristics that impact how the respective feedstocks size-reduce within the milling units. These characteristic differences will have a greater impact on the preprocessing operation than they have had on any of the previous receiving, handling, and queuing operations. Because the preprocessing operation directly feeds the conversion process, end-product particle size and distribution are the primary feedstock characteristics to consider. Data collected during three full-scale grinding tests demonstrate that feedstock type and moisture can cause large variations on the particle size and distribution of the final ground material (Figure 2-36).

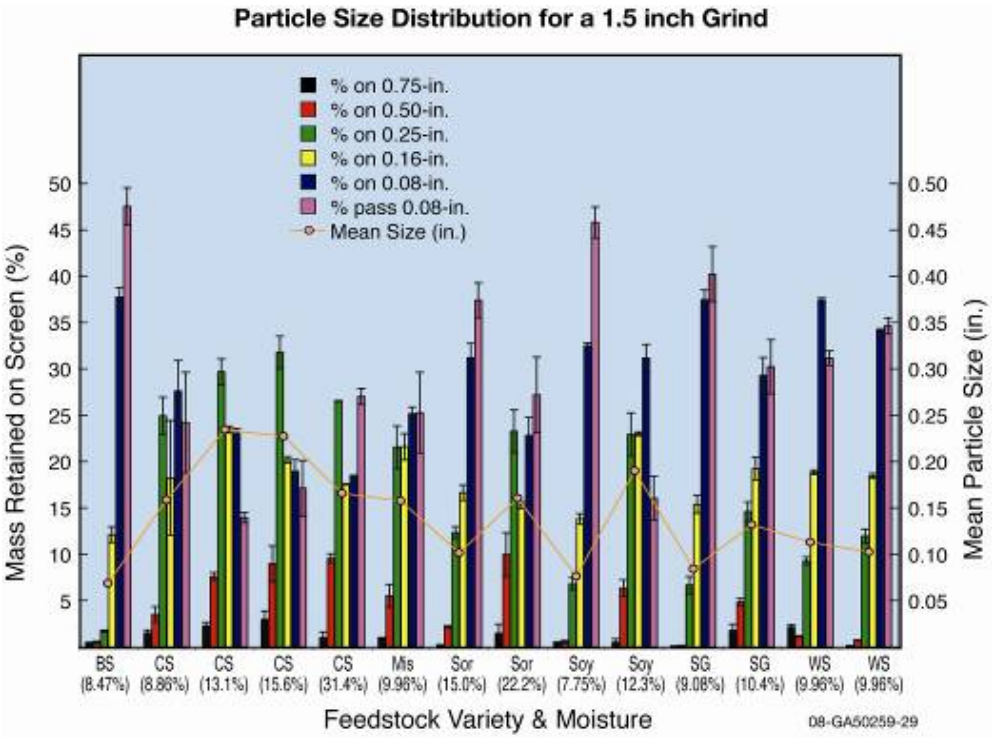


Figure 2-36. Mean particle size and particle-size distribution for different feedstock varieties at different moistures (% w.b.). Feedstocks represented include barley straw (BS), corn stover (CS), *Miscanthus* (Mis), grain *Sorghum* stover (Sor), soybean stubble (Soy), switchgrass (SG), and wheat straw (WS).

Mean particle size and distribution was determined using a forage particle separator (ASABE, ANSI/ASAE S424.2, 2007).

Some of the regulatory issues that must be addressed in the receiving and preprocessing operation include dust control, fire prevention, and rodent control. Bale handling during truck unloading and bale queuing does not generate a sufficient amount of dust and particulate emission to require mitigation. However, dust and particulate emissions are a significant issue within preprocessing. Dust collection systems are included as part of the overall preprocessing system to meet both regulatory emission standards as well to capture ground product too valuable to lose. Fire prevention is largely addressed by limiting the stack sizes and clearances in the bale yard according the requirements of the International Fire Code (ICC, 2003), but fire suppression systems such as hydrants should be located throughout the bale yard as well. Dust collection systems within preprocessing should also be designed to meet the National Fire Protection Agency's (NFPA) standard for dust explosion (NFPA 2006, 2007, 2008).

2.4.1.1 Biomass Deconstruction, Fractionation, and Physical Property Changes

The physical characteristics of biomass feedstocks are related to the ultra structure of the different plant components, such that even though the same grinding mechanism is used, each anatomical plant part and the component plant tissues contribute to very different end-product properties of stover and switchgrass (Table 2-30). Grinding corn stover in a tub or horizontal grinding system with hammers or fixed cutters results in a significant amount of strong fibrous material that does not easily reduce in size and flow through the separation screen. This material becomes interlocked, forming a low-bulk-density mat that sits on top of the grinding chamber after the rest of the stover has been discharged from the system (Figure 2-37a). This mat of fibrous stover tissues can significantly reduce the overall capacity of the grinder and even plug the grinder separation screen and discharge area. The matting problem can be overcome by increasing milling shear forces (e.g., knives, shear plates, etc.) to more efficiently size-reduce this highly fibrous material. Of course, the non-fibrous stover tissues rapidly size-reduce with impact forces, such as hammers or blunt cutters. For many biomass resources, like corn stover, a combination of multiple size-reducing actions may be the most efficient way to reduce feedstock material to the desired format and particle size. This can be achieved with a two-stage grinding system or a system where the two actions are combined in one machine.

Table 2-30. Corn stover and switchgrass characterization after the conventional-bale preprocessing operation.

Feedstock (1 1/2-in. minus)	Corn Stover	Switchgrass
Mean Particle Diameter	4.0 mm	2.1 mm
Particle-Size Distribution (wt%)	29.9% > 6.35 mm 2.03 mm < 45.9% < 6.35 mm 24.2% < 2.03 mm	6.9% > 6.35 mm 2.03 mm < 52.9% < 6.35 mm 40.2% < 2.03 mm
Bin Density (10-ft diameter bin)	7.4 lbs/ft^3	10.3 lbs/ft^3
Compressibility (Δ% 0-500 lb/ft2)	66.0 ± 0.5%	52.5 ± 3.1%
Flowability Factor [a]	0.8 (non-flowing)	1.0 (very cohesive)
Springback	40.6 ± 1.4%	28.1 ± 3.6%
Angle of Repose	39.6 ± 4.3°	44.2 ± 4.8°

[a] Flowability factor ranges: <1.0, non-flowing; 1.0–2.0, very cohesive; 2.0–4.0, cohesive; 4.0–10.0, easy flowing; and > 10, free flowing.

Other feedstocks, like switchgrass, tend to size-reduce in a more uniform fashion, with limited amounts of long, intact fibers (Figure 2-37b). These feedstocks flow better through the grinding and discharge systems and show very little tendency to mat in the grinding chamber or plug the screens during discharge. Nevertheless, both corn stover and switchgrass produce a wide particle-size distribution after grinding (Figure 2-38).

(a)

(b)

Figure 2-37. Corn stover (a) and switchgrass (b) ground with a tub grinder through a 1-1/2-in. screen. The corn stover picture (a) shows the fibrous mat that remains in the grinding chamber at the end of the grinding process. All of the switchgrass (b) is discharged from the system, leaving no fraction in the grinding chamber.

The physical deconstruction characteristics between corn stover and switchgrass feedstock ground in the systems of this conventional-bale design result in a mean particle size and particle-size distribution difference of 0.20±0.14 in. for corn stover and 0.10±0.12 in. for switchgrass (Figure 2-38). These feedstock particle sizes and distribution may ultimately need to be improved based on conversion process requirements and material handling/flowability constraints. For the conventional-bale design, a general mean particle size target of ¼-in. minus, with no range constraint or lower size limit, is being used as a baseline. With this said, it is generally true that smaller particle-size requirements will mean lower grinder capacities and higher preprocessing costs.

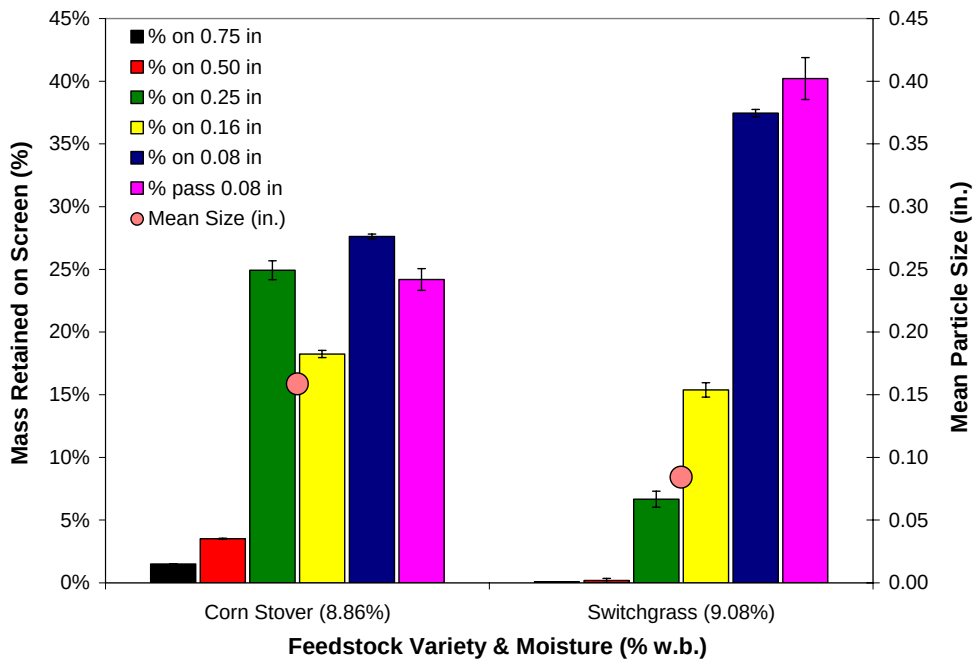


Figure 2-38. Mean particle size and particle-size distribution for corn stover and switchgrass at the noted moisture (% w.b.). Mean particle size and distribution were determined using a forage particle separator (ASABE, ANSI/ASAE S424.1, 2007).

Additional considerations for particle size may be dictated by bulk-flow properties required by the biomass conveyance systems that feed the conversion processes. For example, 1 ½-in.-minus ground switchgrass is a very cohesive but flowable material, but corn stover ground to the same size is not flowable (Table 2-30). As such, more aggressive preprocessing of corn stover may be required to achieve equivalent material property characteristics, which can affect biomass feed rates and solids-loading specifications of specific conversion processes.

2.4.1.2 Format and Bulk Density Impact on Supply System Processes

There are a number of methods for unloading bales from a truck, including automated methods using rail-mounted cranes or walking-floor trailers (Cundiff et al., 2004), or manual methods using self-propelled loaders. Just-in-time delivery is particularly conducive to automated bale-handling systems, where bales are unloaded from the truck directly into a bale conveying system bound for the preprocessing operation. On the other hand, if bales must be stored in a large bale yard for some duration and later retrieved for feeding to the plant, automated systems become large and complex. While these receiving and handling systems are generally constrained to the specific bale format(s) for which they are designed, the respective bale handling systems are generally indifferent to the type of feedstock being delivered in terms of the number of bales per hour that can be received and handled. As such, bale format and bulk density are more important to receiving system performance. Bale format is a function of the type of baling equipment that is used. If bale receiving systems are needed to handle additional bale formats, changes will be required in the bale handling equipment, queue yard stack configuration, de-baling and twine/net removal equipment, and grinder feed mechanism. For the conventional-bale design, all equipment is configured for the 4×4×8-ft square bale. Equipment and systems for using other bale formats will be discussed in Section 3, Pioneer Uniform-Format Feedstock Supply System.

As-received bale bulk density is influenced by both the baling equipment and the type of feedstock being baled. New high-density balers can produce 3×4×8-ft square bales with the same weight per bale

(1,100–1,300 lb w.b.) as the 4×4×8-ft square bales used in this design, and bale bulk density difference resulting from feedstock type can be just as dramatic. The switchgrass feedstock modeled in this design produces bales that are 10% higher in bulk density than corn stover bales (Tables 2-2 and 2-3). For these higher bulk density switchgrass bales, the ton per hour capacity of the receiving and handling systems is increased by 10% over corn stover because the bales per hour capacity is similar between stover and switchgrass. Another interesting point about feedstock type and bulk densities is the change in feedstock bulk density from the bale to the ground bulk format. Corn stover is received in a bale at a bulk density of 9 lbs/ft^3, and after grinding, the feedstock bulk material bulk density declines to 7.4 lbs/ft^3 (Tables 2-2 and 2-30). Switchgrass is received in a bale at a bulk density of 10 lbs/ft^3, and after grinding to a bulk format, switchgrass remains at 10 lbs/ft^3 (Tables 2-3 and 2-30). In order to get ground corn stover to exhibit similar bulk densities as switchgrass, additional preprocessing is required (INL data or report to reference here?).

2.4.1.3 Biomass Moisture Impact on the Supply System Process and Material Stability

Feedstock moisture, bale condition, mold, and dirt are some of the feedstock quality parameters that will provide the basis for dockage withheld from the feedstock payment or, in an extreme case, rejection of select bales or the entire truckload of bales. Moisture level is easily assessed using a moisture probe, whereas the other quality parameters listed are more subjective. Each plant may have its own receiving criteria, but, as a general rule, feedstock moisture will be limited to an amount suitable for stable aerobic storage. Moisture content will generally be less than 20% for most biomass feedstocks, with higher moistures indicative of poor storage conditions and excessive sugar losses. Nevertheless, specific moisture requirements will be based on regional constraints and specific feedstock characteristics.

Once received, bale moisture will be controlled by maintaining a well-drained storage surface and continuously rotating the supply as it moves into the preprocessing system. By employing these moisture management methods, it is assumed that only the top layer of bales in each stack will become wet during any weather event and that these bales will not be exposed long enough (at most 72 hours) to cause unacceptable damage. Thus, other, more active, moisture mitigation methods (i.e., tarps, covered structures, etc.) are not necessary and are not included in the conventional-bale design.

Managing moisture at the plant is also essential for maintaining the rated capacity and efficiency of the grinding equipment. In fact, it has been reported that an increase in straw bale moisture from 10% to 20% reduces hammer mill capacity by ~12.5% (Antares, 2008). Using data from INL full-scale grinding tests and the Chariton Valley Biomass Project, a relationship between grinding capacity and biomass moisture content has been developed (Figure 2-39). To minimize the negative effects of bale moisture on grinding capacity, top bales that become wet due to weather events will be mixed in with dryer bales during grinding. For the purpose of this conventional-bale design, bales are assumed to be approximately 12% moisture w.b., as shown in Table 2-29.

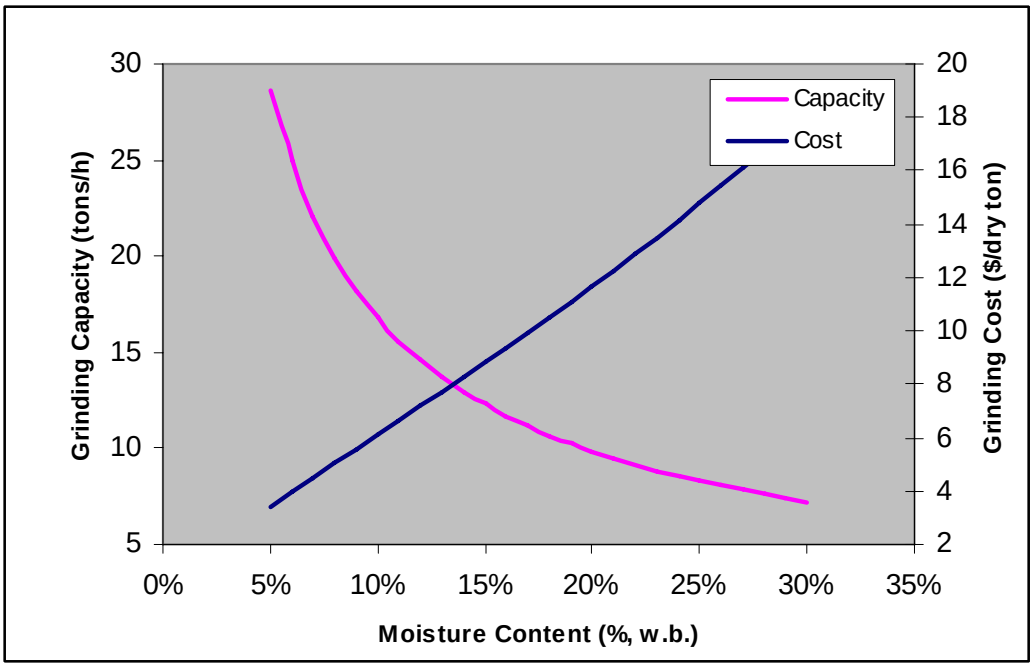


Figure 2-39. Relationship between biomass moisture content at the time of grinding and both grinding capacity and grinding cost taken from the Chariton Valley Biomass Project (Antares, 2008) data and the INL feedstock supply system model.

2.4.2 Conventional-Bale Receiving and Preprocessing Equipment

The conventional-bale design uses the same set of equipment to receive and preprocess both corn stover and switchgrass feedstocks. The decision not to alter equipment for each feedstock is based on the fact that the receiving system is not impacted by feedstock variety when handled in bale format, and the preprocessing system can adjust to the different feedstocks by simply changing operational parameters without changing equipment. The only appreciable difference between corn stover and switchgrass when handled with the same equipment is the resulting mean particle size and particle-size distribution of the ground material entering the conversion process (Table 2-30). Nevertheless, this difference does not significantly alter the performance of the feed system into the conversion process.

2.4.2.1 Receiving Equipment

Conventional-bale receiving includes the equipment and systems necessary to accept truckloads of biomass at the biorefinery and conduct a transaction between the buyer (i.e., biorefinery) and the seller (i.e., producer). For the conventional-bale design, this transaction is based on weight and moisture only. Biomass quality assessment laboratories may also become part of the receiving system as biomass trading quality factors become better understood. A quality laboratory is itemized in Appendix ??, but the equipment and costs are not included in the conventional-bale design.

Other processes included in the receiving and preprocessing unit operation are truck unloading and bale-yard queuing. The receiving equipment specifications used for the conventional-bale corn stover and switchgrass models are shown in Table 2-31.

Table 2-31. Receiving equipment specifications for the conventional-bale design.

	Receiving	Unload and Stack	Bale Yard Queuing
Equipment	Scales Unlimited, Inc. Model AGETS-11711-NTEP Semi-truck Scale	Caterpillar TH220B Telehandler	826,500 ft^2 (~20-acres) 3/6/12 Asphalt Pad
Rated Capacity	15 trucks/h	100 bales/h	13,714 bales
Field Capacity	11 trucks/h; 2,667 DM tons/day	80 bales/h	6,857 DM tons; 11,900 bales
Operational Efficiency (%)a	75% b	80% b	N/A
Dry Matter Loss (%)	0%	0%	0%
Operational Window			
hrs/day	14.0	14.0	24.0
days/year	300	300	300

a. Estimate of the operating time that is actually spent working and the amount of capacity used.
b. Published efficiency input into the analysis model (Appendix B-2).

The truck scale implemented in this design scenario is the AGETS-11711-NTEP model from Scales Unlimited, Inc. (Figure 2-40). This model is an above-ground unit with a weight capacity of 100 ton. It is 11-ft wide and 130-ft long. The truck net weight (weight of bales only) will be determined with the truck scale by weighing loaded trucks as they arrive at the receiving area (gross weight) and then subtracting the weight of the unloaded truck (tare weight). The tare weight of a truck will be taken after each load, even though the same truck may make several deliveries per day.

Figure 2-40. Scales Unlimited, Inc. AGETS-11711-NTEP truck scale.

A Caterpillar TH220B Telehandler, described in further detail in Section 2.2.2 and shown in Figure Figure 2-21, is used to unload the bales from the semi-tractor trailers and stack them in the queuing bale yard. The queuing bale yard covers approximately 19 acres and does not include the area needed to receive and weigh incoming and outgoing trucks. The surface of the bale yard is paved to maintain workable conditions given the large volume of truck and loader traffic. The paved surface eliminates mud, controls water runoff, facilitates snow removal, and allows for cleanup of loose biomass from broken bales and biomass lost from bales during unloading and retrieval. Given the restrictive stack size limits imposed by fire code (Section 2.4.1.2), the bale yard for a biorefinery can become quite large. The layout of the bale yard and preprocessing system used in this design is shown in Figure 2-41. An important note with this particular layout is that it satisfies all current international fire codes regulating aggregated biomass. Within this configuration, up to 7,000 tons of biomass can be stored at any given time.

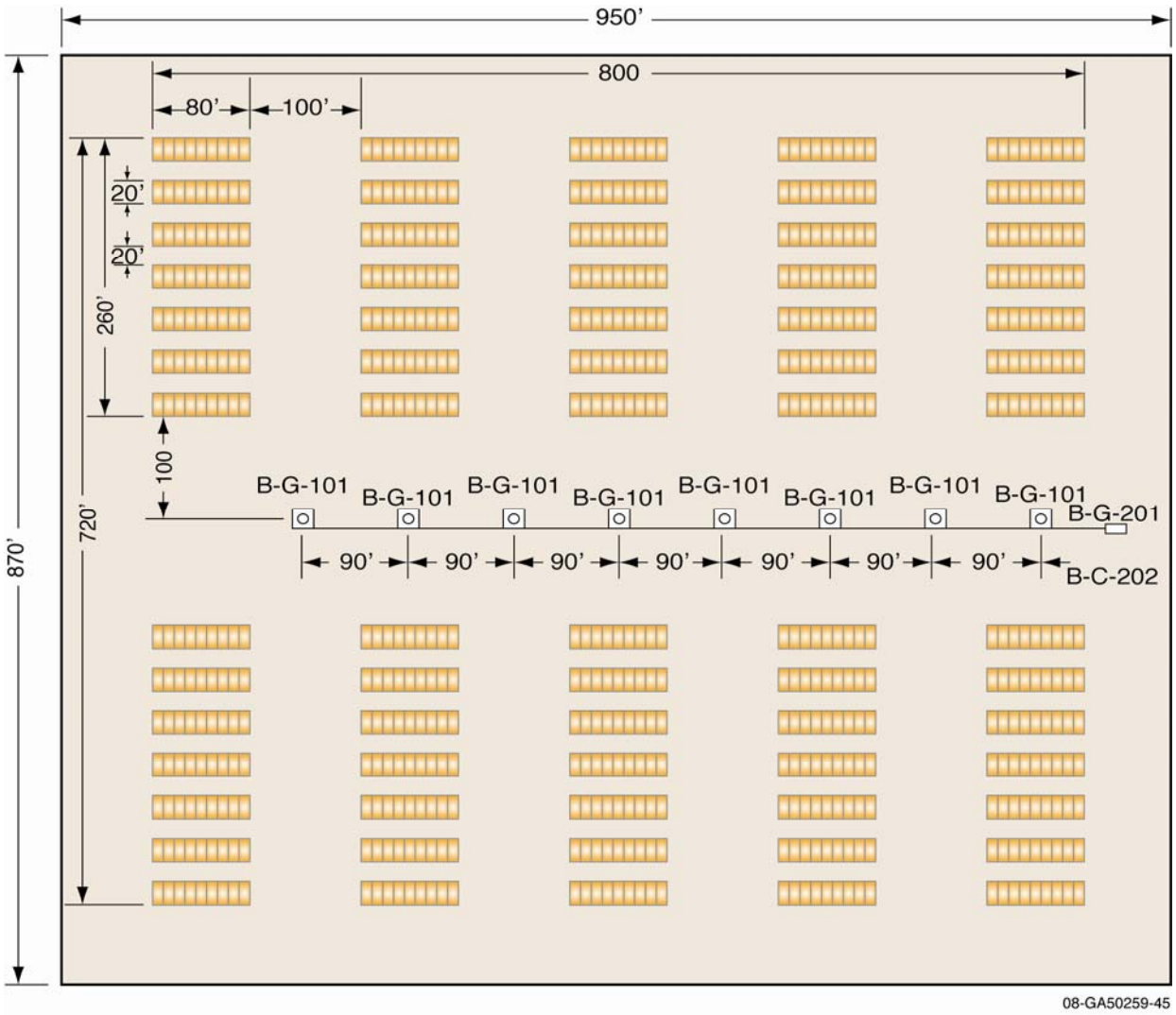


Figure 2-41. Bale receiving layout.

2.4.2.2 Preprocessing Equipment

Conventional-bale preprocessing is located at the biorefinery and includes all milling, conveyance, dust collection, and biomass material surge systems necessary to size-reduce the biomass and insert it into the conversion process (e.g., biochemical or thermochemical). The preprocessing equipment and specifications used for the conventional-bale corn stover and switchgrass models are shown in Table 2-32.

Table 2-32. Preprocessing and conversion equipment specifications for the conventional-bale design.

	Load Grinder from Stack	Preprocessing			Bale and Twine Disposal
Equipment	Caterpillar TH220B Telehandler	Grinder In-feed System (Warren & Baerg D-Stringer, conveyor)	Vermeer HG6000 Horizontal Grinder	Cyclone, Baghouse, and other Conveying Equipment	Dump Truck
Rated Capacity			17 tons/hr		
Field Capacity	45 bales/hr	14.6 tons/hr	14.6 tons/hr	14.6 tons/hr	
Operational Efficiency (%)[a]	92[a]		85[a]		
Dry Matter Loss (%)	0	0	0	0	
Operational Window					
hrs/day	24.0	24.0	24.0	24.0	24.0
days/year	350	350	350	350	350

a. Estimated capacity based on the actual operating time and the amount of capacity used.
b. Published efficiency input into the analysis model (Appendix B-2).

A Caterpillar TH220B Telehandler, described in further detail in Section 2.2.2 and shown in Figure 2-21, is used to remove the bales from the queuing bale yard stacks and load the bales into a Warren & Baerg D-Stringer, which removes the bale strings and conveys an even flow of bales into the preprocessing grinder (Figure 2-42).

Figure 2-42. Warren & Baerg D-Stringer conveyor grinder in-feed system (Chariton Valley Project).

The Warren & Baerg D-Stringer conveyor feeds a Vermeer HG6000 horizontal grinder. The conventional-bale design uses eight of these systems operating in parallel (Figure 2-41, note grinder stations B-G-101). The HG6000 is modeled with an equivalent 630 hp electric motor and has a 60-in. feed table with a 48-in. feed conveyor. The HG6000 has a feed throat height of 32 in. with a 36-in. diameter feed roller. The screen used in this scenario has 1 1/2-in. square openings. Figure 2-43 shows a Vermeer HG365E electric horizontal grinder and shows what an equivalent HG6000 would look like if an electric version was in production. The model uses grinding performance parameters based on HG6000 data collected by INL but substitutes an equivalent electric energy use for the rated diesel horse power.

Figure 2-43. Vermeer HG6000 630 hp Horizontal Grinder.

Once the ground biomass passes through the screen, the material exits the grinder on a 48-in. continuous conveyer belt. Based on capacity and the need for redundancy, eight grinders were selected in this design (grinder configuration layout shown in Figure 2-41). The dust control system is a Koger A-B cyclone connected to a Farr GS-16 baghouse (Figure 2-42). The cyclone is used as a pre-cleaner system for dust and particulate-laden air leaving the preprocessing operation. As part of a closed system, the cyclone separator reduces the final filter load before the dust-laden air moves to the attached baghouse. The cyclone used in this scenario has an inlet diameter of 20 in., a body diameter of 80 in., and a capacity of 9,150 cfm @ 2 in. static pressure (sp). In coordination with the cyclone unit, the Farr GS-16 baghouse serves as the final dust collection unit (Figure 2-44). With this unit in the system, dust created and released during preprocessing is filtered from the air and captured. This process is important for two reasons: first, the dust is generally material with value in the conversion process, and second, dust release in ambient air is typically restricted through government regulation.

Figure 2-44. High-efficiency cyclone and baghouse for dust control and filtering (Antares, 2008).

2.4.2.3 Conversion Process Feed System

The conversion process feed system includes equipment necessary to convey the ground biomass, which now is in a bulk form, from the preprocessing system to the conversion processes at a constant and steady-state feed rate. While equipment and operation specifications for both the low- and high-pressure thermochemical conversion process (thermochem) feed systems are given in Table 2-33, only the biochemical conversion process (biochem) feed system is modeled in the conventional-bale system. This biochem feed system will handle the preprocessed material from both corn stover and switchgrass, with the corn stover being the more technically challenging material to handle (Table 2-30, Material properties of stover and switchgrass.).

Table 2-33. Conversion process feed system equipment specifications for the conventional-bale design.

	Biochem Evenflow and Feedsystem	Low-Pressure Thermochem Evenflow and Feed System	High-Pressure Thermochem Evenflow and Feed System
Equipment	Surge Bin, Foreign Material Eliminators and other Conveying Equipment	Surge Bin, Foreign Material Eliminators and other Conveying Equipment	Surge Bin, Foreign Material Eliminators and other Conveying Equipment
Rated Capacity		100 tons/hr	100 tons/hr
Operational Efficiency (%)[a]	1,500 ft^3, 14.6 tons/hr	95% [b]	95% [b]
Dry Matter Loss (%)	0%	0%	0%
Operational Window			
hrs/day	24.0	24.0	24.0
days/year	350	350	350

a. Estimate of the operating time that is actually spent working and the amount of capacity used.

b. Published efficiency input into the analysis model (Appendix B-2).

In order to feed the ground feedstock into the conversion process, a Warren & Baerg Metering Bin, sometimes referred to as a "surge bin," collects the pulsating biomass material flows from the eight grinding units and meters out the biomass in an even flow of material to the conversion process reactors. (Figure 2-45). This evenflow system is equipped anti-bridging and clumping mechanisms that keep the material flowing continuously. The flow rate of the metering bin is adjustable to fit specific process in-feed requirements.

Figure 2-45. Biomass feed system for a biochem or low-pressure thermochem conversion processes, including the evenflow metering bin (large blue elevated bin) and the augers and pneumatic conveyance equipment that enters and exits the metering bin (Antares, 2008).

2.4.2.4 Equipment Capacity and Operational Efficiency

The capacity of the conventional-bale receiving and preprocessing system is easily scaled by changing the number of telehandler loaders used. The most significant impediment to efficiency of this design is broken bales. Altering the design to automated handling system can improve both capacity and efficiency; however, the impact of broken bales on automated systems can be more detrimental to these systems than just using loaders. As such, bale integrity is a key factor in the operational efficiency and capacity of the receiving and preprocessing systems. Biomass moisture will alter grinder capacity and efficiency, but this design assumes a relatively narrow moisture range, with off-spec bales being rejected. However, the biomass material being ground can greatly alter grinder capacity and power ratio (Table 2-34).

Table 2-34. Grinder capacities and power ratios for different types of feedstock varieties.

	Capacity (DM tons/hr)	Capacity (DM tons/kW·h)	Power Ratio (kW·h/ DM ton)	Nominal Separation Screen Size (in.)	Mean Particle Size (in.)
Barley Straw	23.7	0.037	27.0	1.5 round × 1.0 thick	0.068±0.119
Corn Stover	15.1	0.010	100	1.5 square × 1.0 thick	0.159±0.136
Switchgrass	20.3	0.017	58.8	1.5 square × 1.0 thick	0.084±0.123
Wheat Straw	17.8	0.010	100	1.5 square × 1.0 thick	0.102±0.128

2.4.2.5 Operational Dry Matter Losses (Shrinkage)

Dry matter loss in preprocessing is the quantity of feedstock material that is not recovered from dust emissions and equipment leaks during the fractionation and discharge processes. In general, these losses cause significant impacts on the economic, environmental, and social aspects of the system (Figure 2-46). For the most part, the economic impact alone will require a mitigation strategy to be developed and implemented.

Fig. 2-46. Dust emissions as corn stover bales are preprocessed in a tub grinder.

This is particularly true when considering a conventional-bale supply system where the preprocessing operation is located at the biorefinery and the lost material is at its highest value (considering the cumulative investment of all prior operations, including harvest, collection, storage, handling, and transportation). Thus, dust emission and equipment leaks in the conventional-bale design are controlled with a cyclone separator and baghouse collection system (Figure 2-44). This system collects nearly all dust and other small particulates emitted by the grinding process and provides a way to reintroduce the collected material back into the feed system and thereby minimize net material losses. The conventional-bale model uses this dust collection system and does not factor in operational dry matter losses in the analysis.

2.4.2.6 Operational Window

The receiving operation at the biorefinery will not operate on the same schedule as the conversion process. Instead, it will run an extended regular schedule of 14 hours per day, six days per week. This

schedule will allow receiving to provide bales to the both the bale queuing yard to maintain the prescribed 72-hour inventory and directly to the preprocessing operation. Preprocessing, on the other hand, is an integral part of the conversion process and is designed to operate on the same schedule as the biorefinery. This schedule will allow the preprocessing operation to accommodate biomass from both the bale queuing yard and received trucks; thus, preprocessing will operate 24 hours a day, 350 days a year.

2.4.3 Conventional-Bale Receiving and Preprocessing Cost and Sensitivity Analysis

2.4.3.1 Static Model Cost Summary

A breakout of the costs associated with each piece of equipment used in the Receiving and Preprocessing unit operation identifies significant cost components that are valuable for making individual comparisons and identifying areas of research potential (Table 2-35). These costs are reported in terms of DM tons entering each process.

Table 2-35. Static model costs for major receiving and preprocessing equipment in the conventional-bale corn stover and switchgrass scenarios.

		Receiving		Preprocessing				Biochem Feed System
	Equipment	Truck Scales and Asphalt Storage	Loader – Caterpillar TH220B Telehandler	Loader – Caterpillar TH220B Telehandler	Grinder In-feed System	Grinder – Vermeer HG6000 Horizontal Grinder	Dust Collection System	Surge Bin, Foreign Material Eliminator Conveying Equipment
Corn Stover	Quantity of Equipment	1	5	3	8	8	8	8
	Installed Capital[a]	1.88	0.41	0.25	5.12	4.14	2.87	2.51
	Ownership Costs[b]	0.20	0.14	0.17	0.56	1.77	0.41	0.26
	Operating Costs[c]	0.17	0.65	0.60	0.92	5.39	1.24	0.47
	Labor	0.13	0.53	0.44	N/A	1.46	N/A	N/A
	Non-Labor	0.04	0.12	0.16	0.92	3.93	1.24	0.47
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A [d]	N/A	N/A
	Energy Use (Mbtu/DM ton)	0.1	4.2	5.7	6.1	125	76.5	2.2
Switchgrass	Quantity of Equipment	1	4	3	8	8	8	8
	Installed Capital[a]	1.88	0.33	0.25	5.12	4.14	2.87	2.14
	Ownership Costs[b]	0.20	0.12	0.15	0.56	1.77	0.41	0.22
	Operating Costs[c]	0.17	0.59	0.54	0.92	5.39	1.24	0.41
	Labor	0.13	0.48	0.39	N/A	1.46	N/A	N/A
	Non-Labor	0.04	0.11	0.15	0.92	3.93	1.24	0.41
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A [d]	N/A	N/A
	Energy Use (Mbtu/DM ton)	0.1	3.8	5.1	6.1	125	76.5	2.2

a. Installed capital costs are $ per annual DM ton capacity.

b. Ownership costs include depreciation, interest, taxes, insurance, and housing (Appendix A-2, Table A-7).

c. Operating costs include repairs, maintenance, fuel, lubrication labor, and consumable materials (Appendix A-2, Table A-7).

d. Potential dry matter losses from grinding are captured with a cyclone separator and baghouse dust collection system.

2.4.3.2 Cost Sensitivity Analysis

A histogram of the receiving and preprocessing cost (Figure 2-47) for corn stover shows that with 90% confidence the cost of the unit operation ranges between $11.90 and $16.13 per DM ton. Further, the mean and standard deviation of this range is $13.74 ±1.31 per DM ton. The mode value of the receiving and preprocessing cost is $13.16 per DM ton. This value closely represents the result of the static model,

which is $12.95 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

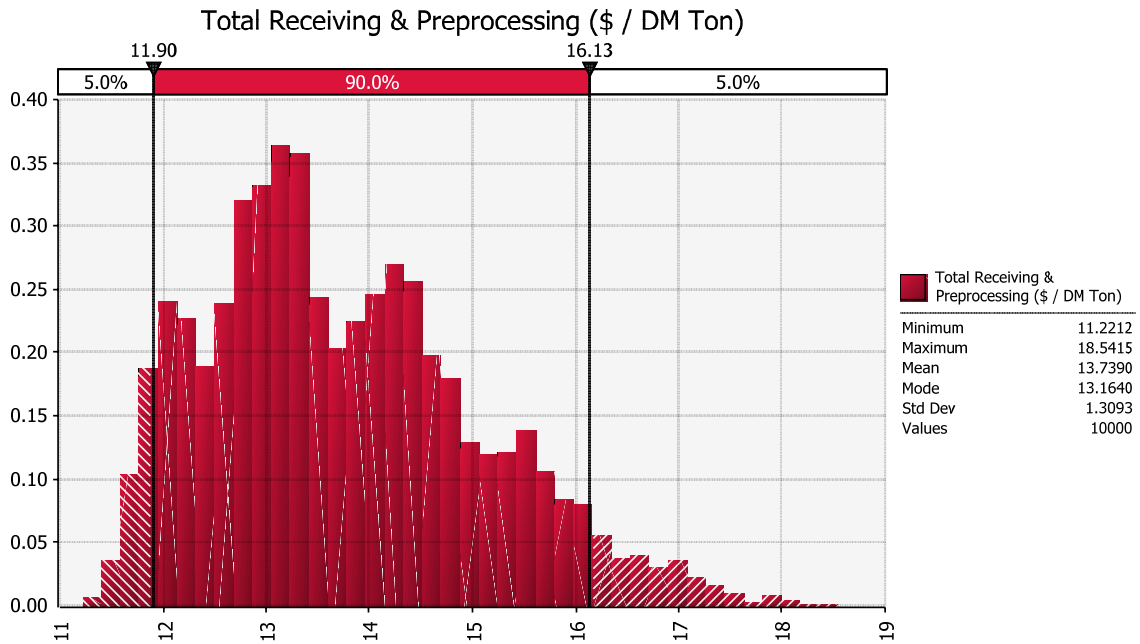


Figure 2-47. Conventional-bale receiving and preprocessing cost distribution histogram from @Risk analysis for corn stover.

Similarly, a histogram of the receiving and preprocessing cost (Figure 2-48) for switchgrass shows that with 90% confidence the cost of the unit operation ranges between $11.65 and $15.84 per DM ton with the mean and standard deviation of this range being $13.47 ± 1.30 per DM ton. The mode value of this cost range is $13.08 per DM ton, which closely represents the result of the static model of $12.69 per DM ton.

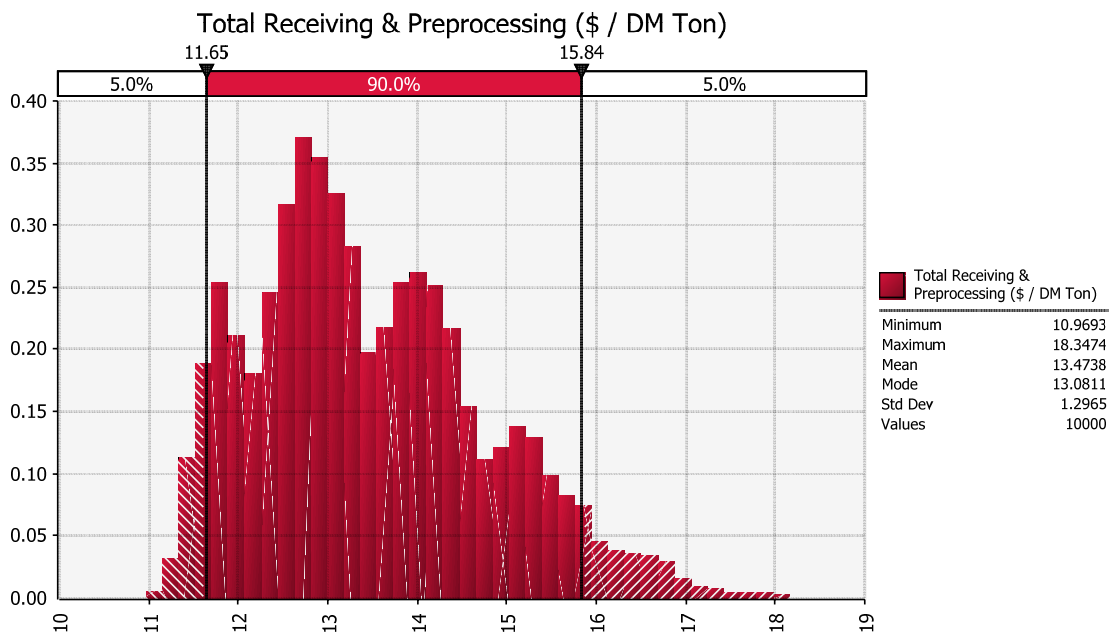


Figure 2-48. Conventional-bale receiving and preprocessing cost distribution histogram from @Risk analysis for switchgrass.

The overall costs associated with the conventional-bale receiving and preprocessing unit operation for both corn stover and switchgrass are provided in Table 2-36 on a per-DM-ton and per-bale basis. These costs, reported in terms of a mean and standard deviation, come as a result of 10,000 model iterations of the simulated conventional-bale feedstock supply system.

Table 2-36. Receiving and preprocessing cost summary for the conventional-bale corn stover and switchgrass scenarios.

		Receiving		Preprocessing				Biochem Feed System	Total Receiving and Preprocessing
	Equipment	Truck Scales and Asphalt Storage	Loader – Caterpillar TH220B Telehandler	Loader – Caterpillar TH220B Telehandler	Grinder In-feed System	Grinder – Vermeer HG6000 Horizontal Grinder	Dust Collection System	Surge Bin and Conveying Equipment	
Corn Stover	Modeled Cost Totals[a]	0.37 ± 0.01 $/DM ton	0.84 ± 0.09 $/DM ton	0.76 ± 0.04 $/DM ton	1.54 ± 0.09 $/DM ton	7.71 ± 0.96 $/DM ton	1.76 ± 0.19 $/DM ton	0.76 ± 0.05 $/DM ton	13.74± 1.31 $/DM ton
		0.14 ± 0.01 $/bale	0.17 ± 0.01 $/bale	0.16 ± 0.01 $/bale	0.90 ± 0.07 $/bale	4.53 ± 0.63 $/bale	1.01 ± 0.11 $/bale	0.44 ± 0.03 $/bale	7.35 ± 0.70 $/bale
Switchgrass	Modeled Cost Totals[a]	0.37 ± 0.01 $/DM ton	0.76 ± 0.08 $/DM ton	0.68 ± 0.04 $/DM ton	1.54 ± 0.09 $/DM ton	7.71 ± 0.95 $/DM ton	1.76 ± 0.19 $/DM ton	0.65 ± 0.04 $/DM ton	13.47 ± 1.30 $/DM ton
		0.14 ± 0.01 $/bale	0.17 ± 0.01 $/bale	0.18 ± 0.01 $/bale	0.90 ± 0.07 $/bale	5.02 ± 0.68 $/bale	1.01 ± 0.11 $/bale	0.37 ± 0.02 $/bale	7.79 ± 0.74 $/bale

	Receiving		Preprocessing				Biochem Feed System	Total Receiving and Preprocessing
Equipment	Truck Scales and Asphalt Storage	Loader – Caterpillar TH220B Telehandler	Loader – Caterpillar TH220B Telehandler	Grinder In-feed System	Grinder – Vermeer HG6000 Horizontal Grinder	Dust Collection System	Surge Bin and Conveying Equipment	
a. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.								

2.5 Conventional-Bale Feedstock Supply System Cost and Sensitivity Analysis

The objectives of the sensitivity analysis are:

1. To evaluate the effects of variability and uncertainty on supply system economics
2. To identify the probability of meeting the DOE feedstock cost target with this supply system design
3. To identify key feedstock barriers for improvement and optimization of supply systems economics.

2.5.1 Selection and Definition of Input Parameters

A single-point sensitivity analysis is a straightforward analysis to represent variations of a single variable, and it was conducted on the conventional-bale design to identify and rank all input factors which affect the delivered feedstock cost. This 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, represented in the tornado chart in Figure 2-49, provide a ranking of input parameters according to the magnitude of their influence on the delivered feedstock cost.

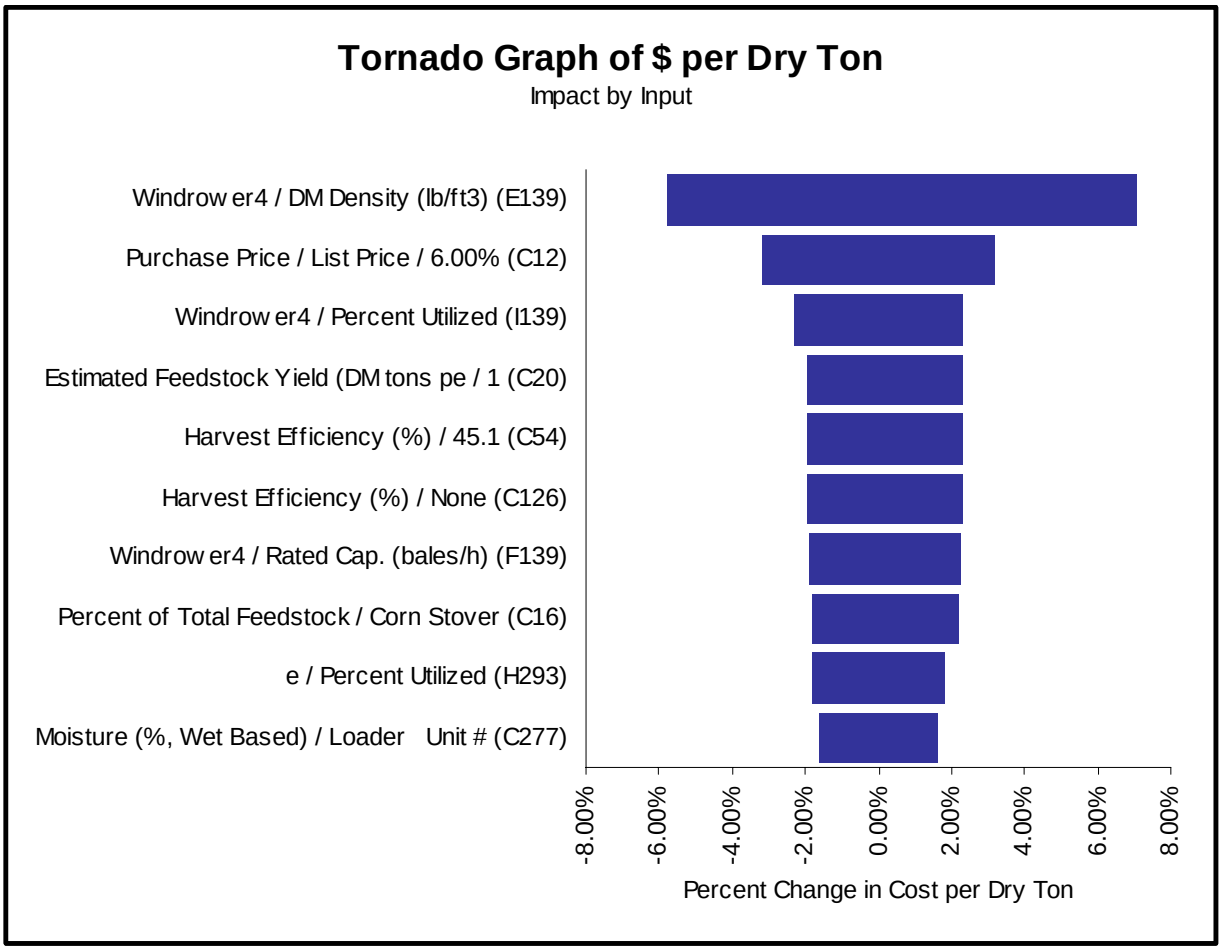


Figure 2-49. Tornado chart of input parameters.

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 2-37). 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 (e.g., field efficiency and field speed ranges published by ASABE (ASAE D497.5, 2006), or range of operating parameters suggested by skilled operators of the equipment. The most likely value included in each distribution is the benchmark value input to the feedstock model.

Table 2-37. Input parameter distributions for sensitivity analysis.

Variable Description	Variable	Distribution Function	Minimum	Maximum	Most Likely
Machine Loss Multiplier	Baling Efficiency (%)[b]	Uniform	33	80	54
Yield	Grain Yield (bushels/acre)	Pert	140	220	180
	Removal Limit (%)[b]	Pert	25	80	50
Harvest	Harvest Window (wks/yr)[a]	Pert	3	9	6
	Shredder (mph)[b]	Pert	3	6	5
	Shredder Field Efficiency (%)[b]	Pert	75	90	80
Baling	Baling Window (wks/yr)[a]	Pert	3	9	6
	Baling Moisture (%)[b]	Pert	10	20	12
	Baler (bales/h)	Pert	30	45	38
	Baler Field Efficiency (%)[b]	Pert	70	90	80
	Bale Bulk Density (lb/ft^3)	Pert	8	12	9
Roadsiding	Roadsiding Window (wks/yr)[a]	Pert	3	9	6
	Roadsiding Distance (miles)	Pert	0.25	1	0.5
	Stinger Load (sec/bale)	Pert	12	25	15
	Stinger Unload (sec/bale)	Pert	1	3	1.5
	Stinger Field Speed (mph)[b]	Pert	10	25	15
	Stinger Road Speed (mph)[b]	Pert	45	55	50
	Stinger Field Efficiency (%)[b]	Pert	70	90	80
Storage	Storage Dry Matter Loss (%)[b]	Pert	4	8	4
	Bale Wrapper (bales/h)	Pert	60	120	80
Transport	Winding Factor	Pert	1.2	1.5	1.2
	Transporter Semi (mph)[b]	Pert	40	55	45
	Transporter Loader (bale/h)	Pert	44	83	80
	Transporter Unloader (bale/h)	Pert	44	83	80
Receiving	Receiving (h/day)	Uniform	16	24	-
	Feedstock Inventory (hours)	Uniform	72	168	-
	FDI/CDI Multiplier	Pert	0.5	2	1
Yield	Grain Yield (bushels/acre)b	Pert	140	220	180
	Feedstock Yield[d]	Pert	3	8	5

Table 2-37. (continued).

Variable Description	Variable	Distribution Function	Minimum	Maximum	Most Likely
Harvest Input	Harvest Window (wks/yr)	Static			=6*Harvest_Window
	Shredder (mph)[c]	Pert	3	6	5
	Shredder Field Efficiency (%)[c]	Pert	0.75	0.85	0.8
	Harvest Collection Efficiency (%)[c]	Pert	0.667	0.75	0.71
	Harvest Collection Efficiency (%)[d]	Pert	0.52	0.9	0.77
	Mower/Conditioner[d]	Pert	5	12	7
	Mower/Conditioner Field Efficiency (%)[d]	Pert	0.75	0.9	0.8
Harvest Window	Harvest_Window	Pert	0.5	1.5	1
	FDI_CDI_Multiplier	Pert	0.5	2	1
Bailing Input	Baling Window (wks/yr)	Static			=6*Harvest_Window
	Baling Collection Efficiency (%)[c]	Uniform	0.33	0.75	0.54
	Baling Collection Efficiency (%)[c]	Uniform	0.73	0.95	0.86
	Baling Moisture (%)	Pert	0.1	0.2	0.12
	Baler (bales/h)	Pert	30	45	38
	Baler Field Efficiency (%)	Pert	0.7	0.9	0.8
	Bale Bulk Density (lb/ft3)[c]	Pert	8	12	9
	Bale Bulk Density (lb/ft3)[d]	Pert	9	12	10
Roadsiding Input	Roadsiding Window (wks/yr)	Static			=6*Harvest_Window
	Roadsiding Distance (miles)	Pert	0.25	1	0.5
	Stinger Load (sec/bale)	Pert	12	25	15
	Stinger Unload (sec/bale)	Pert	1	3	1.5
	Stinger Field Speed (mph)	Pert	10	25	15
	Stinger Road Speed (mph)	Pert	45	55	50
Storage Input	Storage Dry Matter Loss (%)	Pert	0.01	0.08	0.05
	Bale Wrapper (bales/h)	Pert	60	120	80
Transport Input	Winding Factor	Pert	1.2	1.5	1.2
	Transporter Semi (mph)	Pert	40	55	50
	Transport Loader (bale/h)	Pert	44	83	80
	Transport Unloader (bale/h)	Pert	44	83	80
Receiving Input	Feeder Density (DM lb/ft3)[c]	Static			=7.4*FDI_CDI_Multiplier
	Bin Density (DM lb/ft3)[c]	Static			=9.1*FDI_CDI_Multiplier
	Feeder Density (DM lb/ft3)[d]	Static			=10.3*FDI_CDI_Multiplier

Table 2-37. (continued).

Variable Description	Variable	Distribution Function	Minimum	Maximum	Most Likely
	Bin Density (DM lb/ft3)[d]	Static			=11.9*FDI_CDI_Multiplier

a. Harvest Window, Baling Window, and Roadsiding Window are tied into the same distribution function.

b. ASABE, ASAE D497.5, 2006 - Table 3.

c. Corn stover only parameter

d. Switchgrass only parameter

2.5.2 Monte Carlo Analysis

A more sophisticated uncertainty analysis is conducted by allowing the input parameters to change over their respective probability distributions simultaneously, thus representing the combined impacts of the system uncertainty and the interdependence of input parameters. This analysis is conducted using @Risk, which interfaced directly with the Excel-based feedstock model. The simulation consisted of 10,000 iterations. For each iteration, all of the parameters were randomly varied according to the defined probability distributions presented above (Table 2-37), and the resulting total delivered feedstock cost as well as the incremental feedstock costs throughout each stage (5 stages: harvest and collection, storage, transportation, receiving and preprocessing) of the supply chain was recorded. Only the results of the total delivered feedstock cost are presented in this section of the report; the incremental cost analyses are presented in Appendix A-2.5, "Conventional-Bale Sensitivity Analysis."

A histogram of the final cost for delivered corn stover to the throat of the conversion reactor at a biorefinery (Figure 2-50) shows that with 90% confidence the cost ranges between $48.93 and $62.94 per DM ton. Further, the mean and standard deviation of this range is $55.40 ± 4.31 per DM ton. The mode value of the final cost is $53.70 per DM ton. This value closely represents the result of the static model, which is $51.88 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

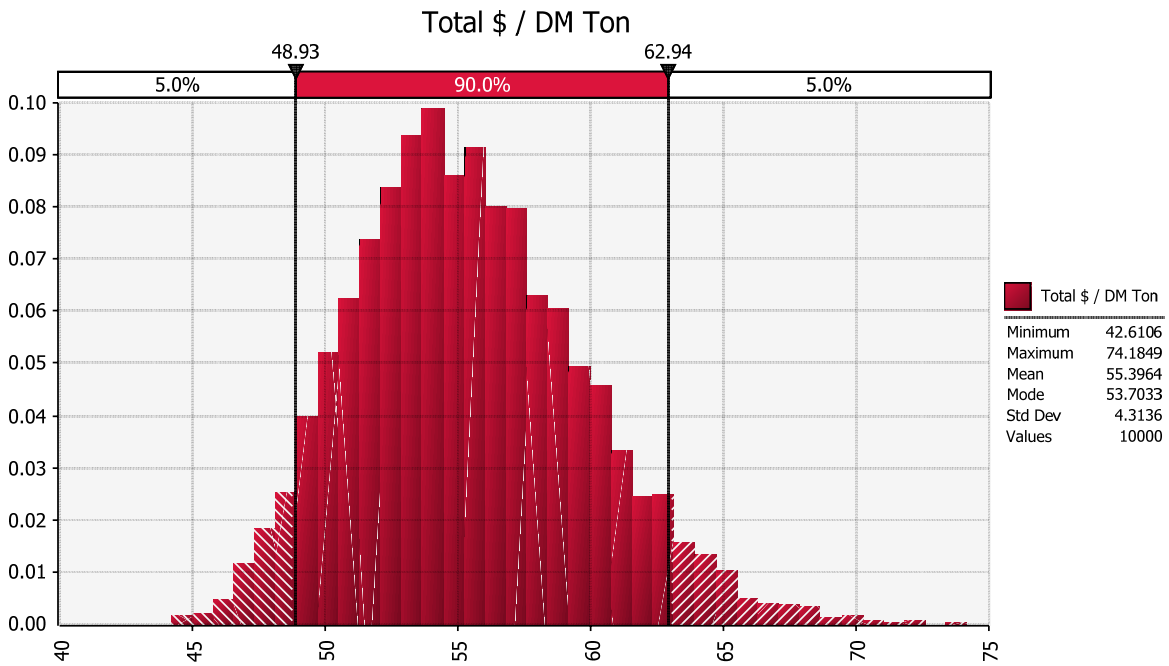


Figure 2-50. Total conventional-bale supply system design cost distribution histogram from @Risk analysis for corn stover.

Similarly, a histogram of the final cost for delivered switchgrass to the throat of the conversion reactor at a biorefinery (Figure 2-51) shows that with 90% confidence the cost ranges between $44.59 and $55.12 per DM ton with the mean and standard deviation of this range being $49.61 ± 3.20 per DM ton. The mode value of the final cost is $49.62 per DM ton, closely representing the static model result of $48.79 per DM ton.

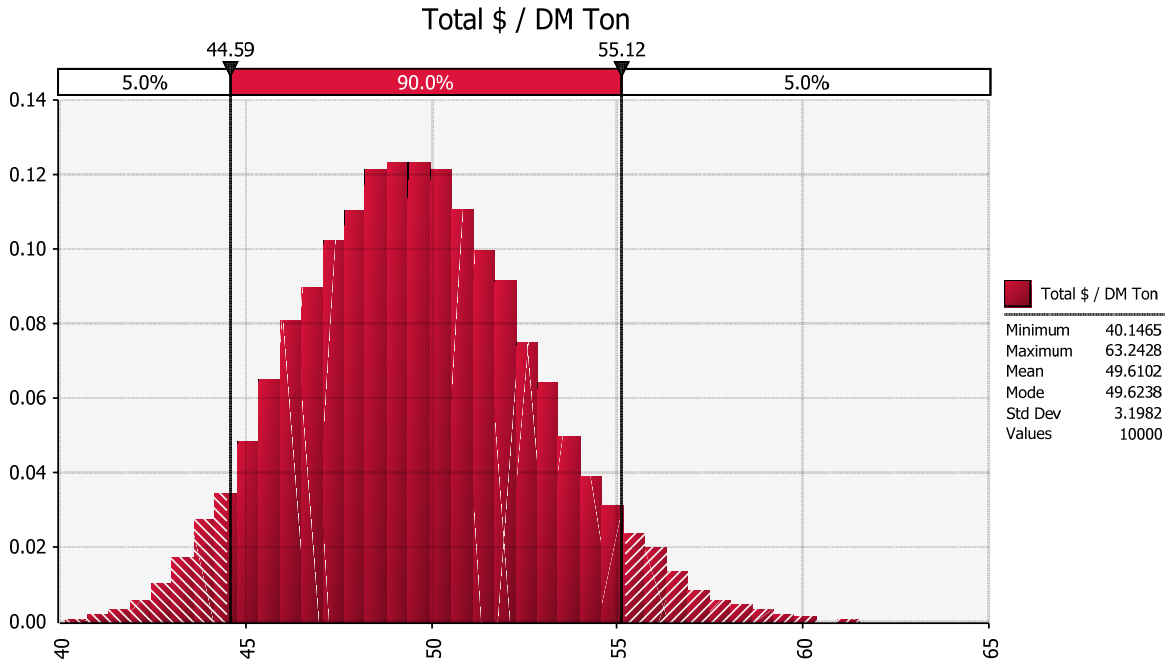


Figure 2-51. Total conventional bale supply system design cost distribution histogram from @Risk analysis for switchgrass.

The probability curves of the total delivered feedstock cost (Figures 2-50 and 2-51) show that both the corn stover and switchgrass feedstock supply systems, as configured in the conventional-bale design, have a 0% probability of hitting the 2012 DOE feedstock cost target of $34.70 per DM ton.

2.5.3 Ranking of Input Parameters

The @Risk simulation also produced a ranking of input parameters based on the statistical relationship between each parameter and the delivered feedstock cost. The top fourteen parameters from this ranking were further analyzed to produce the correlations shown in Figure 2-52, which represents the response of feedstock cost changes to these top fourteen parameters. This analysis was conducted by incrementing each parameter throughout the defined distribution 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 2-52). 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.

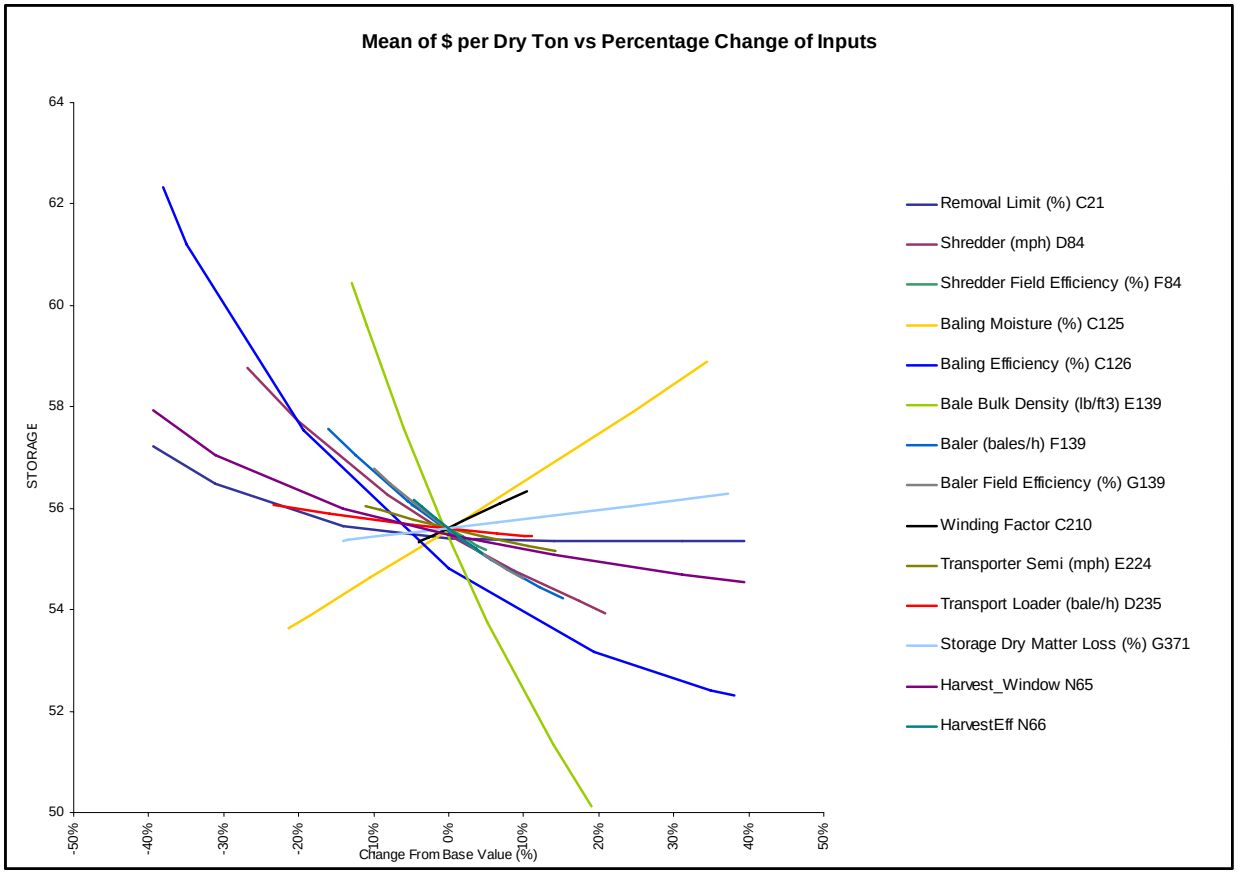


Figure 2-52. Percent change of variable to output.

In order to resolve the sensitivity rankings of these parameters, this graph was further analyzed to isolate the individual influences. Approximating the slope using a linear regression of each response curve, followed by normalization with respect to the highest slope (bale bulk density), provides a good relative sensitivity comparison (Figure 2-53). Similarly, normalizing the delta-Y with respect to the highest ranking parameter (baling efficiency) provides a clear comparison of the overall potential impact of each variable on the delivered feedstock cost (Figure 2-54).

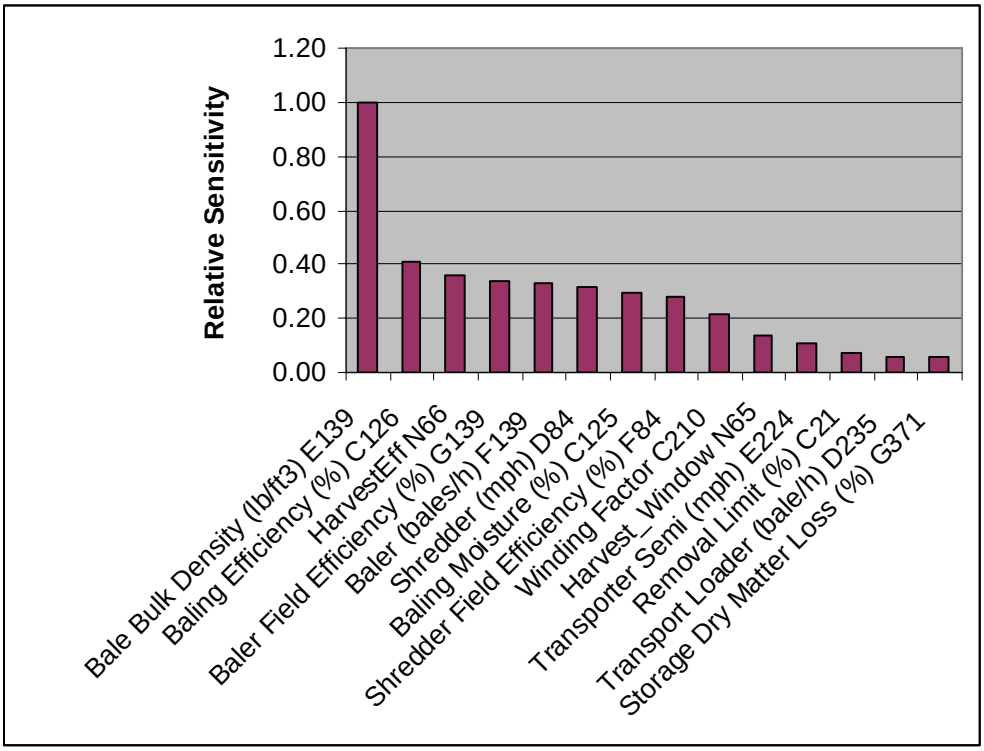


Figure 2-53. Relative sensitivity of individual supply system parameters.

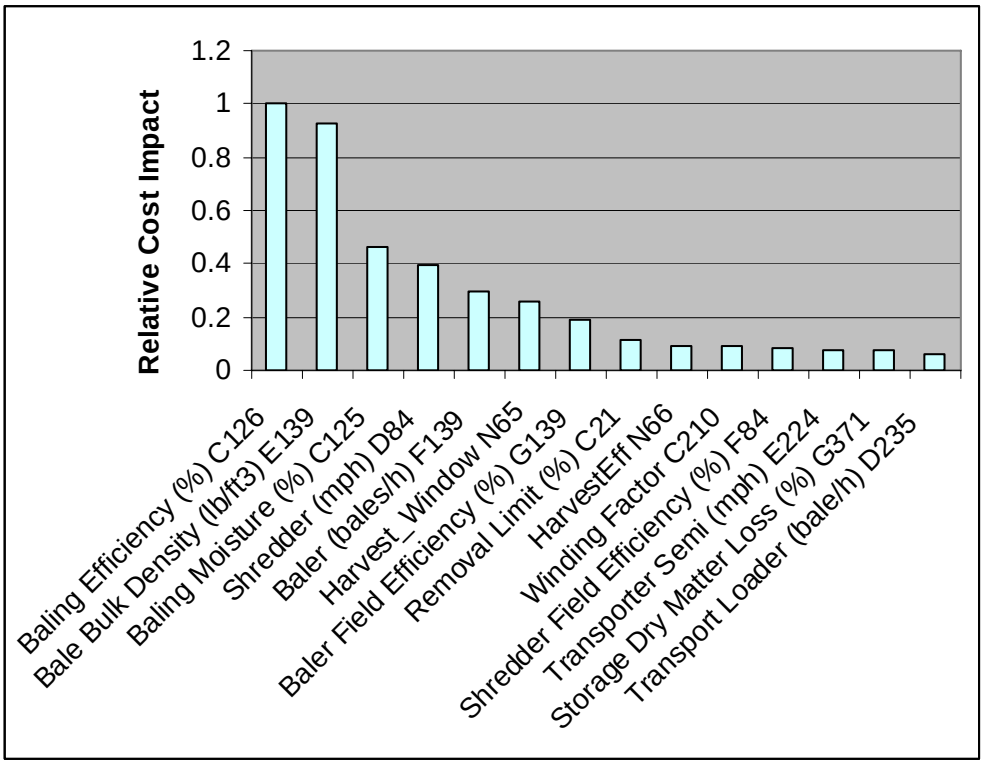


Figure 2-54. Relative cost impact of individual supply system parameters.

Comparing the rankings of these two figures shows that although the feedstock cost may be highly sensitive to changes in a specific variable (i.e., steep slope), the uncertainty or variability of that variable may be small (i.e., short line) and the corresponding impact on cost is likewise small (i.e., delta-Y); thus, the two rankings are not consistent. For example, harvest efficiency is ranked as the third highest parameter in terms of its potential influence on feedstock cost (Figure 2-53), but it ranks among lowest (9th in Figure 2-54) in actual impact.

This reveals a dual-role of sensitivity analysis, and requires an important distinction in the objective of the analysis. If the objective is to optimize the conventional-bale design, the rankings in Figure 2-53 would be most relevant. Design optimization is the driving force behind the pioneer-uniform and the advanced-uniform designs, so this will be discussed in detail in each of those sections of this report. The objective of the sensitivity analysis of the conventional-bale design is to quantify the uncertainty in the design, and thus the rankings shown in Figure 2-54 are most relevant. As such, the final ranking of input parameter for the conventional-bale design, expressed in a tornado chart that represents the uncertainty or variability in delivered feedstock cost, is shown in Figure 2-55. The tornado chart shows that baler field losses, bale bulk density, and bale moisture are the top three parameters in order of decreasing uncertainty.

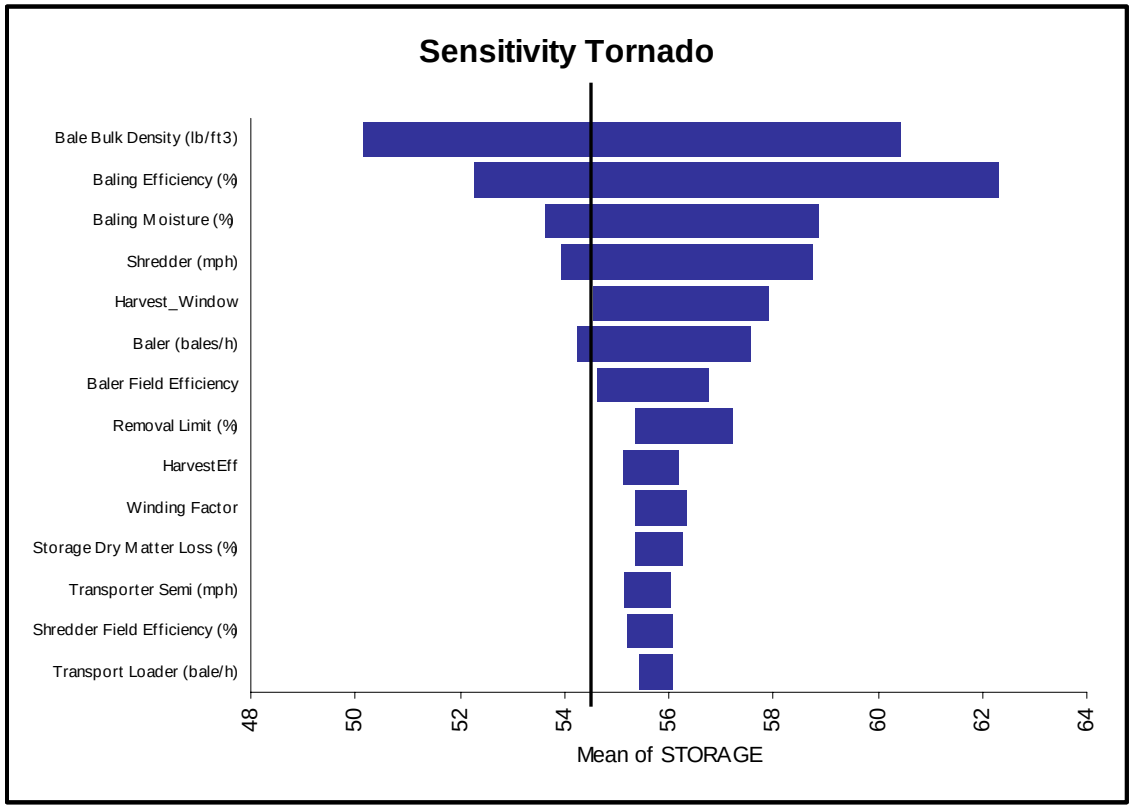


Figure 2-46. Tornado chart reflecting the final cost in dollars according to the distribution ranges defined.

Finally, additional analyses were conducted to examine the cause-and-effect relationship of the parameters shown in the tornado chart since this relationship is not necessarily intuitive. This was accomplished by evaluating and comparing the sensitivity of each unit process (harvest and collection, storage, transportation, and receiving and preprocessing) to each of the highest-ranking feedstock parameters. These relationships are summarized as follows:

- Bale bulk density has a wide ranging effect (Figure 2-56), affecting harvest and collection, handling and transportation, and storage.
- Baling field losses has the largest influence on harvest and collection costs, followed by transportation, with just a minor impact to storage (Figure 2-56). The effect of baling efficiency on harvest and collection costs is fairly intuitive because it directly impacts the net biomass yield; as baling efficiency increases, net biomass yield increases, and the per ton baling costs decreases as well. Higher biomass yield achieved by increased baling efficiency also reduces the total production acres, the supply radius, and the final transportation distance to the biorefinery. The effect of baling efficiency on storage is indirect in that any increases or decreases in costs prior to storage are reflected in the cost of dry matter loss.
- Although the effect of bale moisture is fairly significant in the supply chain, its impact in the conventional-bale design is limited to preprocessing due to its effect on grinding capacity (see capacity vs. moisture graph – Figure 2-39).
- The next four parameters—shredder field speed, baler capacity, harvest window, and baler field efficiency—all relate to machine capacity, which is an obvious parameter affecting feedstock costs. Increasing machine productivity without proportionate increase in machinery costs has a significant impact on cost.
- In comparison, the uncertainty of the remaining parameters is too small to warrant consideration.

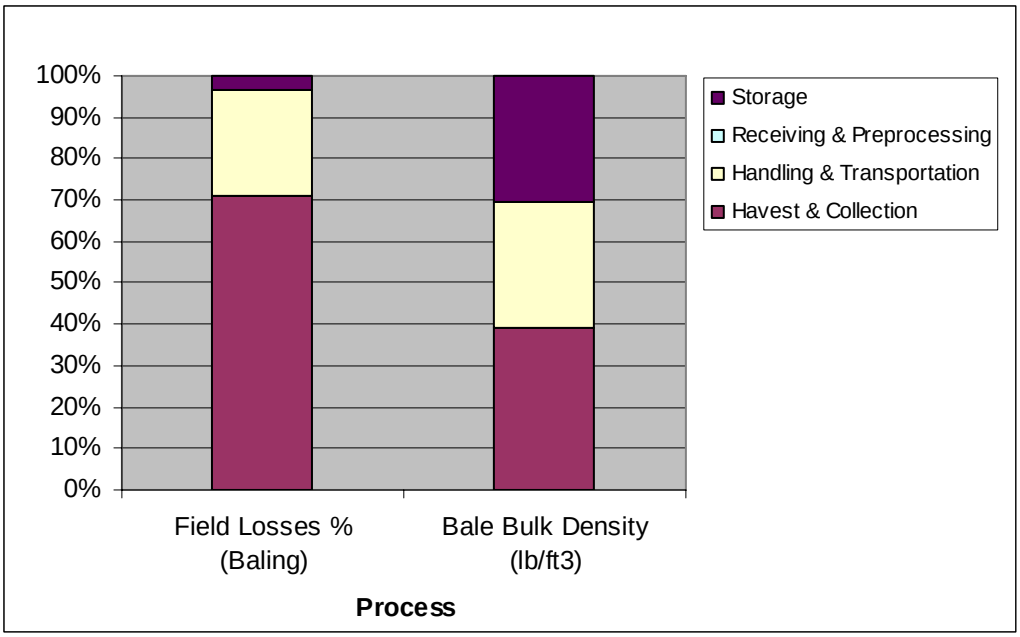


Figure 2-56. Effect of baling efficiency on supply chain processes.

3. PIONEER UNIFORM-FORMAT FEEDSTOCK SUPPLY SYSTEM

The pioneer uniform-format feedstock (pioneer-uniform) supply system design introduces a forward deployed preprocessing operation to occur at a distributed storage location established by a group of growers, an independent business entity, or by the biorefinery. This distributed storage location will be referred to as the preprocessing depot and will encompass a number of operations including short to medium-term storage, moisture management, size reduction and separation, and queuing and loading of transportation systems. The pioneer-uniform supply system design addresses three fundamental constraints of the Conventional-bale supply system: (1) significant inefficiencies in the handling and transport of baled biomass due to a combination of low bulk densities and bale size and shape, (2) inadequate systems to manage high feedstock moisture content, limiting the system to medium or low moisture feedstocks, and (3) complex, capital-intensive feed systems at the front end of the biorefinery that limit the portability of biorefinery designs from one location to another. These three fundamental constraints can add significant costs and logistical barriers that will ultimately hinder progress toward national and industrial biofuel goals and slow the growth of the cellulosic biorefinery industry.

Similar to the discussions presented in the conventional-bale supply system, Section 2, the following section will describe the impact of feedstock format intermediates and machinery on each unit operation in the order it occurs within the pioneer-uniform supply system (see Figure 3-1). However, only the format intermediates and machinery that are different from the conventional-bale supply system are discussed in the respective sections. For example, a discussion of the harvest and collection unit operation does not include details on format intermediated or machinery already discussed in the pioneer-uniform supply system (Section 2). On the other hand, an extensive discussion of several format intermediates and machinery options associated with the preprocessing unit operation is presented because of significant changes in the preprocessing operation resulting from its forward deployment in the pioneer-uniform supply system. In addition, individual sections focus on one unit operation, providing a full description, in terms of cost, performance, logistics, and operational assumptions for an integrated pioneer-uniform feedstock supply system. Additional cost and performance detail for each unit operation in the pioneer-uniform supply system is provided in Appendix A.2.

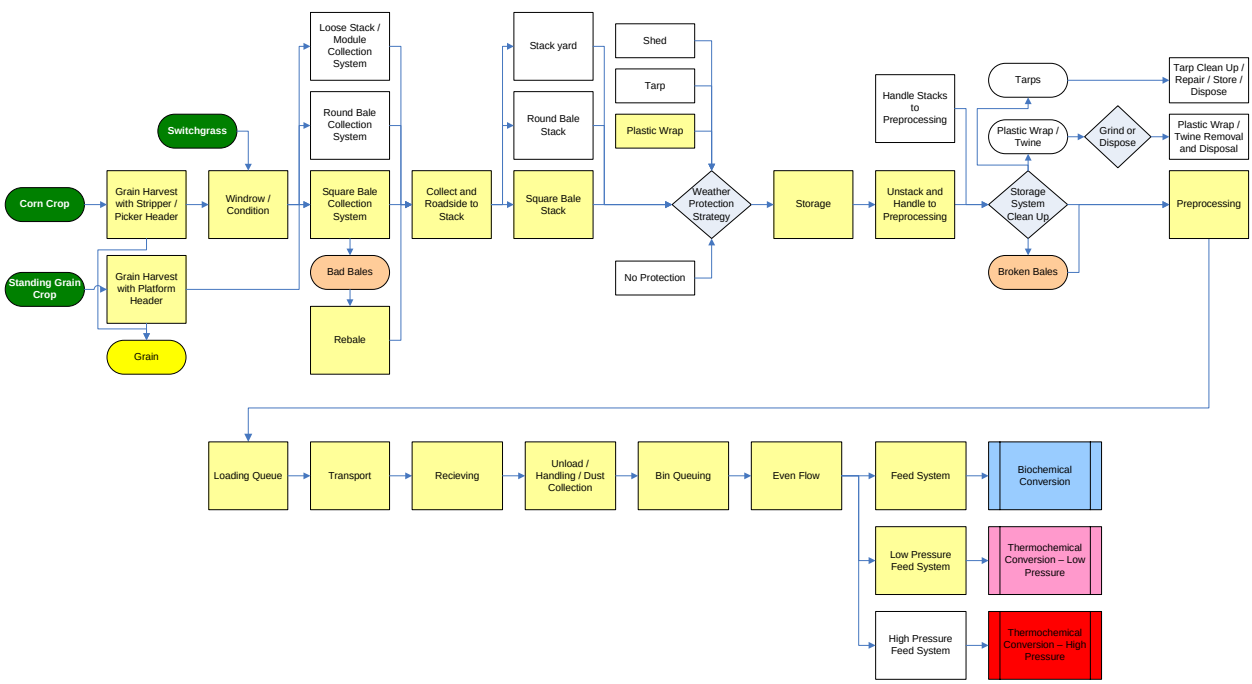


Figure 3-1. Order of unit operations in the pioneer-uniform feedstock supply system.

4. ADVANCED UNIFORM-FORMAT FEEDSTOCK SUPPLY SYSTEM

The Advanced Uniform-Format Feedstock Supply System (advanced-uniform) moves the preprocessing unit operation as far forward in the supply system as practically possible (see Figure 4-1). By doing this, a supply system moving bulk, flowable material emerges where the material is engineered to allow for optimization of the supply system logistics and the conversion processes. This supply system design addresses one additional fundamental constraint: the inefficiency of expending energy to package biomass just to expend more energy to unpackage this same biomass in order to meet the requirements of the conversion process. This fundamental constraint adds complexity and can add significant cost to the overall supply system. However, by formatting the biomass into a uniform product at the point of harvest, the resulting product resembles a grain commodity that can be handled, stored, blended, and shipped similar to grain commodities today. This aspect of the system has the potential to achieve efficiencies and establish markets similar to grain and other more mature commodities.

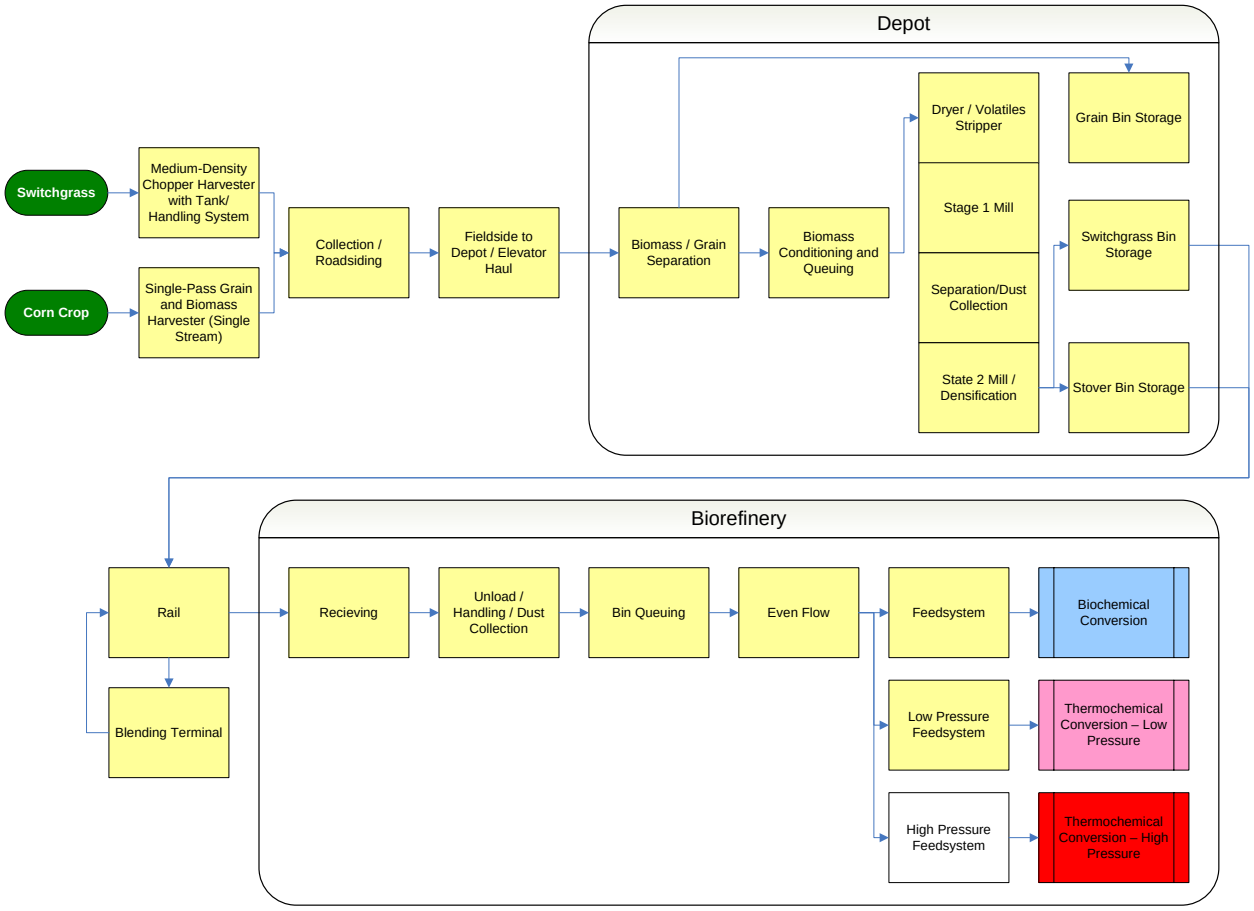


Figure 4-1. Advanced-uniform feedstock supply system design order of unit operation. (Green ovals represent format intermediates, yellow rectangles represent unit operations modeled in this report and white rectangles represent options not modeled in this report.)

The advanced-uniform design is unique from the conventional-bale and pioneer-uniform designs in that it cannot simply implement existing equipment and systems into the various unit operations. Instead, the advanced-uniform design will require new, or improved, equipment and processes to achieve the advanced-uniform vision. Thus, the case study describing the advanced-uniform design is attribute-driven with research targets defining the cost and operational parameters for equipment and processes that do not

currently exist. The base parameters from which this case study is constructed are consistent with the previous conventional-bale and pioneer-uniform cases. Specifically, the feedstock still consists of 100% corn stover within a dry supply system (i.e., 15% or lower moisture). A key point to note for this case study is that the uniform format is required to have flowability attributes similar to grain. The size of the biorefinery has little impact on this scenario as the advanced-uniform supply system concept represents the creation of a lignocellulosic biomass commodity market with capabilities for handling local resource availability variations. Table 4-1 shows the overall supply system parameters and the initial feedstock-based attributes used in this advanced-uniform supply system case study.

Table 4-1. General case study parameters.

Plant Operation Size	800,000 dry ton (U.S. short ton – 2,000 lb) per year
Plant Location	Kansas
Vehicle Length Limit	85 ft
Gross Vehicle Weight Limit	85,500 lb
State Sales Tax	5.30%
Federal Excise Tax	12.00%
Interest Rate	6.00%
Purchase Price/List Price	0.90
Cost Index Year	2007
Feedstock	Corn Stover
Feedstock Moisture	15.0% w.b.
Grain Yield	180 bushels per acre
Harvest Index	0.50
Estimated Feedstock Yield	4.26 dry tons per acre
Harvest Efficiency	38%
Estimated Residue Removed	1.60 dry tons per acre
Total Dry Matter Losses	7.5%
Acres Harvested Annually	540,808
Feedstock Harvested Annually	863,698 dry tons
Feedstock Harvested Annually	1,016,115 as-received tons

The first essential component of the advanced-uniform supply system is harvesting equipment which can selectively remove the biomass and grain in a single pass while reducing size and making the residue denser. To mitigate multi-stream logistical challenges, the advanced-uniform design also requires the harvester to merge all harvested material into a single, combined grain and residue stream. The combined stream is then taken from the harvester to the roadside by basic grain cart style equipment. These grain carts or analogous equipment could require modifications to ensure flowability of the combined grain and residue stream. At the roadside, the carts will unload into bulk active bed semi trailers. The critical bulk density target at the time of truck loading is 12 lb/ft^3 to ensure that the loads achieve maximum tonnage capacity. The feedstock will then be hauled for further processing and storage within a co-op elevator, or depot-type facility. The average haul distance is taken to be 10 miles. At the storage location, the trucks are unloaded into separation equipment that separates the biomass and grain into unique streams. The biomass stream is then moved to storage barring any further need for moisture or bulk density based preprocessing. The storage mechanisms used in this design scenario are large corrugated steel bins. As previously stated, the uniform-format is required to have flowability attributes of at least 4ff, so the bins

are assumed to be fit with standard grain loading and unloading systems. The advanced-uniform design provides two options for transport from storage to the plant: (1) bulk semi truck and trailer, or (2) rail car. This is an important characteristic of a uniform format, a commodity-based system, because it allows the system to handle variations in biomass availability. As will be presented in the following discussions of cost breakdowns, the ability to economically use rail systems for transport provides a much larger radius of available resources. This allows the system to mitigate local variations in yields. The plant receiving system will then feature a single queuing system capable of holding a 72-hour supply again in corrugated steel bins and hoppers that may require active internal unloading systems to effectively deal with the uniform-format material.. The plant will need unloading pits for both unloading rail cars and trucks, but these pits are relatively low cost, and both receiving systems can convey the material to a single set of downstream handling equipment. The following discussion gives a more detailed look at each of the unit operations.

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