UNIFORM-FORMAT BIOENERGY FEEDSTOCK SUPPLY SYSTEM DESIGN REPORT SERIES

COMMODITY-SCALE PRODUCTION OF AN INFRASTRUCTURE-COMPATIBLE BULK SOLID FROM HERBACEOUS LIGNOCELLULOSIC BIOMASS

J. Richard Hess
Kevin L. Kenney
Leslie Park Ovard
Erin M. Searcy
Christopher T. Wright

April 2009

INL/EXT-09-17527

UNIFORM-FORMAT BIOENERGY FEEDSTOCK SUPPLY SYSTEM DESIGN REPORT SERIES

COMMODITY-SCALE PRODUCTION OF AN INFRASTRUCTURE-COMPATIBLE BULK SOLID FROM HERBACEOUS LIGNOCELLULOSIC BIOMASS

J. Richard Hess
Kevin L. Kenney
Leslie Park Ovard
Erin M. Searcy
Christopher T. Wright

April 2009

INL/EXT-09-17527

CONTRIBUTORS

Andy Aden
National Renewable Energy Laboratory

Mark E. Delwiche
Idaho National Laboratory

Duane R. Grant
Grant 4-D Farms - Idaho

Kelly N. Ibsen
National Renewable Energy Laboratory

Jacob J. Jacobson
Idaho National Laboratory

Patrick T. Laney
Idaho National Laboratory

David J. Muth
Idaho National Laboratory

Judy K. Partin
Idaho National Laboratory

Robert D. Perlack
Oak Ridge National Laboratory

Peter A. Pryfogle
Idaho National Laboratory

Corey Radtke
Shell Global Solutions (US) Inc

Allison E. Ray
Idaho National Laboratory

William A. Smith
Idaho National Laboratory

Shahab Sokhansanj
Oak Ridge National Laboratory

Anthony F. Turhollow
Oak Ridge National Laboratory

Thomas H. Ulrich
Idaho National Laboratory

Lynn M. Wendt
Idaho National Laboratory

Erin G. Wilkerson
Oak Ridge National Laboratory

INDEPENDENT REVIEWERS

David W. Archer
Agricultural Scientist
Northern Great Plains Research Laboratory
USDA Agricultural Research Service

Bill Belden
Senior Agricultural Specialist
Antares Group Inc.

Kevin Comer
Senior Project Manager
Antares Group Inc.

John Hickman
Biorenewable Energy and Life Sciences
Deere & Company – Moline Technology Innovation Center

Craig Splittstoesser
Grain Operations/Project Engineering
Archer Daniels Midland Co. (ADM)

Bob Wallace
Bioenergy Bridge, Biomass Energy Center
Pennsylvania State University

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of Zia Haq, John Ferrell, Sam Tagore, Alison Goss Eng, and Laura Neal of the U.S. DOE Energy Efficiency and Renewable Energy Office of Biomass Program. Idaho National Laboratory's R&D Support Services also made valuable contributions in the preparation of this report, and the authors would like to thank Kristine Burnham, David Combs, Shaun Eames, and Allen Haroldsen for their graphics support; Quinn Grover, Gordon Holt, Lisa Plaster, Heather Rohrbaugh, Penny Simon, Kim Jackson, and Jan Wright for editorial and text processing support; the INL Research Library staff for research support; and Dan Olsen for drafting support.

EXECUTIVE SUMMARY

U.S. interest is increasing regarding the use of herbaceous lignocellulosic biomass as part of a portfolio of solutions to address climate change issues and improve energy security, in addition to other benefits that an invigorated agricultural industry can provide. One of the principal challenges of establishing lignocellulosic biofuels as a self-sustaining enterprise is organizing the logistics of the herbaceous biomass feedstock supply system in a way that maintains the economic and ecological viability of supply system infrastructures while providing the needed quantities of resources.

This report acknowledges the need for a strategy of progression from a variety of existing, nonuniform, herbaceous biomass supply systems to a commodity-scale, uniform-format supply system. The "Uniform-Format" Vision adapts supply systems incrementally as the industry launches and matures, providing progressive feedstock supply system designs that couple to and build from current state of technology (conventional bale-based systems) and address science and engineering constraints that have been identified by rigorous sensitivity analyses as having the greatest impact on feedstock supply system efficiencies and costs.

MOTIVATION FOR A COMMODITY-DRIVEN SYSTEM

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

While national assessments[a] identify sufficient biomass resource to meet the production targets, much of that resource is inaccessible using current biomass supply systems because of unfavorable economics. Therefore, existing biomass supply systems are incapable of meeting these long-term biomass use goals. Increasing the demand for lignocellulosic biomass introduces many logistical challenges to providing an economic, efficient, and reliable supply of quality feedstock to the biorefineries.

The "Uniform-Format" Vision feedstock supply system design strategies are based on the following assumptions:

- A highly efficient, large capacity, dependable feedstock supply system for bulk solid herbaceous biomass already exists with the nation's commodity-scale grain handling and storage infrastructure.
- No existing supply system design for lignocellulosic biomass is capable of handling the large quantities at the same or greater efficiencies and reliability than the existing grain handling infrastructure.
- The national goal of annually supplying in excess of 700 million dry matter (DM) tons of biomass (530 million DM tons from a variety of lignocellulosic resources) to a bioenergy industry requires the development of harvesting and preprocessing systems that reformat lignocellulosic biomass resources into a "uniform-format" product that can be stored and handled in an expanded grain (i.e., bulk solids) commodity infrastructure.

a Perlack RD, LL Wright, AF Turhollow, RL Graham, BJ Stokes, DC Erbach (2005) Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply, DOE/GO-102005-2135.

This report documents an approach to address these logistic challenges by implementing a strategy of incremental change from existing biomass supply systems to economic and reliable commodity-scale supply systems that provide uniform, aerobically stable, quality-controlled feedstocks to biorefineries. This type of approach has been demonstrated and proven successful for feed grains. For herbaceous lignocellulosic resources, these design increments are termed

- "Conventional Bale," which reflects current practice
- "Pioneer Uniform," which uses current or very near-term technologies and offers incremental improvements over the Conventional Bale system
- "Advanced Uniform," which meets all cost and supply targets and requires some conceptual equipment, such as a single-pass harvester, to provide a commodity-scale bulk solid feedstock.

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

Biomass commodities are storable, transportable, and have many end uses. Implementing a commodity-based feedstock supply system promotes cropping options beyond local markets, which in turn promotes crop diversity and enhances crop rotation practices. Figure 1 shows a schematic of the end-state commodity supply system for all types of lignocellulosic biomasses resources, with emphasis on dry herbaceous agricultural resources for this report.

The "Uniform-Format" Vision feedstock supply system incorporates many species and types of biomass that are formatted at specialized preprocessing depots distributed near resource production locations, similar to grain storage elevators. At the preprocessing depots, the biomass is preprocessed to optimize handling efficiencies and then transported to a central processing terminal, where it may be upgraded or blended to end-use specifications to form a consistent, uniformly formatted and aerobically stable product. The biomass is then managed as a commodity to be distributed to the biorefinery.

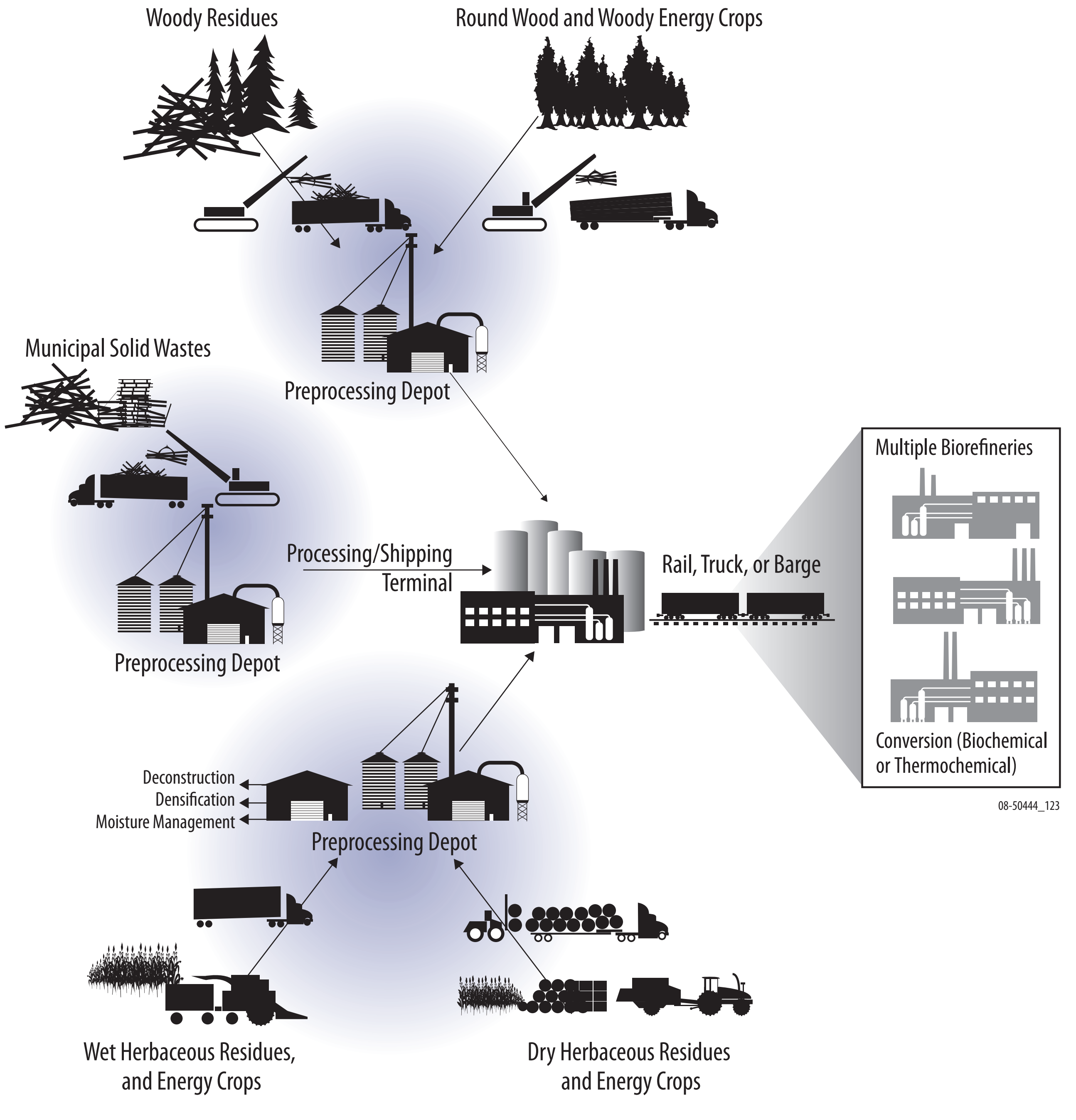


Figure 1. *The "Uniform-Format" Vision feedstock supply system emulates the current grain commodity supply system, which manages crop diversity at the point of harvest and at the storage elevator, allowing subsequent supply system infrastructure to be similar for all biomass resources.*

UNIFORM-FORMAT SOLID SYSTEM OVERCOMES FEEDSTOCK SUPPLY BARRIERS

The current Conventional Bale feedstock supply system is not capable of supplying the U.S. DOE target of 700 million DM tons of biomass annually (530 million DM tons from herbaceous and woody lignocellulosic biomass resources) for less than 25% of the ethanol production cost. The proposed Uniform-Format supply system meets the biomass cost, quantity, and quality supply goals. Transitioning from the Conventional Bale to the Uniform-Format system, however, presents many challenges, including limitations in existing harvesting and collection equipment and incorporation of biomass depots and blending terminals early in the feedstock supply chain. Figure 2 shows the current least-cost feedstock supply system path and barriers that need to be overcome for the incremental progression toward meeting performance targets.

The three dashed lines in the left half of Figure 2 represent improvements needed in bulk density, grinder capacity, and harvest and collection efficiency to transition from the Conventional Bale to the Pioneer implementation of the Uniform-Format system (Pioneer Uniform). These improvements were identified through a rigorous sensitivity analysis performed by Idaho National Laboratory (INL). The five dashed lines in the right half of Figure 2 represent the incremental improvements required to transition from the Pioneer Uniform to the final, or Advanced, implementation of the Uniform-Format system (Advanced Uniform) design.

The Uniform-Format system will enable a long-term decrease in the delivered cost of biomass sufficient to achieve cost targets while increasing supply volume. This will be accomplished by addressing key material property and machine/engineering barriers to achieve more efficient biomass supply logistics.

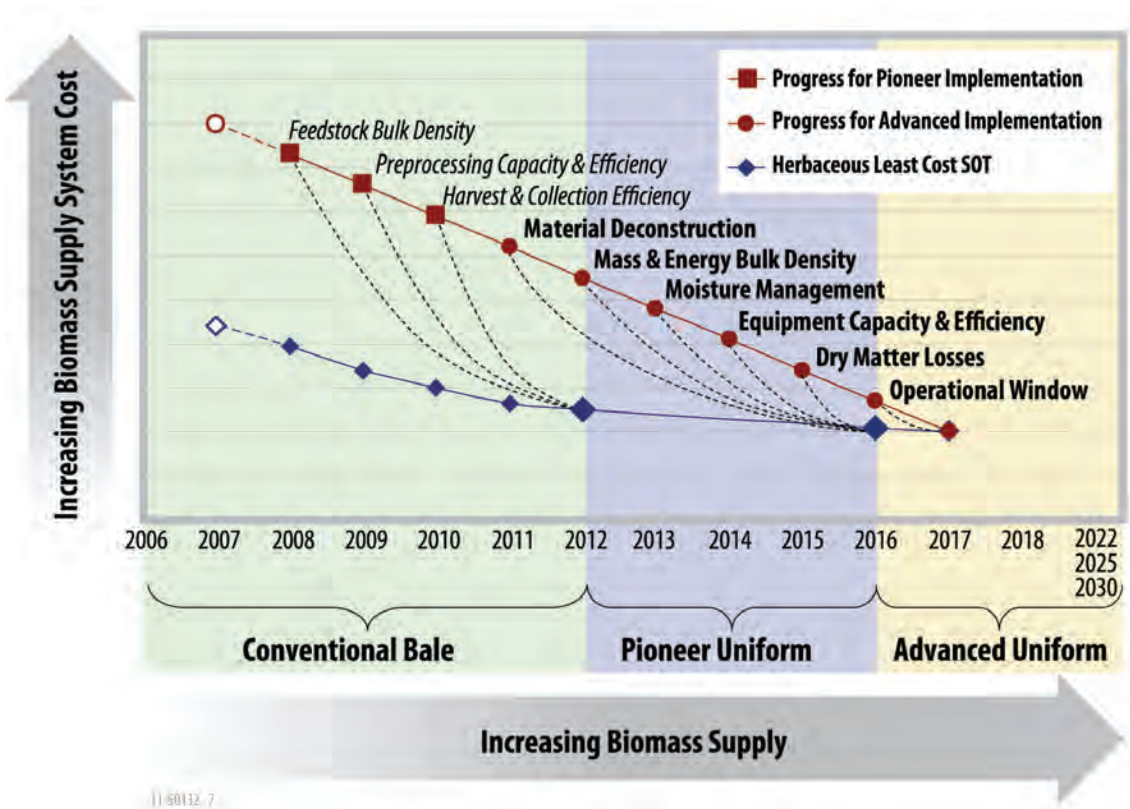


Figure 2. *The estimated progression in herbaceous feedstock logistic costs moving from the Conventional Bale to the Uniform-Format supply system.*

Table 1 compares attributes of the three systems and shows how the designs progress to the Advanced Uniform system, which achieves all national cost and supply goals while overcoming material property and engineering barriers and addressing long-term sustainability issues.

The Uniform-Format design overcomes the physical and equipment barriers inherent in working with biomass. This is accomplished by increasing the material dry matter bulk density through size reduction, reducing moisture content through drying, improving equipment performance to minimize dry matter losses, and taking advantage of biomass material properties to facilitate material deconstruction. The Uniform-Format system produces a commodity product, reduces plant handling costs, and is conducive to long-term biomass supply sustainability required to meet the annual biofuel production goals of 60 million gallons by 2030.

This commodity system promotes cropping options beyond local markets by providing access to diverse markets and increasing cropping options to promote enhanced sustainable crop rotation practices. The Advanced Uniform supply system will stimulate rural economies as a vast network of preprocessing depots are deployed across the nation to convert a diverse, low-density, perishable feedstock resource into an aerobically stable, dense uniform-format, bulk solid resource that can enter the existing agricultural bulk-solid commodity infrastructure. This approach will advance the bioenergy industry in a logical, cost-effective manner.

Table 1. *Attributes of the three feedstock supply systems compared to show progression to the Advanced Uniform system, which achieves all national goals while overcoming material property and engineering goals, and addressing long-term sustainability issues.*

	Non-Uniform	Uniform-Format	
Design Attributes	**Conventional**	**Pioneer**	**Advanced**
National Goals			
Can be economically scaled up to help meet DOE-projected biofuel production goal to displace 30% of 2004 gasoline use by 2030	○	○	●
Can meet 2012 ($35/DM ton) and 2017 (25% of ethanol production cost) DOE cost targets[b] for delivered biomass[c] to the conversion process	○	◒	●
Barriers: Material Properties			
Produces aerobically stable material for all feedstock types (moisture content of 15–20% or less for all resources)	○	○	●
Achieves target dry matter bulk density of >30 lb/ft^3 after preprocessing	○	○	●
Leverages biomass material deconstruction properties to improve capacity and efficiency of all engineered systems and matches systems to material composition	○	◒	●
Barriers: Machine/Engineering			
Optimizes all machinery operation and capital for operational window	○	◒	●
Achieves all equipment efficiency/capacity goals within cost and energy consumption targets (i.e., target harvesting efficiency of 35 DM[d] ton/hr)	○	◒	●
Can meet total supply chain material loss of <5%	○	●	●
Commodity System Attributes			
Ensures reliable feedstock supply (biomass can be acquired from many sources beyond 200 miles, reducing supply risk)	○	○	●
Produces aerobically stable and flowable product	○	◒	●
Formats material to fit all common high-capacity solids handling equipment	○	◒	●
Broadens feedstock accessibility (biomass can be purchased and sold through regional and national markets)	○	◒	●
Sustainability			
Expands regional cropping options (handles various biomass formats, moisture content, and composition)	○	○	●
Enables access to remote biomass resources (able to reach DOE goal of 25 DM ton biomass by 2012, 110 DM ton by 2017, and 530 DM ton by 2030)	○	◒	●
Allows efficient transport of feedstock beyond a 200-mile supply radius	○	◒	●
Addresses feedstock supply risks associated with weather, competition, pests, and other local issues	○	◒	●

[a] ○ = does not meet requirement; ◒ = partially meets requirement; ● = meets requirement.
[b] DOE-EERE Office of the Biomass Program (OBP), 2007. Biomass Multi-Year Program Plan, October 2007.
[c] Includes harvesting and collection, storage and queuing, preprocessing, and transportation and handling costs, in 2007 $U.S.
[d] Dry matter.

ENGINEERING APPROACH TO UNIFORM-FORMAT SOLID FEEDSTOCK SUPPLY SYSTEM FOR HERBACEOUS BIOMASS

For maximum supply system efficiency, herbaceous biomass transportation and handling costs must be minimized. One way to achieve this is to reduce the variety of equipment necessary to move biomass from the field to the biorefinery. For example, a Conventional Bale feedstock supply system changes the biomass format at least three times from the field to the biorefinery (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, there are multiple bale formats (round and square in a variety of sizes) with their respective lines of harvesting and handling equipment. Supply system radius also comes into play, with transportation and handling costs increasing dramatically the further the resource is from the biorefinery. Thus, managing feedstock format diversity by increasing feedstock bulk density and flowability as near to the feedstock production location as is practical can greatly improve supply logistics efficiency. However, the cost and energy inputs required to reformat biomass and achieve optimum densities and product quality must also be improved.

> Achieving national biofuel goals can 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 receiving systems of standardized and highly replicable biorefinery designs.

Supply logistics costs vary substantially between regions and are impacted by weather, crop species, moisture content, and feedstock types as well as transportation highway load limits and other regulations. Cropping systems and storage methods also can have substantial impact on supply logistics costs. These inherent complexities and diverse feedstock types need to be managed so as to optimize supply logistics and minimize costs in the biofuel production system. However, this design document discusses an industrywide set of herbaceous lignocellulosic biomass feedstock supply chains; therefore, site-specific logistical solutions are not always preeminent. When considering the development of an entire industry that can be rapidly deployed, a uniform-format feedstock supply system becomes key for both conversion facilities and equipment manufacturers, who require capital assets to be broadly applicable across the industry so that they can be optimized on a national scale. Modularized feedstock supply systems, such as those comprising the "Uniform-Format" Vision, are better suited to manage feedstock diversity than capital-intensive systems located at biorefineries.

Figure 3 shows a high-level strategy of progression between the feedstock supply systems described in this report. The preprocessing operation is advanced incrementally in the two implementations of the Uniform-Format design.

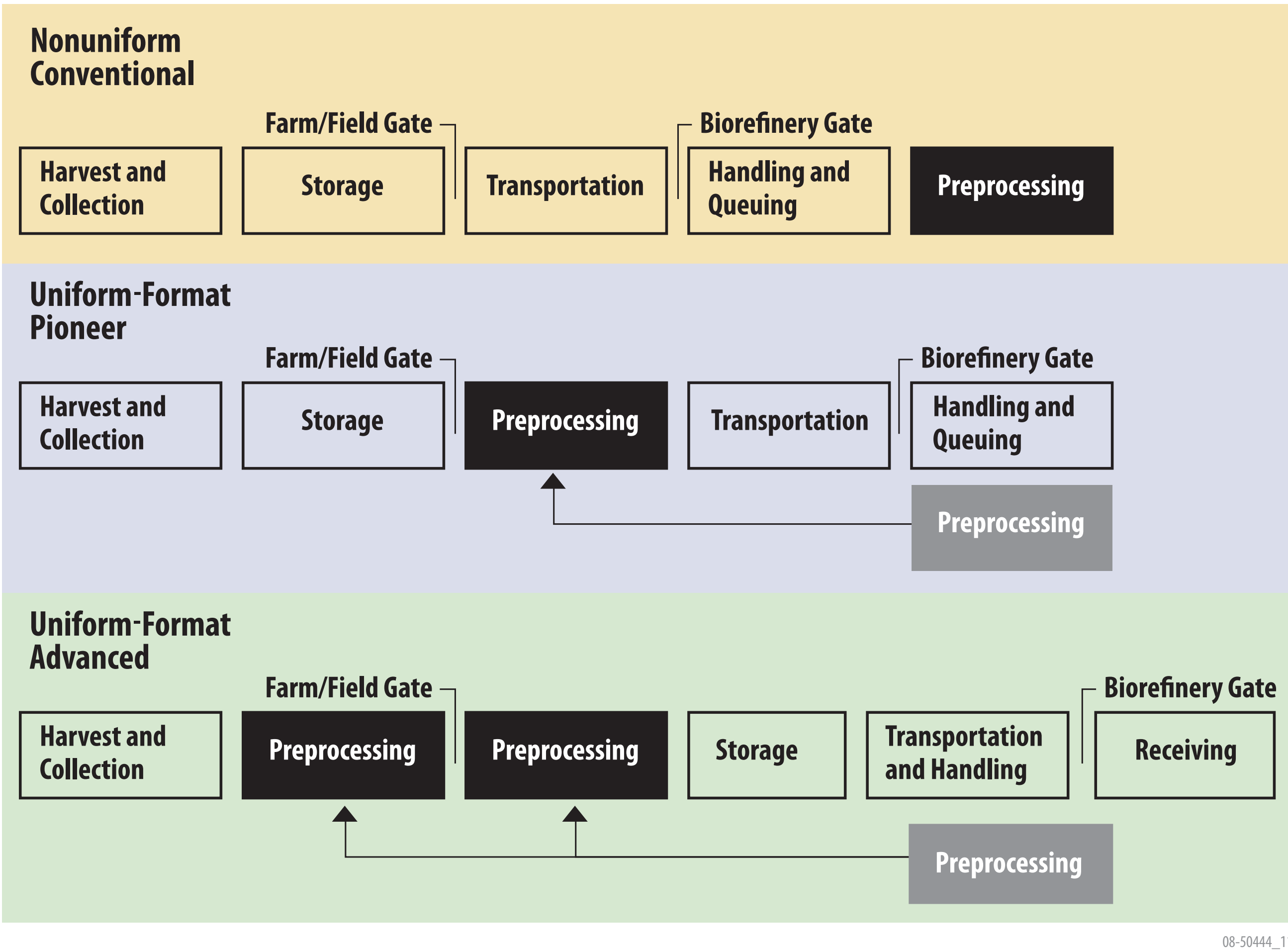


Figure 3. *Progression of the preprocessing operation in herbaceous feedstock supply system designs detailed in this report.*

The Conventional Bale system represents present technology and practices. The Pioneer Uniform system represents the first implementation of the Uniform-Format supply system design; it employs existing or very near term equipment and locates the preprocessing operation earlier in the supply chain, enabling a transition to the commodity-based Advanced Uniform design. The Advanced Uniform supply system requires development of concept equipment and achieves all long-term biomass supply targets.

CONVENTIONAL BALE FEEDSTOCK SUPPLY SYSTEM

The Conventional Bale design represents herbaceous biomass material handling technologies, costs, and logistics that are achievable today for supplying lignocellulosic feedstocks to first generation biorefineries. The general architecture of these systems locates the preprocessing operation inside the biorefinery receiving gate. Because each biorefinery will be designed to accept a specific local feedstock, the burden of adapting to the diverse feedstock resources is assumed primarily by the biorefinery. Supply logistic operations could likely be performed by any number of business entities such as a co-op of small-farm operators, large-farm operators, custom operators, and large commodity-handling agribusinesses. Over time, these operators will select and invest in more efficient and higher capacity systems. The supply systems will then handle more feedstock diversity issues, which will allow biorefinery optimization efforts to focus on biomass compositional and recalcitrance diversity and innovations to increase efficiencies and capacities.

UNIFORM-FORMAT SOLID FEEDSTOCK SUPPLY SYSTEM

As Uniform-Format feedstock supply systems for herbaceous biomass emerge, all feedstocks will arrive at the biorefinery gate in a quality-assured and quality-controlled uniform format, such that the diversity of biomass formats (not biomass composition) will be managed primarily by the feedstock supply system rather than the biorefinery. This will be accomplished by deploying the preprocessing operation earlier in the supply system.

The Pioneer Uniform design presented in this report reduces the resource formats handled by the biorefinery to one uniform-format solid bulk product derived from a limited number of herbaceous biomass resources. A key feature of the Pioneer Uniform design is the flexibility of the system to interface with a wide variety of feedstock resource supplies and formats that are not optimized for downstream transportation; they are designed to deliver a standardized format material to the biorefinery. The Pioneer Uniform design also overcomes the diverse design approaches of pioneer biorefinery and feedstock infrastructures, which will facilitate the more rapid deployment of biorefinery facilities across the United States. The Pioneer Uniform system enables an incremental transition between the Conventional Bale and Advanced Uniform feedstock supply systems, gradually incorporating technological improvements as they become available.

The fundamental premise of the Advanced Uniform design vision presented in this report series is that high-capacity and high-efficiency supply logistic systems already exist (e.g., grain and petroleum crude commodity market systems) and that handling low-density and aerobically unstable herbaceous material is inherently inefficient. As such, the Advanced Uniform design vision employs preprocessing technology to remedy the density and stability issues that prevent herbaceous biomass from being handled in high-efficiency bulk dry solid systems. The design produces a single, uniform-format feedstock supply system in which the diversity of a large variety of biomass formats will be eliminated as early in the supply system as is practically possible through some type of preprocessing. The preprocessing may occur during harvest and collection or at centralized preprocessing depots. From the depot, biomass will be transferred to a processing terminal for upgrading or blending to a consistent, uniformly formatted and aerobically stable product, which then enters the commodity distribution infrastructure (Figure 1).

The Advanced Uniform design concept changes herbaceous 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 other target properties beneficial to the conversion process. The Advanced Uniform design concept does not have both wet and dry supply delivery lines. Instead, all herbaceous biomass will be preprocessed into one flowable, aerobically stable format: a high-density, dry solid product (i.e., flour, granules, select pellet concepts).

SCOPE OF THE DOCUMENT

This design report considers all supply system elements, from the biomass standing in the field to the biorefinery's conversion process infeed system. The content boundaries are as follows:

- The designs are modeled as dry herbaceous feedstock supply systems, with some inclusion of wet/dry hybrid feedstock systems in the Uniform-Format design concepts.
- Woody feedstocks are a recognized resource input into these designs but are not presented in detail or modeled. Harvesting and preprocessing systems that make these resources available and adaptable to current and future uniform-format feedstock supply chains are presented in another design report within this series.
- While these designs encompass 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 and will be covered more thoroughly in a grower payment analysis report prepared by Oak Ridge National Laboratory (ORNL) (in progress).
- The grower payment, which represents resource cost and availability, is purposely omitted from the scope of this design document because these payments do not describe or directly constrain the engineering operations or the logistics of the supply system.
- This report assumes that all feedstocks passing through the supply system meet conversion process quality specifications, and that supply system quality control measures are inherently acceptable for all designs. This is a recognized oversimplification requiring that these design elements be more fully addressed in future studies.
- Only the high-density, bulk solid, herbaceous lignocellulosic biomass feedstock design concept will be presented in this report. Woody lignocellulosic biomass and liquid formats are discussed in another design report within this series

DOCUMENT CONTENT

This report outlines the "Uniform-Format" Vision for herbaceous lignocellulosic feedstock supply system design. The report is distributed in three volumes that represent incremental stages of feedstock supply system development.

Section 1: The "Uniform-Format" Vision justifies the need for an incrementally staged feedstock supply system design to meet cost, quantity, and quality targets. Section 1 defines unit operations and other industry terminology and identifies parameters for system analysis. It also outlines the design basis, design scope, and analysis approach (including resource and biorefinery coupling; and economic, energy use, and sensitivity analysis approaches) for the Uniform-Format Solid Feedstock Supply System for Herbaceous Lignocellulosic Biomass.

Section 2: Conventioanl Feedstock Supply System Design models and analyzes an herbaceous feedstock supply system comprised of conventional equipment and operations available today (Conventional). Supply chain logistics are modeled for both an agricultural residue (corn stover) and an energy crop (switchgrass) using conventional square bale technologies (Conventional Bale). Logistics challenges within each unit operation are discussed and opportunities for innovation and improved efficiency are identified for handling aerobically stable, dry herbaceous material. The conventional technologies analyzed were designed and optimized for other production enterprises, and they are modeled herein to serve as a baseline for subsequent design improvements that will be optimized for biomass material handling.

Harvest and collection equipment choices vary by crop species, regional agronomic markets, and user preference, but sensitivity analyses indicate that the efficiency of most systems can be improved by optimizing machine capacity, operational windows, and mitigating losses. In the Conventional Bale design, harvested biomass is stored near the point of harvest. Storage facilities differ with crop species, ambient conditions, and costs necessary for managing moisture stability. Analysis suggests that Conventional Bale systems can often employ inexpensive mitigation strategies, like field drying and bale wrapping, to cost-effectively reduce material degradation.

The fixed and variable costs of transportation and handling in Conventional Bale supply systems limit the distance that biomass can be cost-effectively transported. Feedstock format, bulk density, moisture content, transportation distance, load capacity and weight limits, and dry matter losses all impact the cost efficiencies of transportation and handling. Costs are analyzed to determine the break-even points in various transportation and handling configurations and distances.

In the Conventional Bale system, preprocessing occurs at the biorefinery. Biomass resources must be stored and queued in sufficient quantities to keep the biorefinery supplied and minimize down time. Conventional Bale systems will rely on high-integrity bales, good quality biomass, and specialized equipment to handle and convey the resource cost effectively. Biomass will be preprocessed at or near the biorefinery by grinding or other means to make a bulk-flowable product that can be fed into the conversion process. Analysis indicates that potential material losses during preprocessing will require that dust control functions are included in the designs to reduce losses, meet regulatory requirements, and minimize impacts to air quality.

The parameters of highest influence on the system, identified through a rigorous sensitivity analysis, are bale bulk density, baling efficiency, and moisture content. Therefore, the focus of the follow-on Pioneer Uniform system design is to minimize the impact of these three parameters on supply system costs.

Section 3: Pioneer Implementation of the "Uniform-Format" Solid Feedstock Supply System models and analyzes a Pioneer implementation of the Uniform-Format system (Pioneer Uniform) for herbaceous lignocellulosic biomass. It is an interim-stage Uniform-Format supply system design. Supply chain logistics are modeled for both an agricultural residue (corn stover) and an energy crop (switchgrass) using conventional square and round bale technologies and cob handling technologies.

The Pioneer Uniform system addresses three fundamental constraints that add significant costs and logistical barriers to Conventional Bale herbaceous supply systems:

- Inefficiencies in the handling and transport of baled biomass due to a combination of low bulk densities and bale size and shape
- Inadequate systems to manage high feedstock moisture content, limiting the system to medium- or low-moisture feedstocks
- Complex, capital-intensive feed systems at the receiving area of the biorefinery that limit the transferability of biorefinery designs from one location to another.

As the first implementation of the Uniform-Format system for herbaceous lignocellulosic biomass, the Pioneer Uniform harvest and collection systems are the same as those for Conventional Bale designs, but impacts of alternate material formats (i.e., round bales and bulk cobs) are explored. Round bales were chosen for a case study scenario because many producers already have the equipment for creating and handling round bales; and while square bales are easier to transport due to their shape and higher bulk density, round bales are more resistant to water penetration and, therefore, do not require plastic wrapping. Other expanded harvest and collection equipment choices are analyzed to enable supply system coupling to existing agronomic systems and increase resource options. The Pioneer Uniform storage requirements are the same as Conventional Bale storage.

In the Pioneer Uniform design, the preprocessing operation is implemented earlier in the supply chain, at a biomass preprocessing depot. The preprocessing depot effectively transfers the preprocessing operation from the biorefinery in the Conventional Bale design to a forward-deployed location while providing the same biomass size reduction and dust collection capabilities as the Conventional Bale system.

The Pioneer Uniform system does not incorporate drying into the preprocessing operation. The densified biomass is transported to the biorefinery at a lower cost than the biomass in the Conventional

Bale scenario, and plant handling costs are reduced because the received material is more consistent in format. The improvements still do not meet DOE cost and material targets, which prompts a discussion on supply system barriers that can be addressed in an advanced implementation of the Uniform-Format design vision (Advanced Uniform), which takes into account science and technology innovations on the horizon and new concepts in equipment and processes that are optimized for handling commodity-scale volumes of biomass material from a variety of resources.

Volume C: Advanced Implementation of the "Uniform-Format" Solid Feedstock Supply System presents the Advanced Uniform solid feedstock supply system design concept for herbaceous lignocellulosic biomass, which formats all biomass types into a consistent, uniform format early in the supply chain. Material format and handling targets can be achieved with existing or near-term technology and are discussed in a state-of-technology (SOT) Uniform-Format design. However, a cost analysis indicates that the SOT scenario does not meet cost targets.

A comparison of the attributes of both the Conventional Bale and Pioneer/Advanced Uniform-Format designs is presented and shows (1) the Conventional Bale system does not meet any of the material or cost targets; (2) the Pioneer Uniform system meets some of the material property targets but fails to sustainably provide a sufficient, cost-effective feedstock supply; and (3) the Advanced Uniform system is capable of reaching identified materials and cost targets.

The Advanced Uniform design vastly increases the availability of biomass resources and enables DOE biomass supply targets to be met. The commodity-based system produces a stable, storable, flowable product early in the supply chain. This design promotes diversity in cropping systems and prevents the stranding of biomass resources. Securing a sustainable biomass feedstock supply to biorefineries allows scaling based on capital economy rather than resource availability.

FEEDSTOCK SUPPLY SYSTEM LOGISTICS MODEL

The Feedstock Supply System Logistics Model developed by INL focuses on improving feedstock logistics, efficiencies, and costs, and uses a baseline feedstock production quantity/cost input. Feedstock inputs (influenced by materials, supplies, labor, logistical issues, and material losses) and outputs (material throughput of particular equipment) are used for comparing and optimizing the logistics of different supply systems.

The model contains equipment cost, operation efficiency, hours of operation, and various other parameters for several herbaceous lignocellulosic biomass feedstock formats, including:

- Conventional Bale feedstock supply system (square bale only)
  - Corn stover, the modeled low-moisture herbaceous residue
  - Switchgrass, the modeled low-moisture herbaceous energy crop
- Pioneer Uniform feedstock supply system
  - Corn cobs
  - Corn stover (both round and square bales)
  - Switchgrass (both round and square bales)
- Advanced Uniform feedstock supply system
  - Switchgrass (both round and square bales)
  - Corn stover (both round and square bales).

The model also contains @Risk sensitivity analyses, as well as regional labor and transportation databases.

Accessing the "Uniform-Format" Design Report Series Full Reports and Feedstock Supply System Logistics Model

The full version of this report volume and other reports in this series, along with the accompanying Feedstock Supply System Logistics Model, can be accessed at:

www.inl.gov/bioenergy/uniform-feedstock

CONTENTS

FIGURES

TABLES

1. THE "UNIFORM-FORMAT" VISION

U.S. interest is increasing regarding the use of lignocellulosic biomass as part of a portfolio of solutions to address climate change issues and improve energy security, in addition to other benefits that an invigorated agricultural industry can provide. One of the principal challenges of establishing lignocellulosic biofuels as a self-sustaining enterprise is organizing the logistics of the biomass feedstock supply system in a way that maintains the economic and ecological viability of supply system infrastructures while providing the needed quantities of resources.

This report acknowledges the need for a progressive transition from present-day feedstock supply systems to a uniform-format supply system that accommodates a variety of resource types. Supportive designs are provided that transition incrementally as the industry launches and matures. These designs couple to and build from current state of technology and address science and engineering constraints that have been identified by rigorous sensitivity analyses as having the greatest impact on feedstock supply system efficiencies and costs.

The "Uniform-Format" Vision feedstock supply system design strategies are based on the following assumptions:

- A highly efficient, large capacity, dependable feedstock supply system for bulk solid herbaceous biomass already exists with the nation's commodity-scale grain handling and storage infrastructure.
- No existing supply system design for lignocellulosic biomass is capable of handling the large quantities at the same or greater efficiencies and reliability than the existing grain handling infrastructure.
- The national goal of annually supplying in excess of 700 million dry matter (DM) tons of biomass (530 million DM tons from a variety of lignocellulosic resources) to a bioenergy industry requires the development of harvesting and preprocessing systems that reformat lignocellulosic biomass resources into a "uniform-format" product that can be stored and handled in an expanded grain (i.e., bulk solids) commodity infrastructure.

The purpose and objective of the "Uniform-Format" Report Series is threefold:

1. Provide (a) a design basis for development of feedstock supply system designs using conventional technology and operations and (b) sufficient supply system attribute and modeling data to evaluate the efficacy of those designs
2. Set forth design concepts for pioneer implementation of uniform-format feedstock supply systems that 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 implementation of 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 *Biomass Multi-Year Program Plan: July 2009* (U.S. DOE-OBP 2009).

1.1 MOTIVATION FOR A COMMODITY-DRIVEN FEEDSTOCK SUPPLY SYSTEM

The U.S. Department of Energy (DOE) aims to displace 30% of the 2004 gasoline use with biofuels (60 billion gal/yr) by 2030. Of those 60 billion gallons, 15 billion are projected to come from grains, and the remaining 45 billion from lignocellulosic resources. This means that of the 700 million tons of biomass required annually, 530 million tons must come from a diverse variety of herbaceous and woody resources. Establishing a reliable feedstock supply system of this scale will require the concerted efforts of research and development, policy makers, and industry to overcome substantial barriers.

Interim milestones to reach that goal are challenging as well. In fact, when estimating biomass needs to reach the 20 in 10 goal (Bush 2007), an annual amount of up to 70 million tons of lignocellulosic biomass is required annually to meet the 2017 ethanol production target (based on conversion efficiencies cited in the biochemical and thermochemical technologies [Aden et al. 2002; Phillips et al. 2007]). Given current biorefinery designs (Aden et al. 2002; Phillips et al. 2007), potentially more than 100 biorefinery facilities will need to be constructed by 2017 to process this quantity of lignocellulosic biomass. Under the most optimistic circumstances, and anticipating that the commercial-scale biorefineries currently planned will be successful, the U.S. lignocellulosic ethanol capacity will likely be less than 1 billion gallons annually by 2012. Therefore, during the subsequent 5 years, 2012 to 2017, biorefineries will need to be replicated and scaled to produce between 4 and 6 billion gallons of ethanol.

Such a rapid replication and expansion of the industry cannot be accomplished with multiple custom-designed feedstock supply system infrastructures and conversion facilities. While the volume of lignocellulosic biomass feedstock that must be managed (530 million tons annually by 2030) is of commodity scale, it comes from diverse resources for which there are few or no existing commodity markets. The diversity of resources requires different preprocessing operations to make them suitable for conversion, and managing this diversity at the biorefinery requires front-end preprocessing systems that are capital intensive and custom designed for a limited variety of resources. The modular nature of feedstock supply system operations make it better suited to manage this diversity, as preprocessing can occur throughout the system while increasing efficiencies and reducing downstream logistics costs.

To accomplish the expansion of the industry necessary to meet interim milestones and ultimate targets for biofuels production, this design document proposes that lignocellulosic conversion facilities (biochemical and thermochemical alike) must be able to access feedstocks at commodity scales from standardized feedstock supply system infrastructures that have the following capabilities:

(1) Tolerate wide variations in feedstock resources and moisture content levels

(2) Decouple capital-intensive, custom-designed preprocessing operations from conversion facilities and reduce capital investment and operational overhead

(3) Produce uniform, aerobically stable, quality-controlled feedstocks for conversion infeed systems

(4) Demonstrate compatibility with existing commodity supply system infrastructures.

1.1.1 Barriers in Conventional Feedstock Supply Systems

There are no operations in the proposed uniform-format 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 and dedicated energy crops. 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. Many conceptual designs are available 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 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).

The logistics of the feedstock supply system activities represent one of the largest barriers to the biofuels industry and can make up 40 to 60% of total ethanol production costs (Fales et al. 2007). By 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).

While national assessments (Perlack et al. 2005) identify sufficient biomass resource to meet DOE's production targets, much of that resource is inaccessible using current biomass supply systems because of unfavorable economics. In order for the biofuels industry to be an economically viable enterprise, the lignocellulosic feedstock supply system cannot consume more than 25% of the total cost of biofuel production, or there will be little profit incentive for biomass producers and biorefinery operators and the industry's expansion will be stifled (Appendix A-1). The analyses in this report show that current feedstock supply systems are not capable of supplying the U.S. DOE biomass target annually for less than 25% of the ethanol production cost.

Achieving national biofuel goals can be accomplished by developing a uniform-format feedstock supply system consisting of modularized harvesting and preprocessing systems that can (1) be adapted to the diversity of feedstocks and (2) connect to uniform-format receiving systems of standardized and highly replicable biorefinery designs.

1.1.2 Uniform-Format System Overcomes Feedstock Supply Barriers

Supply logistics costs and constraints vary substantially among regions, depending on weather, crop species, moisture content, and feedstock types as well as highway load limits and other regulations. Cropping systems and storage methods can also change supply logistics costs and constraints. These inherent complexities and diverse feedstock types must be managed to optimize feedstock supply system logistics and maximize revenue in the biomass biofuel production system.

Many opportunities for optimization are within the feedstock supply system. For maximum efficiency, transportation and handling costs and constraints 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 between the field and 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. Supply system radius also comes into play, with transportation and handling costs increasing dramatically the further the resource is from the biorefinery (Appendix A-2). Thus, the cost and energy inputs required to reformat biomass and achieve the optimum densities must be improved.

This design report series documents an approach to address these logistic challenges by implementing a strategy of incremental change from existing biomass supply systems to economic and reliable commodity-scale supply systems that provide uniform, aerobically stable, quality-controlled feedstocks to biorefineries. The design increments are termed "Conventional," "Pioneer Uniform," and "Advanced Uniform."

Sections 1 and 2 of this report present an overview of the "Uniform-Format" Vision and outlineº the scope, assumptions, and methods of analysis used for developing herbaceous lignocellulosic biomass feedstock supply system designs. Analysis is presented for a feedstock supply system design using existing, nonuniform, bale-based biomass supply systems (Conventional Bale), which demonstrates the limitations that current systems have in providing adequate feedstock to support a biofuels industry.

Sections 3 and 4 detail a Pioneer Uniform system, which uses current or very near-term technologies and offers incremental improvements over the Conventional Bale system and (2) an Advanced Uniform system vision, which meets all cost and supply targets and requires some conceptual equipment to provide a commodity-scale bulk solid feedstock. This design report series 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.

Transitioning from conventional to uniform-format feedstock supply systems presents many challenges, including limitations in existing harvesting and collection equipment and incorporation of biomass depots and blending terminals early in the feedstock supply chain. However, achieving the Advanced Uniform implementation will allow lignocellulosic biomass to be traded and supplied to biorefineries in a commodity-type market similar to grain. In addition, the Advanced Uniform supply system will stimulate rural economies as a vast network of harvesting and preprocessing depots are deployed across the nation to convert a diverse, low-density, perishable feedstock resource into a densifiied, aerobically stable, uniform-format, bulk solid resource that can enter existing agricultural bulk solid commodity infrastructures. This approach will advance the bioenergy industry in a logical, cost effective manner.

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 designs 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).

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.

In conventional designs, the burden of adapting to feedstock resources is assumed primarily by the biorefinery, because each biorefinery is designed for a specific feedstock or set of feedstocks. As Conventional Bale designs emerge in herbaceous crop residue markets, supply logistic operations will be performed by a co-op of small-farm operators, large-farm operators, custom operators, and, 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 manage more of the feedstock diversity issues, leaving biorefineries to focus on biomass compositional and recalcitrance diversity while striving for increasingly greater conversion 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 receiving and processing systems. This will be accomplished by advancing the preprocessing operation in the supply system (Figure 1-3).

While the biorefinery 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.

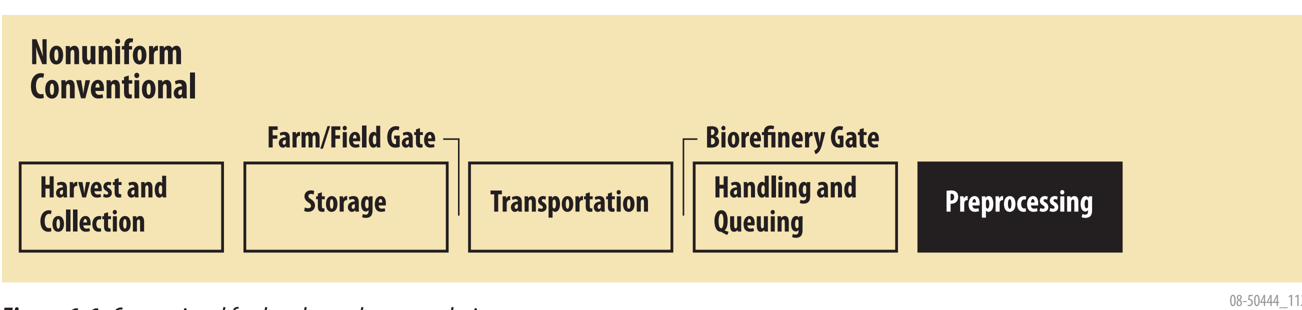


Figure 1-1. *Conventional feedstock supply system designs (Conventional) rely on existing technologies and agribusiness systems to supply biomass feedstocks to pioneer biorefineries and require biorefineries to adapt to the diversity of the feedstock.*

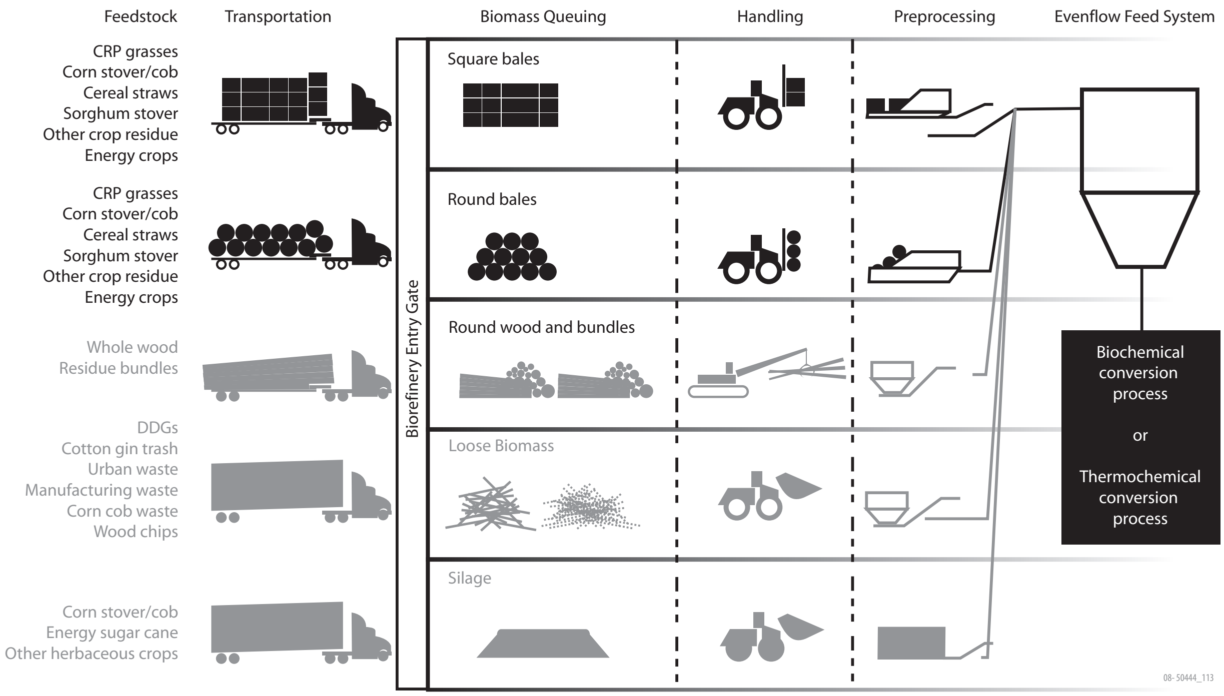


Figure 1-2*. Conventional designs are tailored for each facility and respective feedstock resource. No two are alike, and components are only replicable to the extent that feedstock sources and local conditions are similar. Conventional Bale dry herbaceous square bale systems (top row) are the focus of this report volume.*

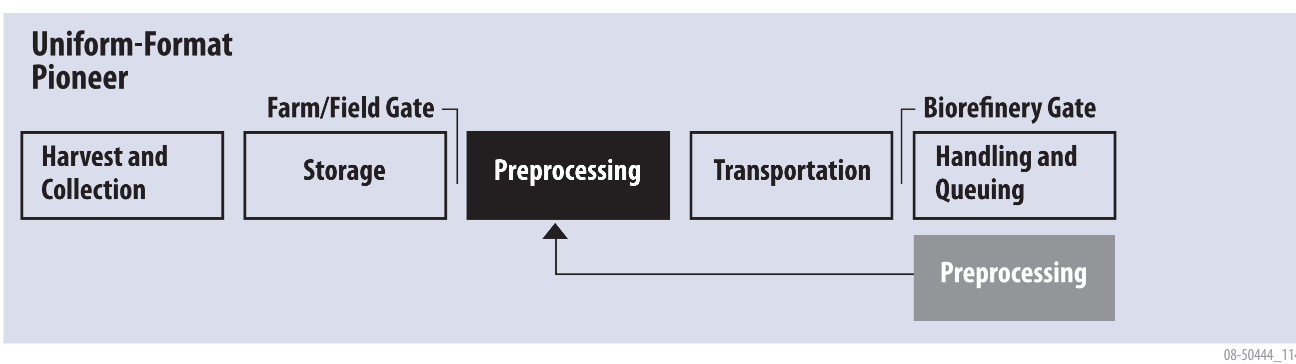


Figure 1-3*. Pioneer uniform-format feedstock supply system (Pioneer Uniform) designs move preprocessing from inside the biorefinery gate to the point of storage, either on-farm or at-depot storage.*

At harvest, most biomass will contain sufficient moisture to be classed as aerobically unstable, or wet (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, 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 just-in-time delivery and conversion could also be an option in some areas for handling aerobically unstable biomass.

A key feature of the Pioneer Uniform design is the flexibility of the system to interface with multiple existing feedstock resources and deliver a standardized format material to the biorefinery (Figure 1-4). This system will demonstrate improvements in overall supply system efficiencies and capacities for biomass harvest 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 facilitate the more rapid deployment of biorefining facilities across the United States by overcoming key limitations resulting from regional, custom-designed approaches of pioneer biorefineries and feedstock infrastructures.

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 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 preprocessing. The preprocessing may occur during harvest and collection and at centralized preprocessing sites (feedstock depots) that resemble existing depot-type systems like the grain elevator or beet dump. From the depot, downstream feedstock supply operations will become uniform, using commodity-scale equipment and handling systems (Figures 1-5 and 1-6).

The Advanced Uniform design transitions lignocellulosic biomass from a local bought and sold product to a large-scale commodity, thereby allowing long distance transportation (50+ miles), bulk-flowable handling, and feedstock blending to achieve standardized feedstock physical, chemical, and other target properties beneficial to the conversion process(es).

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, unitized handling systems may continue to be the systems 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 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 on major advances in harvesting and preprocessing technologies; however, if this can be accomplished, all lignocellulosic biomass material (energy crops, residues, wood, and manufacturing wastes) will have common physical-properties formats 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

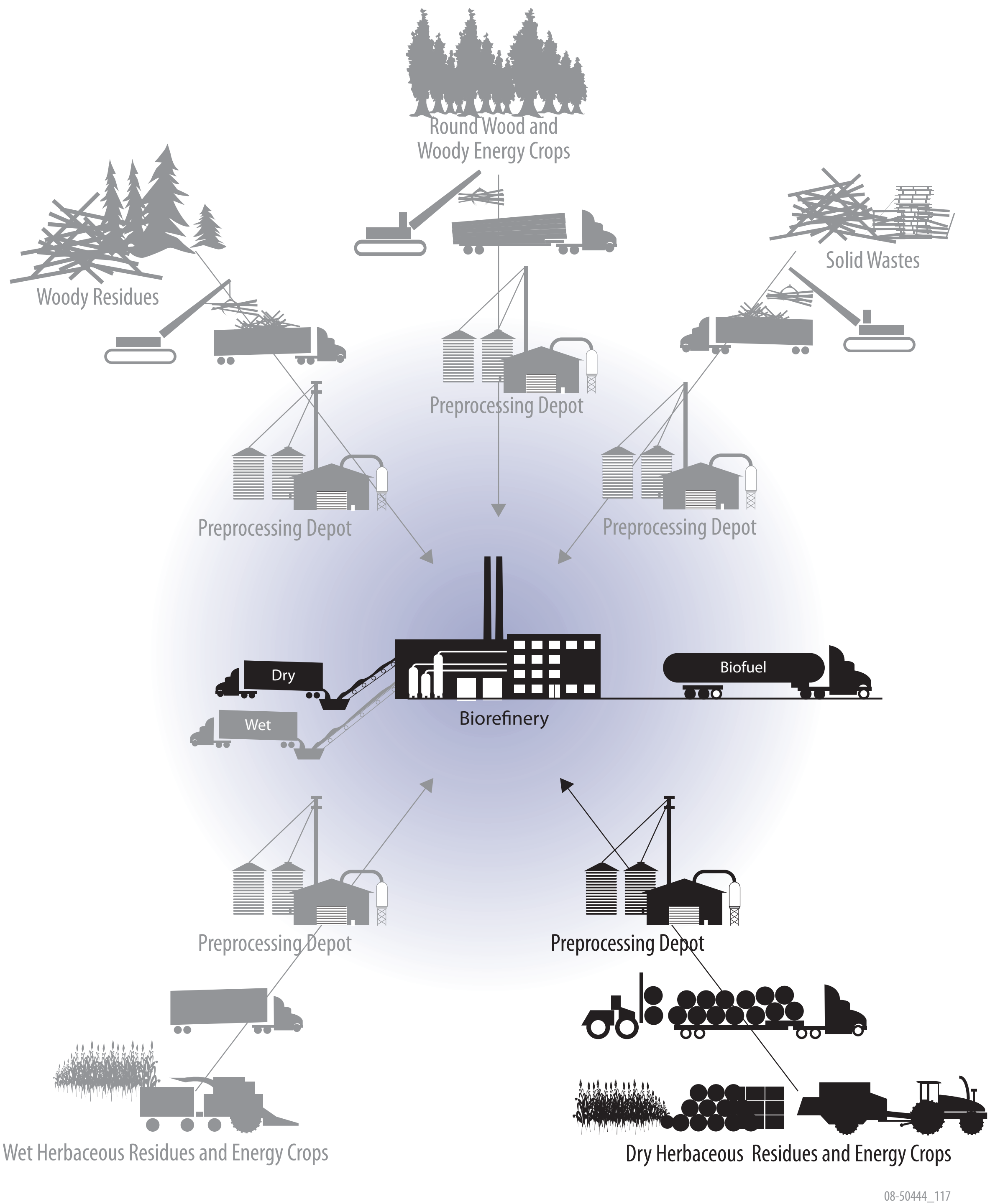


Figure 1-4. *Pioneer Uniform designs will allow lignocellulosic biomass to arrive at the biorefinery gate in two quality-assured and controlled bulk-flowable formats: wet or dry. Dry herbaceous baled and bulk agricultural resources (in bold) are discussed in detail in Section 3 design report .*

and marketing feedstocks (i.e., single processor and producer relationships are no longer inseparably linked). In addition, 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 HERBACEOUS UNIFORM-FORMAT FEEDSTOCK SUPPLY SYSTEM

The scope of the herbaceous 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 transfer from the producer) and "plant gate" (point of transfer to the 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 to the point of insertion into the biorefinery conversion process reactors. Specifically, 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 Section 3 and 4 of 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 in this report. Series Report 2 will present a uniform-format woody feedstock supply system design.
- While this design encompasses all feedstock logistics activities from harvest to biorefinery conversion infeed, the feedstock production costs and quantity issues (i.e., resource production) are not addressed in this report series but will be covered more thoroughly in a grower payment analysis report (Perlack and Turhollow, in process). The models in this report series focus on improving feedstock logistics efficiencies/cost and use a baseline feedstock production quantity/cost input.
- This "Uniform-Format" design report series 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 report series is focused solely on the feedstock supply logistic elements from harvest to conversion handling and queuing systems, it is recognized that no part of the system is truly independent. As such, the designs presented in these reports include a high degree of coordination

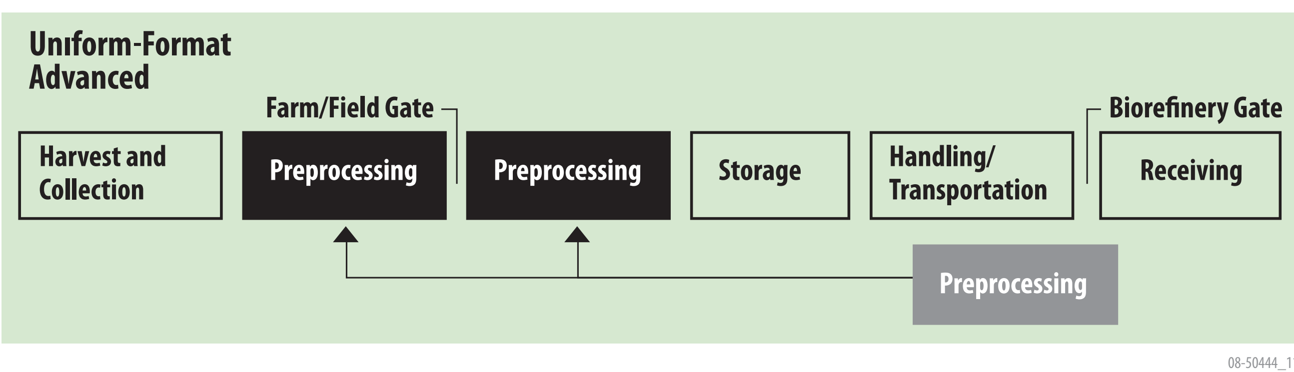


Figure 1-5. *Advanced uniform-format feedstock supply system (Advanced Uniform) designs adapt lignocellulosic biomass to current high-efficiency logistics systems by preprocessing the biomass into a high-density/aerobically stable material at or near the point of the resource origination.*

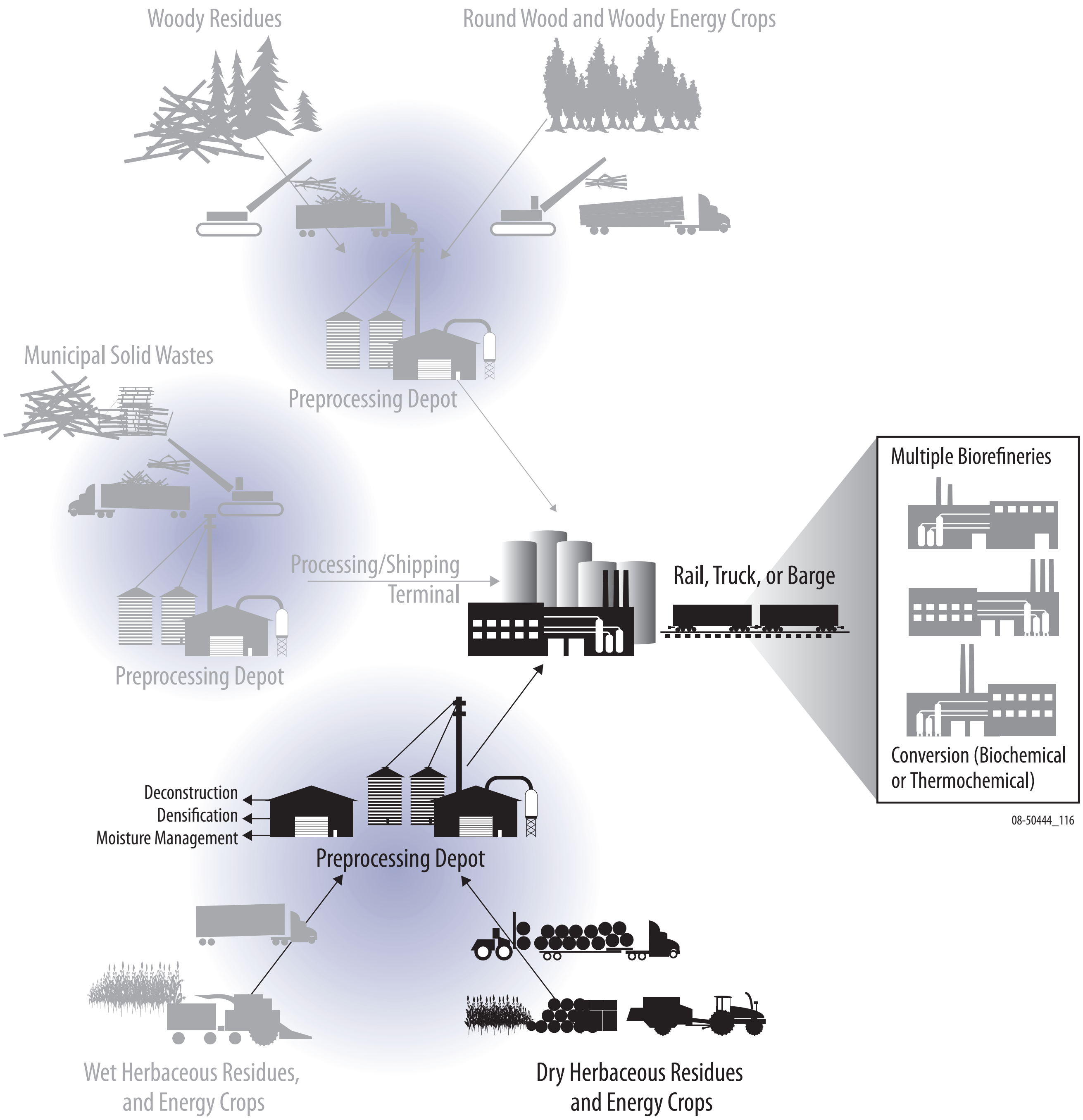


Figure 1-6. *Advanced Uniform designs follow the model of the current commodity grain supply system, which manages crop diversity at the point of harvest and the storage elevator, allowing all subsequent feedstock supply system infrastructure to be similar for all biomass resources. Note: Dry herbaceous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

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. (This is not a farm gate 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.

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.

$$\text{Feedstock cost (\$/ton)} = \underbrace{\text{Grower payment (\$/ton)}}_{a} + \underbrace{\left[\frac{\text{Inputs (\$/hr)}}{\text{Outputs (ton/hr)}}\right]}_{b} \pm \underbrace{\text{Quality (\$/ton)}}_{c}$$

Equation 1.1

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, although is the subject of on-going research at INL (Partin and Hess 2008; Partin et al. 2008).

Because this report series focuses 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 these reports. 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 Logistics

The feedstock supply system begins at the location of biomass production and ends at the biorefinery's conversion reactor infeed system ("reactor throat"). The boundaries of this design document are the logistical operations occurring between production and conversion (Figure 1-7). The production operation, which includes all processes involved in producing biomass feedstocks to the point of harvest readiness, is excluded from this analysis because production efficiencies and costs are impacted by so many issues that are independent of and do not constrain engineering operations and logistics (i.e., selection of feedstock type, land-use issues, policy issues, and agronomic practices that drive biomass yield rates and directly affect harvest and collection operations).

The feedstock supply system logistics operations encompass all of the activities necessary to move lignocellulosic biomass feedstock from the production location to the conversion reactor of the biorefinery. These logistics processes can be generally grouped into four unit operations (Figure 1-7) (Hess et al. 2003):

- *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 or swathing) and hauling, this often includes some form of densification, such as baling to facilitate handling and storage.
- *Storage and Queuing* are essential operations for accommodating seasonal harvest times, variable yields, and delivery schedules. The objective of a storage system is to provide the lowest-cost method, including costs from losses, of holding the biomass material in a stable form until it is called for by the biorefinery.

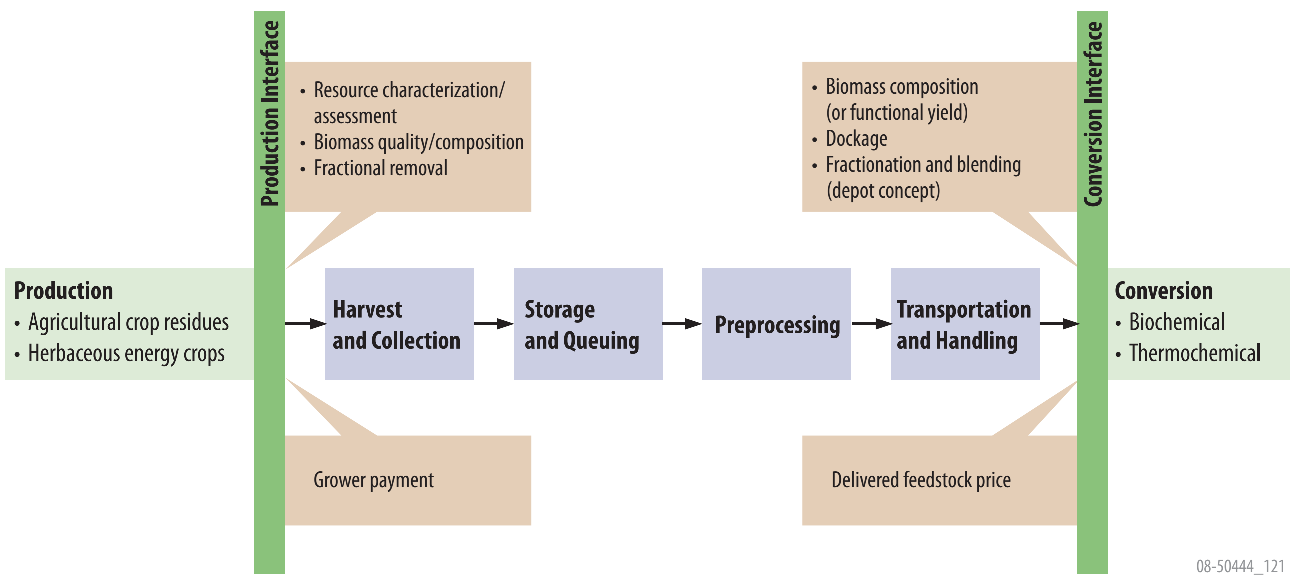


Figure 1-7. *Design boundaries (green) and boundary-interface issues (tan) for an herbaceous lignocellulosic feedstock supply system that allows logistical units of operations (blue) to be reordered to achieve optimum supply system performance.*

- *Preprocessing* includes operations that physically transform the feedstock into the format required by the biorefinery. Preprocessing can be as simple as grinding the biomass decreased particle size and increased bulk density, 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.

As the design reports in this series will demonstrate, these unit 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. Recognizably, transportation and handling occur throughout the supply system.

While various business units may be involved in or control these unit operations, the systems in these design reports are defined by the technical aspects of the operations, rather than the business 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 logistics 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, 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 into a mature industry 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 Cost Targets

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). 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 more than 19% of the total production cost of a gallon of lignocellulosic fuel ethanol, so feedstock logistics cost targets (DOE-EERE,OBP 2009) have been established for the Pioneer and Advanced Uniform designs that are on par with the corn grain supply system, allowing for added costs in the areas of preprocessing and storage. These cost targets 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 20012 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 dry (< 15% moisture w.b.) and wet (> 15% moisture w.b.) herbaceous feedstock types.

To overcome supply system constraints imposed by feedstock moisture, feedstock bulk density, and feedstock flowability, an Advanced Uniform feedstock supply system design is needed that simultaneously meets the 2017 cost target of $27.00/dry matter (DM) ton (2007$) and the 2030 tonnage target of 600 to 700 million DM tons annually (Foust et al. 2008). The design objective of the Advanced Uniform feedstock supply system is to produce a uniformly formatted feedstock that has the following characteristics:

1. Is sufficiently dry for aerobic stability and minimal movement of moisture through the system
2. Has a bulk density that minimizes long-term storage footprints and maximizes handling/transportation systems capacity
3. Is flowable in typical, perhaps modified, storage containers and conveying/pumping equipment
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 infrastructure.

An Advanced Uniform state of technology (SOT) design is established in a forthcoming report that relies on currently available technologies capable of meeting the feedstock material performance targets. Analysis shows that 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. 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 for wet herbaceous feedstocks, which will increase the cost of the feedstock supply system. However, when considering that this design is targeted to overcome the challenges associated with processing both dry and wet herbaceous feedstocks at one location, this transition puts the supply system on an appropriate path to meet both cost and tonnage targets for all types of biomass feedstocks.

1.3.3 Supply Radius

Traditionally, biorefinery supply has been limited to biomass collection within 50 miles of the biorefinery; however, this approach introduces many risk factors and limitations. For example, a localized biomass supply is more susceptible to local weather (i.e., floods, drought, fire, hurricane), diseases, and pest infestations. It is much more likely that a 50-mile area will be destroyed by such occurrences than, say, a 200-mile area. Depending on a limited supply area also makes the biorefinery much more vulnerable to crop price increases due to market shifts (cyclical demand) and grower demands, as well as competition caused by an overlapping supply radius. Limiting the supply radius to 50 miles eliminates the opportunity to incorporate stranded resources (i.e. smaller pockets of biomass and/or areas of naturally low yield) into the pool of available biomass. These stranded resources are needed to meet the biomass quantities required to achieve long-term biofuels production goals (Perlack et al. 2005). Also, limiting the biomass draw area limits the plant size to around 2,000 ton/day, which, depending on the biomass yields, may be well below the plant size where economies of scale are realized (Searcy and Flynn 2008). This causes an increase in biofuels production costs. Finally, operating under a 50-mile supply radius paradigm forces biorefinery siting decisions to be based on biomass resource availability rather than industrial infrastructure availability. This impacts not only feedstock logistics costs, but also biorefinery construction and operation depending on available utilities (i.e., natural gas, electricity, or water), access to an appropriately skilled labor force, and access to the most economical transportation and distribution infrastructures (see Appendix A-2 for Supply Radius methodology used for analysis in this design report).

In other words, this uniformly formatted feedstock could be classified as a commodity product and put into the existing commodity market infrastructure.

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 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 adaptability to physically and logistically couple to the resource. The analyses of Conventional Bale and Pioneer Uniform designs are accomplished by coupling existing technologies with existing biomass resources, where the diversity of the resource is managed by the selection of appropriate equipment and supply system logistics. These analyses are highly location-dependent, with location determining feedstock type and available quantity, feedstock harvest and collection timeframe, weather considerations relating to storage options, and infrastructure restrictions that govern the quantity of biomass being transported on the roadways. The analysis of the Advanced Uniform design to be detailed in a forthcoming report, like the Conventional Bale and Pioneer Uniform designs, demonstrates flexibility in coupling to the resource but diverges from the Conventional Bale and Pioneer Uniform designs in that all resources are preprocessed into a standardized commodity format as early in the supply chain as possible.

1.4.1 Resource Coupling Analysis

As explained in Section 1.3, the resource coupling analysis within this report is simplified. However, the key elements of resource coupling that impact technology selections are included as important design considerations.

In addition to the resource cost, quantity (i.e., yield/acre and quantity/square mile), and physical characteristics, other issues come into play, including merchandizing biomass to multiple markets (i.e., food/feed/lumber/fiber versus fuel), sustainability, and local environmental and 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
- Supply radius
- 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 Resources

This resource supply factor refers to variables in the diversity of feedstock resources that the supply logistic designs must accommodate, including:

- The resources and the associated characteristics of each
- The quantity of resource that exists or could potentially exist (i.e., total quantity, yield/acre).

The Billion-Ton Study (Perlack et al. 2005) identified more than 1.3 billion ton of biomass feedstock 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.

While the design objective of the “Uniform-Format” Vision is to accept and manage this resource diversity and create a commodity-scale biomass feedstock for biorefining, the actual design scenario analyses in this report series rely on a subset of model feedstock resources. Series Report 1 limits its analysis 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]). Series Report 2 presents analyses of forest/woody resource supply systems.

Finally, supply logistics are highly dependent on biomass quantity and 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 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 DM 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 2009) 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. 2009.

1.4.1.2 Sustainable Agricultural Crop Residue 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

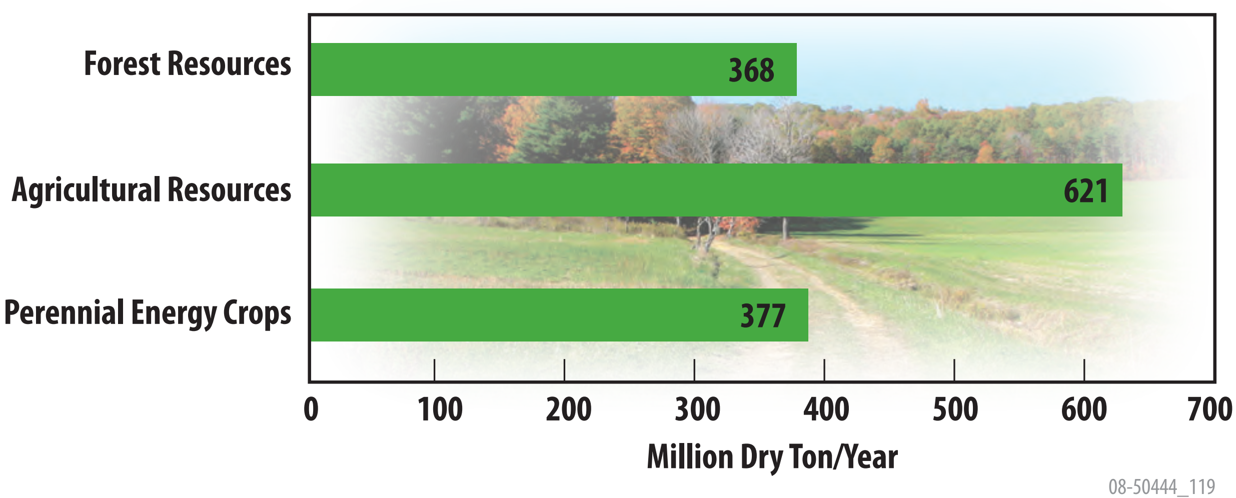


Figure 1-8. *The U.S. agricultural and forest lands resource potential as projected by the Billion-Ton Study (Perlack et al. 2005).*

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.

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 factors, 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 and Binversie 2007), weather during harvesting (Shinners and Binversie 2007), stubble height (the amount of residue left in the field as standing stalks [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 (RMR) 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 for a description of the supply radius calculation methodology). However, the objective of this report and the feedstock designs herein is to represent the capabilities of the engineering system. Thus, the residue removal rate in the feedstock model (used in developing the feedstock designs presented in this report) is set 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. The Conventional Bale and Pioneer Uniform corn stover case studies assume that existing harvesting equipment is capable of collecting, on average, about 38% of the available above-ground stover (see Section 2.1.2.2 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, based on INL corn stover harvest field trials (Abengoa/Kansas - November 11–13, 2008), 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 with 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 biofuels market relative to other potential markets, or, from a feedstock supply perspective, it is the ability of the 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) defining the minimum land area (i.e., square miles) needed to produce the quantity of biomass required for the biorefinery and (2) assessing 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, or, in the case of residues, agronomic cropping practices (i.e., sustainability removal limits) that allow the biomass residue to be accessed and removed. Defining the required land area establishes transportation distances, 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. While all supply system design concepts presented herein accommodate both resource types, detailed design analyses and modeling are 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.
- Biomass resource needs of the biorefinery are directly contracted with the producer on a yearly basis with any shortfalls caused by annual yield variations being 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 harvest, 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 vision (Section 4) assumes that the future commodity marketing strategy for lignocellulosic biomass (the biomass receiving, preprocessing, and storage system) will functionally resemble grain elevators that deliver a standardized product to the biorefinery just as it is needed.

Regardless of the contracting mechanism, the value of the feedstock (the price that must be paid to the producer, i.e., a farmer or forester) must be determined. Different feedstocks have different values (Foust et al. 2008), and their price ranges vary from less than $10/DM ton to $40/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, or grower payment, that represents all of the complexities of the feedstock interface, where 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. 2009). It is important to note that grower payment does not represent a farm-gate pricing structure. Instead, the grower payment represents the price paid for the biomass in the field, 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 agricultural equipment engineering-economic costing methodologies 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 Sokhansanj (2007), who compiled a recommended standard costing methodology for biomass. While the ASABE and AAEA methods apply specifically to agricultural machinery, Turhollow and Sokhansanj (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 Sokhansanj (2007) was used to develop an Excel-based feedstock cost model. The two-step process for biomass costing includes (1) the calculation of machinery cost (represented in $/hr or $/ton), and (2) the calculation of machinery performance (generally represented in $/ton). An overview of the methods used to calculate these two cost parameters is presented in the following two sections and discussed in greater detail in Appendix A-3.1. Note that model development is an iterative process, and therefore model inputs are continuously updated. The costs and performance parameters are taken from the March 2009 version of the model and are represented in 2008 $US.

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 Sokhansanj (2007). These costs are categorized as ownership costs represented in $/yr (fixed costs) and operating costs represented in $/hr (variable costs). For the machinery cost calculations, the annual usage (hr) was calculated based on the harvest window, machine capacity, and number of machines. The ownership costs ($/yr) were divided by the annual use (hr) to provide an hourly ownership cost. The ownership cost ($/hr) and operating cost ($/hr) were then summed to provide a total hourly machinery cost. Ownership and operating costs included in the economic analyses of this report are shown in Appendix A-3.2.1.

1.4.3.2 Equipment Performance

Biomass costs are calculated after the machine has performed a function on the product or on the land; these costs are a function of machinery performance, and are expressed in $/ton, $/item, 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 2006b) or from data provided by expert operators (e.g., custom harvest operators). The source of equipment performance data is included in Appendix B.

1.4.3.3 Cost Escalation

All costs are based on values obtained for a particular year. In order to normalize costs to a common year basis and 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 current and historical cost database exists, 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. For other cost items, such as capital 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. A more detailed discussion of cost escalation methodology used for this model is included in Appendix A-3.2.4.

1.4.3.4 Biomass Cost

As described in Section 1.4.3.1, ownership and operating costs are calculated for all processing machinery, transportation and handling equipment, and storage and queuing infrastructure throughout the supply chain. These costs are summed to provide an hourly usage cost ($/hr) for machinery and a yearly usage cost ($/yr) for infrastructure. The hourly costs ($/hr) are then divided by the machine capacity (ton/hr), and the yearly costs are divided by the annual tons processed to give a cost per ton for each operation. The feedstock cost (FC) is determined by summing the machine cost per ton for each piece of equipment used in the supply system analysis. Finally, the total annual costs are determined by summing the operating costs ($/ton) for each piece of equipment and multiplying the sum by the total annual tonnage (800,000 ton) 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. This methodology is described in greater detail in Appendix A-3.1.

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/dealer quotes, when available. For equipment where specific fuel consumption data are not available, the methodology shown in Appendix A-3.2.4 was used to estimate the average annual diesel consumption.

1.4.5 Sensitivity Analysis

Sensitivity analysis 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. This methodology is described in greater detail in Appendix A-3.2.5.

1.5 ESTABLISHING A PERFORMANCE BASELINE: CONVENTIONAL BALE

Fuels derived from lignocellulosic biomass are an important contributor to the growth of the bioenergy industry. Increasing the use of biomass introduces many challenges related to the economic, efficient, and reliable supply of quality feedstock to the biorefineries. While systems exist to supply virtually any lignocellulosic feedstock to a biorefinery facility, including agricultural crop residues and dedicated energy crops, these technologies are not optimized for biomass material handling, and the processes with highest impact to efficiency need to be identified.

Section 2 of this document describes an herbaceous biomass feedstock supply system design using conventional methods for handling corn stover (representing a crop residue supply system) and switchgrass (representing an herbaceous energy crop supply system). The design analysis is organized by discrete units of operation: harvest and collection, storage, transportation and handling, and queuing and preprocessing. To establish performance baselines for supply chain improvements, the Conventional Bale design is characterized in terms of costs, material flows, and equipment performance parameters, and a sensitivity analysis is performed to determine the opportunities of highest impact for improving system efficiency. These improvements will be incorporated into the Uniform-Format supply system design, which is presented in two implementations (Sections 3 and 4).

A full design report modeling the Advanced Uniform System will be detailed in a later report.

1.6 REFERENCES

Aden A (2008) Biochemical production of ethanol from corn stover: 2007 state of technology model. NREL/TP-510-43205. National Renewable Energy Laboratory, Golden (CO).

Aden A, M Ruth, K Ibsen, J Jechura, K Neeves, J Sheehan, B Wallace, L Montague, A Slayton, J Lukas (2002) Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. NREL/TP-510-32438. National Renewable Energy Laboratory, Golden (CO) http://www.nrel.gov/docs/fy02osti/32438.pdf. Accessed 17 January 2008.

ASABE (American Society of Agricultural and Biological Engineers) (2003) Agricultural Machinery Management. ASAE EP496.2.

ASABE (American Society of Agricultural and Biological Engineers) (2006a) Agricultural Machinery Management. ASAE EP496.3.

ASABE (American Society of Agricultural and Biological Engineers) (2006b) Agricultural Machinery Management Data. ASAE D497.5.

Bush GW (2007) The 2007 State of the Union Address. January 23, 2007. http://georgewbush-whitehouse.archives.gov/stateoftheunion/2007/. Accessed 11February 2010.

Duffy M, D Smith (2008) Estimated costs of crop production in Iowa – 2009. Ag Decision Maker. Iowa State University Dept of Economics. File A1-20. http://www.extension.iastate.edu/agdm/crops/pdf/a1-20.pdf. Accessed 15 December 2009.

Fales SL, WW Wilhelm, JR Hess (2007) Convergence of agriculture and energy II: Producing cellulosic biomass for biofuels. CAST Commentary QTA2007-2. Council for Agricultural Science and Technology (CAST) Ames (IA).

Foust TD, KN Ibsen, DC Dayton, JR Hess, KL Kenney (2008) The biorefinery. In: Himmel M (ed) Biomass recalcitrance: deconstructing the plant cell wall for bioenergy. Wiley-Blackwell, Chichester, pp. 7–23.

Graham RT, S McCaffrey, TB Jain, tech. eds. (2004) Science basis for changing forest structure to modify wildfire behavior and severity, Gen. Tech. Rep. RMRS-GTR-120, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins (CO) http://www.fs.fed.us./rm/pubs/rmrs_gtr120.html. Accessed 15 December 2009.

Hess JR, TD Foust, L Wright, S Sokhansanj, JH Cushman, JL Easterly, DC Erbach, JR Hettenhaus, RL Hoskinson, JJ Sheehan, S Tagore, DN Thompson, A Turhollow (2003) Roadmap for agriculture biomass feedstock supply in the United States, DOE/NE-ID-11129, U.S. Department of Energy, Washington D.C. http://www.inl.gov/bioenergy. Accessed January 17, 2008.

Hoskinson, RL, DL Karlen, SJ Birrell, CW Radtke, WW Wilhelm (2007) Engineering, nutrient removal, and feedstock conversion evaluations of four corn stover harvest scenarios. Biomass Bioenergy 31:126–136.

Johnson, JMF, DC Reicosky, RR Allmaras, D Archer, WW Wilhelm (2006) A matter of balance: conservation and renewable energy. J Soil Water Conserv 61:120A–125A.

Kemanian, AR, CO Stöckle, DR Huggins, LM Viega (2007) A simple method to estimate harvest index in grain crops. Field Crop Res 103:208–216.

Nelson, RG (2002) Resource assessment and removal analysis for corn stover and wheat straw in the eastern and midwestern United States: rainfall and wind erosion methodology. Biomass Bioenergy 22:349–363.

Oak Ridge National Laboratory (ORNL) (2009) Bioenergy conversion factors. ORNL Bioenergy Feedstock Development Program, Oak Ridge (TN) http://bioenergy.ornl.gov/papers/misc/energy_conv.html. Accessed February 16, 2010.

Partin JK, JR Hess (2008) Development of a feedstock assembly system for optimizing biofuels conversion processes. Joint Northwest/Rocky Mountain Regional Meeting of the American Chemical Society, Park City (UT) June 15–18, 2008.

Partin JK, GL Gresham, PA Pryfogle (2008) Development of feedstock quality specifications for optimizing biofuels conversion processes. AIChE Annual Meeting, Philadelphia (PA) November 16–21, 2008.

Perlack RD, JR Hess (2006) Biomass resources for liquid fuels production. The 28th Symposium of Biotechnology for Fuels and Chemicals, Nashville (TN) April 30–May 3, 2006.

Perlack RD, LL Wright, AF Turhollow, RL Graham, BJ Stokes, DC Erbach (2005) Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply, DOE/GO-102005-2135. http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf. Accessed 15 December 2009.

Phillips S, A Aden, J Jechura, D Dayton, T Eggeman (2007) Thermochemical ethanol via indirect gasification and mixed alcohol synthesis of lignocellulosic biomass. NREL Technical Report, TP 510-41168. National Renewable Energy Laboratory, Golden (CO).

Pordesimo LO, S Sokhansanj, WC Edens (2004) Moisture and yield of corn stover fractions before and after grain maturity. 2002 ASAE Annual Meeting, Chicago (IL) July 28–31, 2002. Trans ASAE 47(5).

Rapier R (2008) Updated corn ethanol economics. R-Squared Energy Blog. http://i r squared.blogspot.com/2008/06/updated-corn-ethanol-economics.html. Accessed 24 June 2008.

Richey CB, JB Liljedahl, VL Lechtenberg (1982) Corn stover harvest for energy production. Trans ASAE 25(4):834–44.

Shapouri H, P Gallagher (2005) USDA's 2002 ethanol cost-of-production survey. U.S. Dept. of Agriculture (USDA) Office of Energy Policy and New Uses, Agricultural Economic Report No. 841. http://www.usda.gov/oce/reports/energy/USDA_2002_ETHANOL.pdf. Accessed 15 December 2009.

Sheehan J, A Aden, K Paustian, K Killian, J Brenner, M Walsh, R Nelson (2003) Energy and environmental aspects of using corn stover for fuel ethanol. J Ind Ecol 7(3–4): 117–146.

Shinners KJ, BN Binversie (2007) Fractional yield and moisture of corn stover biomass produced in the northern U.S. corn belt. Biomass Bioenergy 31(8):576-584.

Smith RD, JB Liljedahl, RM Peart (1983) Storage and drying of corn cobs. ASAE Tech Pap 83-3007. Conference: American Society of Agricultural Engineers, Bozeman (MT).

Turhollow AF, EG Wilkerson, S Sokhansanj (2009) Cost methodology for biomass feedstocks: herbaceous crops and agricultural residues. ORNL/TM-2008/105. Oak Ridge National Laboratory, Oak Ridge (TN)

Turhollow AF, S Sokhansanj (2007) Costs of harvesting, storing in a large pile, and transporting corn stover in a wet form. Appl Eng Agric 23(4):439–448.

U.S. Department of Agriculture–National Agricultural Statistics Service (USDA-NASS) (2009) http://www.nass.usda.gov. Accessed 15 December 2009.

U.S. Department of Energy–Energy Efficiency and Renewable Energy (DOE-EERE) Office of the Biomass Program (OBP) (2009) Biomass multi-year program plan: February 2009.

Walsh M (2004) Personal communication to Robert Perlack. Update analysis of state-level supply curves for corn stover and wheat straw.

Wilhelm WW, JMF Johnson, JL Hatfield, WB Voorhees, DR Linden (2004) Crop and soil productivity response to corn residue removal: a review of the literature. Agronomy J 96: 1–17.

2. CONVENTIONAL BALE FEEDSTOCK SUPPLY SYSTEM

The Conventional Bale feedstock supply system design (Conventional Bale) 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) bales. Round bales and other biomass collection formats are addressed in the Pioneer Uniform design. Figure 2-1 shows the process flow and potential waste streams for the Conventional Bale system unit operations.

The Conventional Bale design is presented by discussing each major supply system unit operation in the respective order of appearance within the design, as follows:

- Harvest and collection
- Storage
- Transportation and handling
- Receiving and preprocessing.

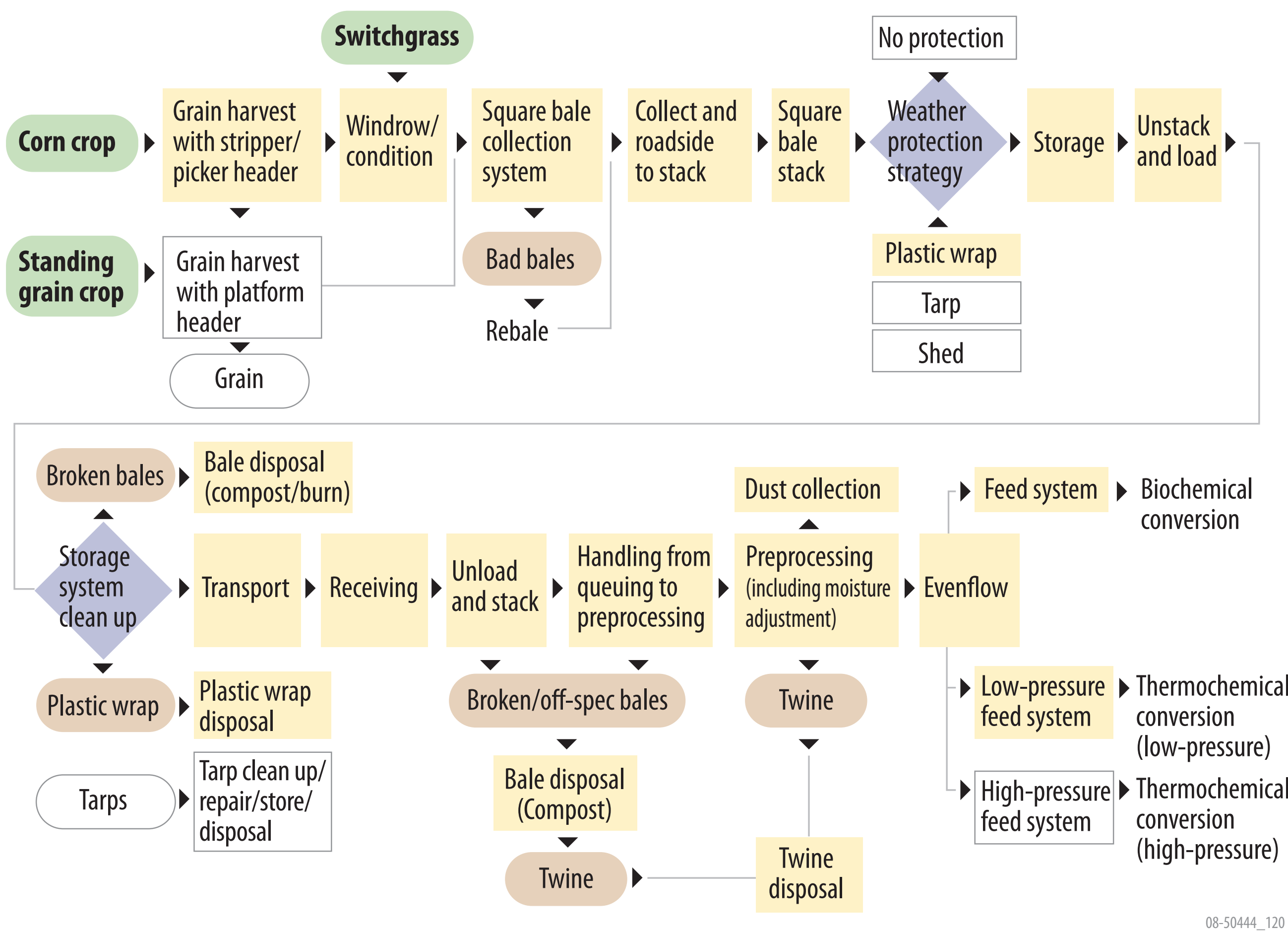


Figure 2-1. *Conventional Bale feedstock supply system design process flow. (Green ovals represent format intermediates, tan ovals represent potential waste streams, yellow rectangles represent individual modeled processes, and white rectangles represent alternate processes that were not modeled.)*

The foundation of the supply system design is the flow and format changes of biomass material as it passes through individual supply system processes from production to conversion (Figure 2-1). Several key feedstock format and machinery attributes have been identified that influence these processes. From a cost, performance, and logistics perspective, each attribute becomes an input 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 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. Equipment modeled for unit operation processes is described in terms of its purpose and function. Equipment specifications assumed for this model are included in Appendix B-1.

The modeled Conventional Bale feedstock supply system is designed to supply a biorefining facility with 800,000 DM ton of dry biomass annually (Table 2-1). This 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.

Delivered feedstock costs for the Conventional Bale Corn Stover and Switchgrass scenarios were calculated using the model and are summarized in Table 2-2. These are static costs and do not represent the impact that variables within each operation can have on the performance of both the unit operation and the overall supply system. Each unit operation is impacted by the performance of another, so each operation section of this report is concluded with a summary analysis of cost, performance, and logistics based on stated format intermediate attributes and equipment operational assumptions. Appendix B-1 provides additional cost and performance detail for each unit operation in the Conventional Bale supply system.

Table 2-1. *Design size annual capacity assumptions for the Conventional Bale–Corn Stover and Switchgrass supply system scenarios.*

	Corn Stover	***Switchgrass***
Plant Operation Size (delivered tons[a])	800,000 (DM ton/yr)	800,000 (DM ton/yr)
Feedstock Harvested Annually[b]	860,000 (DM ton)	860,000 (DM ton)
Cultivated Acres	2,107,000	4,248,000
Acres Available for Contract	1,054,000	212,000
Participating Acres	50%	100%
Acres Harvested Annually	527,000	212,000
Feedstock Supply 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.

Table 2-2. *Total delivered feedstock cost summary for Conventional Bale–Corn Stover and Switchgrass scenarios.*

Operation	***Production***	***Harvest & Collection***	***Storage***	***Transportation & Handling***	***Receiving & Preprocessing***	***Total***
Grower Payment ($/DM ton)[a]	15.90±0.65					15.90±0.65
Logistics–Stover ($/DM ton)[b]		21.61 ± 2.69	8.11 ± 0.66	11.94 ± 1.25	13.74 ± 1.30	55.40 ± 4.31
Logistics–Switchgrass ($/DM ton)[b]		14.92 ± 1.45	7.08 ± 0.52	14.13 ± 1.43	13.74 ± 1.30	49.87 ± 4.71

a. Cost is in 2008$ and represents the weighted average of U.S. regional costs (Hess et al. 2009).
b. Costs are in 2008$ and represent the mean and standard deviations of 10,000 model iterations for the simulated scenarios (Tables 2-3 through 2-6).

2.1 CONVENTIONAL BALE HARVEST AND COLLECTION

Harvest and collection encompasses all processes associated with moving the biomass from 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 (termed "roadsiding").

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 type and format changes between process operations. The feedstock intermediate formats within these processes play crucial roles in determining both the type and size of the equipment used, and the timeliness of the operations necessary to control the feedstock as it moves through the supply system. Tables 2-3 and 2-4 show the equipment and format intermediate attributes modeled for the Conventional Bale–Stover and Switchgrass harvest and collection operation scenarios.

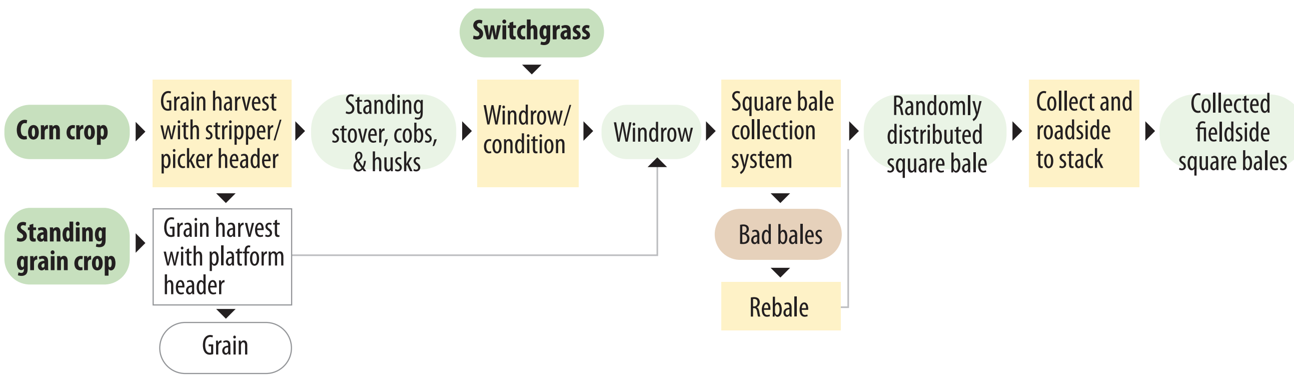


Figure 2-2. *Harvest and collection supply logistics processes and format intermediates. (Green ovals represent biomass format intermediates, tan ovals represent potential waste streams, yellow rectangles represent processes modeled in this report, and white shapes indicate alternate process path.)*

Table 2-3. *Conventional Bale–Stover: Equipment and format intermediate attributes and estimated costs of harvest and collection operation.*

Logistics Processes	*Production*	*Grain Harvest*	*Condition & Windrow*	*Baling*	*Collect & Roadside*	*Dry Matter Loss*	*Total Costs*
Equipment	N/A	Combine with 8 row corn header	180 hp tractor and 15-ft flail shredder with windrower	275 hp tractor and large square baler	Self-propelled stacker		
Format Intermediates	Standing crop	Stubble—standing stalk, cob, and husk on ground	Windrow	Randomly distributed 4×4×8 ft bales[a]	Stacked 4×4×8-ft bales[a]		
Biomass Description	Whole crop (grain and residue)	Stalk, cob, and husk (collectively stover)					
Yield (DM ton/acre)[b]	8.52 (180 bu/acre grain)	4.26	3.0	1.6 (2.8 bale/acre)			
Bulk DM Density	N/A		~0.8–0.9 lb/ft^3 (1.04 ton/1,000 windrow-ft[c])	9 (lb/ft^3 [1,150 lb/bale][d])			
Moisture (w.b.)[e]	50%		12%				
Modeled Costs[f] ($/DM ton)	No Cost[g]		4.16 ± 0.65	10.91 ± 1.11	1.89 ± 0.32	4.65 ± 1.91	21.61 ± 2.69
Modeled Costs[f] ($/acre)	No Cost[g]		12.27 ± 1.53	15.86 ± 3.62	2.75 ± 0.75	6.26 ± 1.38	37.14 ± 4.25

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

b. Process output yield calculations based on equipment dry matter loss: grain harvest 1:1 residue-to-grain ratio, or harvest index of .5; condition and windrow collection efficiency of 71%; baling collection efficiency of 54%; and collect and roadside collection efficiency of 100%.

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 and Binversie 2007.

e. Hoskinson et al. 2007.

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

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

Table 2-4. *Conventional Bale–Switchgrass: Equipment and format intermediate attributes and estimated costs of harvest and collection operation.*

Logistics Processes	Production	Condition & Windrow	Baling	Collect & Roadside	Dry Matter Loss	Total Costs
Equipment		Self-propelled windrower with disc header	275 hp tractor and large square baler	Self-propelled stacker		
Format Intermediates	Standing Crop	Windrow	Randomly distributed 4×4×8 ft bales[b]	Stacked 4×4×8-ft bales[b]		
Biomass Description	Whole crop	Whole crop less stubble (collectively switchgrass)				
Yield (DM ton/acre)[a]	5.0	4.05 (6.3 bale/acre)		N/A		
Bulk DM Density	N/A	1.4 ton/1,000 windrow-ft (~1.1–1.2 lb/ft^3)[c]	10 (lb/ft^3 [1,280 lb/bale][d])			
Moisture (w.b.)	34% [e]	12%[a]				
Modeled Costs ($/DM ton)		3.01 ± 0.77	9.77 ± 0.96	1.70 ± 0.28	0.44 ± 0.21	14.92 ± 1.45
Modeled Costs ($/acre)		11.58 ± 2.01	34.01 ± 7.26	5.92 ± 1.51	1.45 ± 0.57	52.96 ± 8.75

a. Process output yield calculations based on equipment dry matter loss (Table B-1).
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.

2.1.1 Conventional Bale Harvest and Collection Format Intermediates

One variable determining harvest and collection equipment choices is whether the biomass is a secondary residue harvest after a primary grain harvest, such as corn grain and stover, or a primary energy crop harvest, such as switchgrass.

Secondary Harvest (Corn Stover)

Corn crop biomass harvest and collection is typically a two-step process: (1) harvest the grain and then (2) harvest and collect the residue. Table 2-3 shows the modeled equipment and format intermediate attributes for the Conventional Bale–Stover harvest and collection operation and the estimated costs.

The corn stover crop residue harvest and collection process begins with the standing corn crop (Figure 2-3a, background). Following grain harvest, standing stubble, cobs, husks, and some leaves and tops that passed through the harvester and were spread on the ground (collectively "stover") are conditioned and windrowed for baling (Figure 2-3b, ahead of tractor).

For other residues, like cereal straws, 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 is not common practice for corn 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 2-3). 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.

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 size and density of the resulting windrow are important considerations 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 (1.04 ton/1,000 windrow-ft [Table 2-3]). 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.

Once windrowed stover is sufficiently dry, a large square baler stuffs and presses the biomass into the bale, dropping 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.” When the bales are roadsided, the harvest and collection unit operation is complete.

Primary Harvest (Switchgrass)

The principle 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 2-3 and 2-4). Table 2-4 shows the modeled equipment and format intermediate attributes for the Conventional Bale–Switchgrass harvest and collection operation and the estimated costs.

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 (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 (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 (34% [Table 2-4]). 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 are no operational differences between the crop residue and energy crop harvest and collection processes in the Conventional Bale design model (compare Tables 2-3 and 2-4). The switchgrass is allowed to field dry in the windrow to 12% moisture and is then baled into 4×4×8-ft bales (Figure 2-4b).

Condition and Windrow

The Conventional Bale design model includes field drying for both corn stover residue and switchgrass. When field drying is used, the selection of harvest operations takes ambient conditions into consideration. 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 2-3 and 2-4). 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

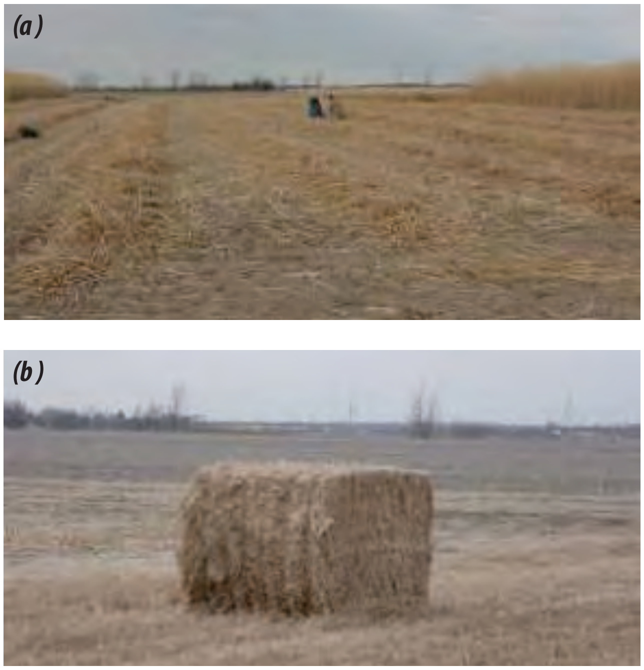


Figure 2-4. *Switchgrass (a) standing in the field (background, right), and after harvest and windrowed with a mower/conditioner (foreground); and (b) baled in a 4×4×8-ft format.*

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, and alternate Conventional Bale harvest and collection scenario costs can vary by more than $10/DM ton (Table 2-5).

The three alternate harvest and collection scenarios represented in Table 2-5 are figured according to the following logic:

- *Corn Stover*—Row-crop residues, such as 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*—Instead of being cut with a self-propelled windrower (also known as a swather), switchgrass 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.

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

Table 2-5. *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

stuffer, which packs 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.

2.1.1.1 Biomass Deconstruction, Fractionation, and Yield

A crop's physical structure and yield are two biomass material attributes that impact the selection and performance of harvest and collection equipment (Tables 2-3 and 2-4). Cereal straw residues are generally harvested or collected differently than residues like corn stover and sorghum stover. A reason for this difference 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 (Wright et al. 2005). Corn and sorghum stover, which typically do not pass though the harvester, require additional equipment to harvest and collect.

Similarly, the high yields and thicker stalks of perennial grasses such as switchgrass and miscanthus 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 self-propelled windrowing or tractor-drawn mowing/conditioning. For both crop residues and perennial grasses, the crop/residue yield will significantly impact the efficiency of harvest and collection equipment (Sokhansanj and Pordesimo 2002).

2.1.1.2 Format and Bulk Density Impact on Supply System Processes

Different biomass crops or residues perform differently in baling equipment (Table 2-5), which, depending on crop yield for each scenario (Tables 2-3 and 2-4), affects bale bulk density and the number of bales per acre. Cereal straw residues produce some of the lowest bale densities, resulting in relatively high bale counts per ton of biomass (Table 2-6). The cost to handle each bale is essentially the same, regardless 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 2-3]). As such, handling efficiencies for high density 3×4×8-ft bales are equivalent to 4×4×8-ft bales. Another advantage of 3×4×8-ft bales is that they stack more efficiently on collection and transportation equipment, allowing more bales to be handled or transported during a collection cycle.

The Conventional Bale design in this report collects and packages crop residues and perennial grasses in large, square 4×4×8-ft bales. These large square bales can be produced in other sizes, including 3×3×8-ft and 3×4×8-ft bales. Regardless of the selected biomass handling format, bale density is a key factor in collection and handling efficiencies, capacity, and, ultimately, costs.

Table 2-6. *Yield and bulk density data for large square bales of various biomass feedstocks.*

	Crop Yield (baled DM ton/acre)	*Bale Density (wet bulk lb/ft^3)*	*Bale Density (DM bulk lb/ft^3)*	*Square Bale 4×4×8-ft (# /acre)*	*Square Bale 3×4×8-ft (# /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 2-3).
b. Shinners and Binversie 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 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 2-7).

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, an alternate strategy must be implemented, such as (1) stabilizing the biomass in the presence of water (e.g., ensiling), (2) removing the water at some later point in the supply system, or (3) providing just-in-time delivery and processing (e.g., year-round green harvest without storage/queuing). These alternate strategies are not included in the Conventional Bale design; thus this design is unsuitable for biomass that cannot be sufficiently dried in field.

Corn stover nearly always requires some level of in-field moisture management (Table 2-7). 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 in-field drying of stover, Hoskinson et al. (2007) suggest a fractional harvest of cobs, husks, and upper stalk only. INL corn stover harvest trials indicate that these fractions may be within the moisture limit for dry storage at the time of grain harvest (Abengoa/Kansas - November 11–13, 2008).

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 moisture requirements of a dry harvest system (Table 2-7). While national harvest moisture content averages for cereal grains, such as wheat and barley, range from 10 to 20% w.b. ([ANSI/ASAE S343.3] ASABE 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). However, after senescence in the fall/winter, switchgrass harvest moisture rapidly drops to the dry biomass range (Table 2-7). 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 windrow density were 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

Table 2-7. *Typical harvest moistures for select crop residues and energy crops.*

Corn Stover	***Wheat Straw***	***Switchgrass***	***Miscanthus***
20–64%[a]	9–25%[b]	12–70%[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; Venturi et al. 2004, Shinners et al. 2006b.

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 harvest and collection design, the only appreciable difference between corn stover and switchgrass equipment is the additional grain harvest equipment (Tables 2-3 and 2-4). 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 stover remains standing in the field after the grain harvest operation, much ends up lying on the ground (Table 2-8). As a result, equipment selected to windrow corn stover is functionally different from that selected for switchgrass, which is cut and windrowed in one process (Figure 2-5) (Table 2-5).

Once the corn stover and switchgrass are in the windrow, all other harvest and collection unit operation equipment is functionally similar. Specific equipment specifications used to model the Conventional Bale scenario in this report are included in Appendix B-1.

Figure 2-5. *Conventional Bale–Stover harvest equipment (combine with grain harvest header [a] and shredder/windrower [b] that is pulled by a tractor) is functionally different than Switchgrass harvest equipment (self-propelled windrower [c]).*

2.1.2.1 Equipment Capacity and Operational Efficiency

Machine field capacity is a function of field speed, crop yield, field efficiency, and machine working width ([EP496.3] ASABE 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, "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 ([D497.5] ASABE 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.

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.

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 the amount of equipment downtime caused by service and maintenance occurring 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.

Table 2-8. *Typical field speeds and field efficiencies for harvesting machines ([ASAE D497.5] ASABE 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.

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

		Yield		Capacity		
	Machine/Equipment	**Value**	**Unit/acre**	**Rated[a]**	**Field[b]**	**Unit/hr**
Corn	Combine[c]	180	bushel	2,000	1,400	bushel
	Small Grain Combine	60	bushel	550	385	bushel
Corn Stover	Shredder[e]	3.02[f]	DM ton	9.1	7.3	acre
	Rake[g]	3.02	DM ton	14.5	11.6	acre
	Large Square Baler[h]	1.63[i]	DM ton	38	30.4	bale
Switchgrass	Windrower[j]	5	DM ton	12.7	10.2	acre

a. Rated capacities are calculated using the field speed shown in Table 2-9.
b. Field capacities are calculated by de-rating the rated capacity by the "typical" field efficiencies shown in Table 2-9.
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 ton/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.

2.1.2.2 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 B-1). It may be argued that these losses are desirable because biomass left behind can help maintain soil productivity, but uncontrolled loss is never desirable. A certain amount of biomass will likely need to remain on the field to maintain soil health, but the amount left should be a controlled return or omission rather than a machine loss.

Harvest efficiency is affected by several equipment and field conditions:

- Cut height of combine harvesters affects the amount of biomass left stranding relative to that lying on 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.
- Use of stripper/picker headers (e.g., corn headers) for corn grain harvest causes significant uncontrolled material losses because they are specifically designed to bring only the grain into the harvester and leave 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.
- 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 (INL corn stover harvest field trials; Abengoa/Kansas - November 11–13, 2008).

- 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.
- Inclement weather that occurs after the residue or energy crop is harvested and lying in the windrow can also have a significant impact on field losses. Rain causes the biomass to become 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.
- Biomass physical properties impact on 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 8365 windrower, the harvest efficiency for the windrowed switchgrass was 90% (Table 2-9). The baling harvest efficiency was also 90% (Table 2-8). The primary reason for these greatly improved harvest efficiencies, in comparison with 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.

2.1.2.3 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 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, 2006b).

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. Delayed field operations result in lost opportunity costs and can 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 2-6, which represents a 5-yr average of corn harvest progress in Nebraska. Based on this data, the statewide harvest window spanned an 11-wk period from Week 36 to Week 47. The Conventional Bale design scenario modeled herein is based on only the most active 6-wk period of the harvest window (Table A-12). 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.

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-wk window.

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 hr/day in wet regions to 14 hr/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 hr/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.

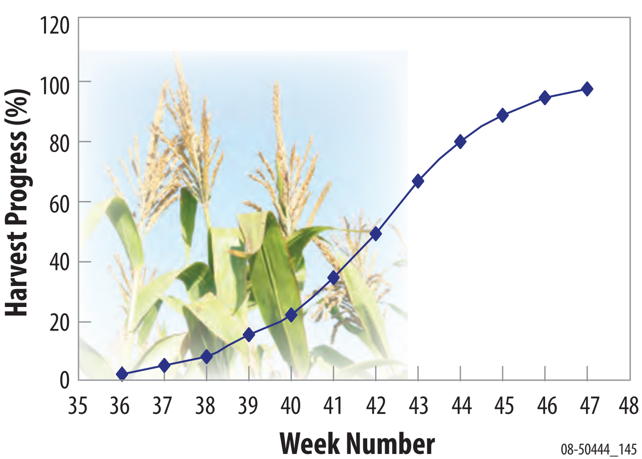


Figure 2-6. *Cumulative corn harvest progress for Nebraska (USDA-NASS 2009).*

2.1.3 Conventional Bale Harvest 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 operation identifies significant cost components that are valuable for making individual comparisons and recognizing areas of research potential (Tables 2-10 and 2-11). 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.*

Logistics Processes	Grain Harvest Only[a]	Condition/Windrow	Bale	Roadside
Equipment	Combine with corn row header	Tractor and 15-ft flail shredder w/windrowing	Tractor and baler	Stacker
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 (Appendix B-2, Table B-1), but in the Conventional Bale design, no additional harvesting costs are incurred.
b. Installed capital costs are $/annual DM ton capacity.
c. Ownership costs include depreciation, interest, taxes, insurance, and housing (Appendix A-3, Table A-7).
d. Operating costs include repairs, maintenance, fuel, lubrication, labor, and consumable materials (Appendix A-3, Table A-7).

Table 2-11. *Static model costs for major harvest and collection equipment in the Conventional Bale–Switchgrass scenario.*

Logistics Processes	Condition/Windrow	Bale	Roadside
Equipment	Windrower w/disc header	Tractor and baler	Stacker
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 $/annual DM ton capacity.
b. Ownership costs include depreciation, interest, taxes, insurance, and housing (Appendix A-3, Table A-7).
c. Operating costs include repairs, maintenance, fuel, lubrication, labor, and consumable materials (Appendix A-3, 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 costs (Figure 2-7) for corn stover shows with 90% confidence that the cost of the operation ranges between $17.79 and $26.49/DM ton. Further, the mean and standard deviation of this range is $21.61 ± 2.69/DM ton. The mode value is $20.61/DM ton, which closely represents the result of the static model ($19.96/DM ton), since the defined value of the parameter distributions was set equal to the static value in the model.

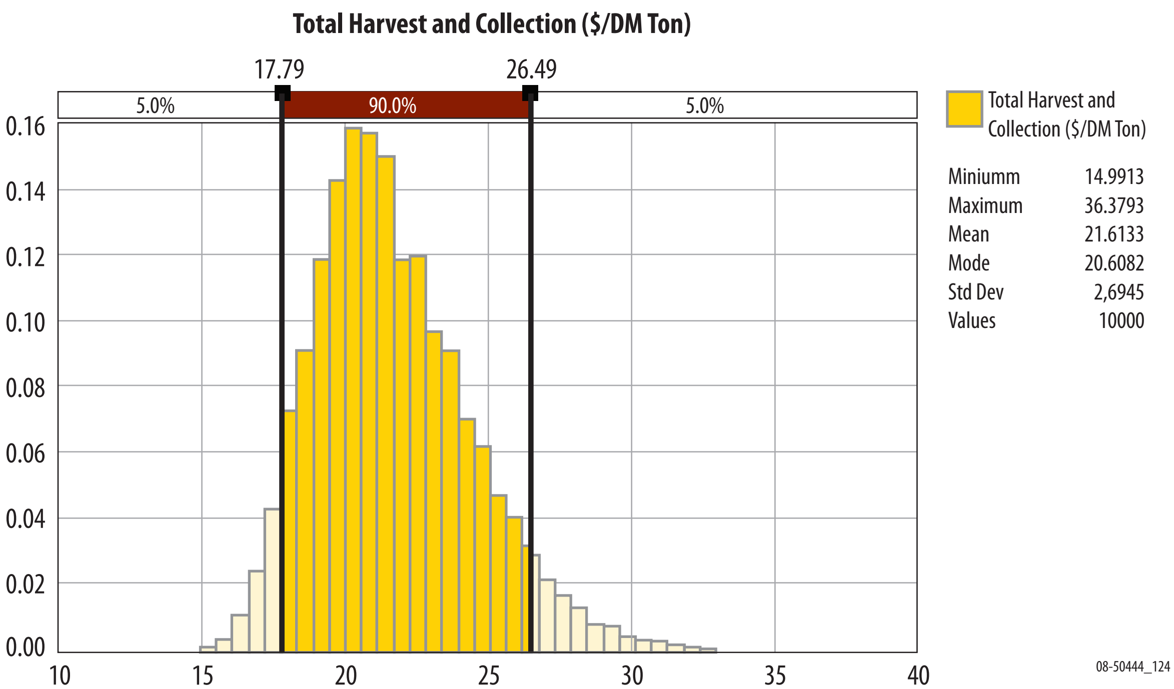


Figure 2-7. *Conventional Bale–Corn Stover harvest and collection cost distribution histogram from @Risk analysis.*

Similarly, a histogram of the harvest and collection costs (Figure 2-8) for switchgrass shows with 90% confidence that the cost of the operation ranges between $12.69 and $17.45/DM ton, with the mean and standard deviation of this range being $14.92 ± 1.45/DM ton. The mode value is $14.46/DM ton, which closely represents the result of the static model of $15.25/DM ton.

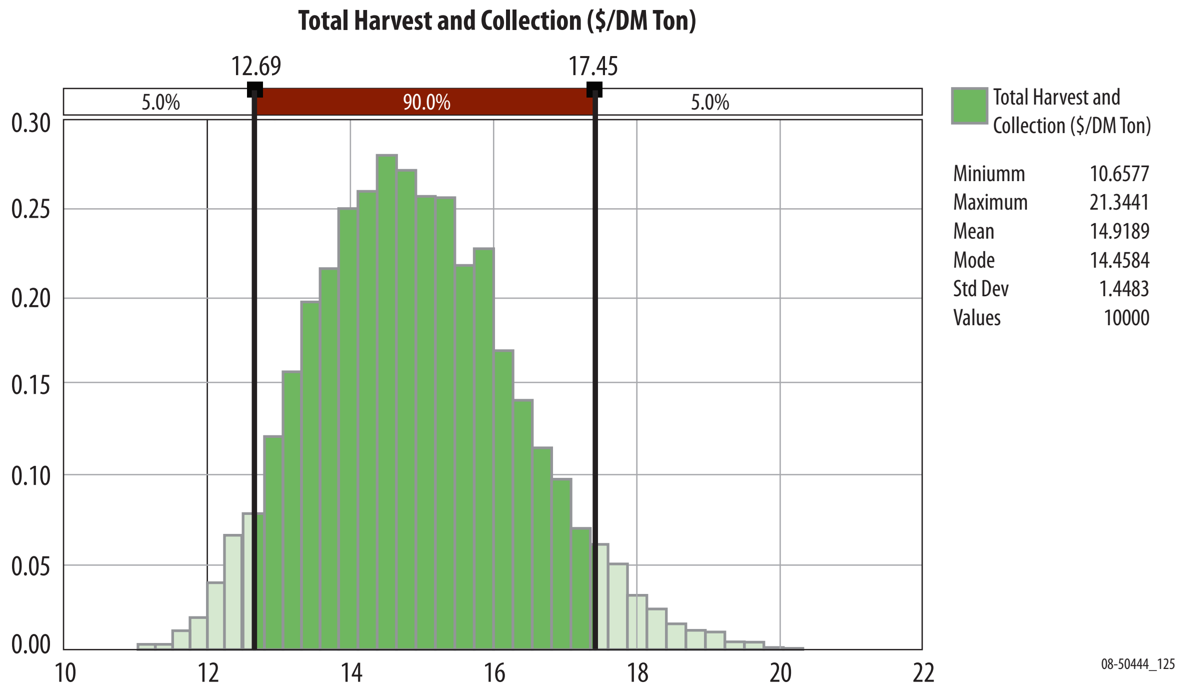


Figure 2-8. *Conventional Bale–Switchgrass harvest and collection cost distribution histogram from @Risk analysis.*

The overall costs associated with the Conventional Bale harvest and collection 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.*

Logistics Processes	Grain Harvest Only[a]	Condition/ Windrow	Bale	Roadside	Dry Matter Loss	Total Harvest and Collection
Equipment	**Combine with 8-row corn header**	**Tractor and flail shredder w/ windrowing**	**Tractor and baler**	**Stacker**		
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.*

Logistics Processes	Condition/ Windrow	Bale	Roadside	Dry Matter Loss	Total Harvest and Collection
Equipment	**Windrower with disc header**	**Tractor and baler**	**Stacker**		
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 2-9). 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 operation, and the stack moisture has already been reduced to ~12%. The Conventional Bale storage design employs technologies and methods to protect the bales from both mechanical and biological losses, but the model assumes a 5% physical loss, or shrink, during storage (Tables 2-14 and 2-15).

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 2-9). The equipment and format intermediate attributes for the Conventional Bale storage operation are shown in Tables 2-14 and 2-15.

Determining the best storage protection strategy depends upon local conditions and may include the option of stacks with no protection, which is a common strategy selected in arid regions of the Western United States (Figure 2-10). 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 2-9 [“plastic wrap”]).

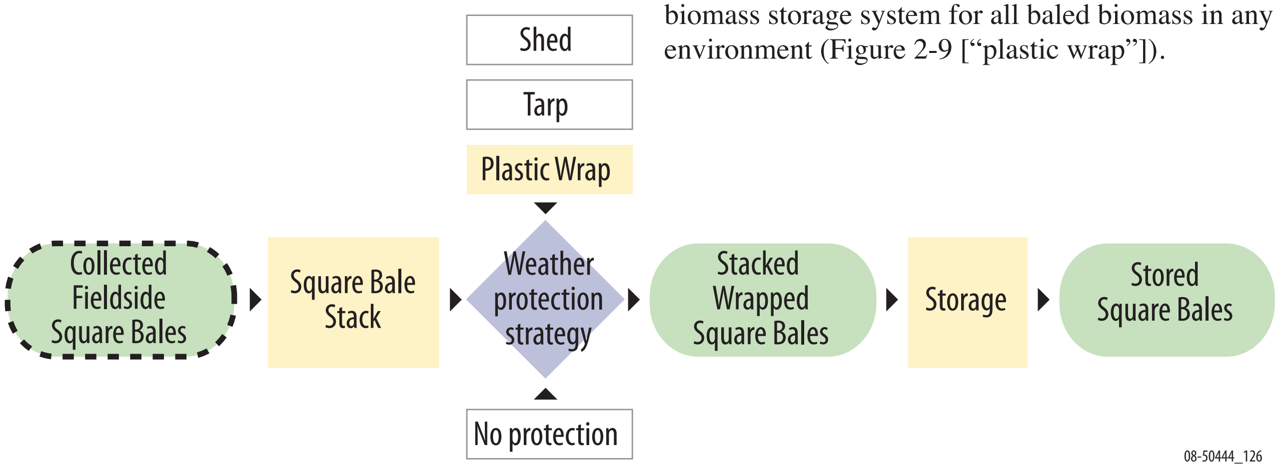


Figure 2-9. *Storage supply logistic processes and format intermediates. (Green ovals represent format intermediates, yellow rectangles represent processes modeled in this report, white rectangles represent processes not modeled in this report, and grey diamonds represent multiple process options.)*

Table 2-14. *Equipment and format intermediate attributes modeled for the Conventional Bale–Corn Stover storage operation and estimated costs.*

Logistics Processes	Stack Bales	Protect Bales	Store Bales	Dry Matter Loss Costs	Total Storage Costs
Equipment	**Self-propelled loader**	**Bale wrapper**	**Insurance, land rent, stack maintenance**		
Format Intermediates	Rows of plastic wrapped 4×4×8-ft bales, stacked 1-bale wide and 2-bales high at field side				
Biomass Description	Stalk, Cob, and Husk (collectively stover)				
Stack Size[a]	200 (DM ton/stack [348 bales])		190 (DM ton/stack [348 bales])		
Bulk DM Density Output[b]	9 (lb/ft^3 stack [0.13 acre/stack])				
Output Moisture (w.b.)	12%				
Modeled Cost Totals[c] ($/DM ton)	0.91 ± 0.13	5.66 ± 0.34	0.10 ± 0.01	1.44 ± 0.44	8.11 ± 0.66

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.
b. Assumes wrapping results in tight stack with the same bulk density as the bales.
c. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

Table 2-15. *Equipment and format intermediate attributes modeled for the Conventional Bale Switchgrass storage operation and estimated costs.*

Logistics Processes	Stack Bales	Protect Bales	Store Bales	Dry Matter Loss Costs	Total Storage Costs
Equipment	**Self-propelled loader**	**Bale wrapper**	**Insurance, land rent, stack maintenance**		
Format Intermediates	Rows of plastic wrapped 4×4×8-ft bales, stacked 1-bale wide and 2-bales high at field side				
Biomass Description	Switchgrass				
Stack Size[a]	200 (ton/stack [313 bales])		190 (DM ton/stack [313 bales])		
Bulk DM Density Output[b]	10 (lb/ft^3 stack [0.11 acre/stack])				
Output Moisture (w.b.)	12%				
Modeled Cost Totals[c] ($/DM ton)	0.82 ± 0.12	5.09 ± 0.28	0.10 ± 0.01	1.07 ± 0.32	7.08 ± 0.52

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.
b. Assumes wrapping results in tight stack with the same bulk density as the bales.
c. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

Figure 2-10. *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 occur, resulting in biomass losses during storage (Figure 2-12). 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 risk of spontaneous combustion in 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 2-12). 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% (Tables 2-14 and 2-15, Footnote a). 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.

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 2-7, compare corn stover and 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 2-16).

Table 2-16. *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 2009.
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).

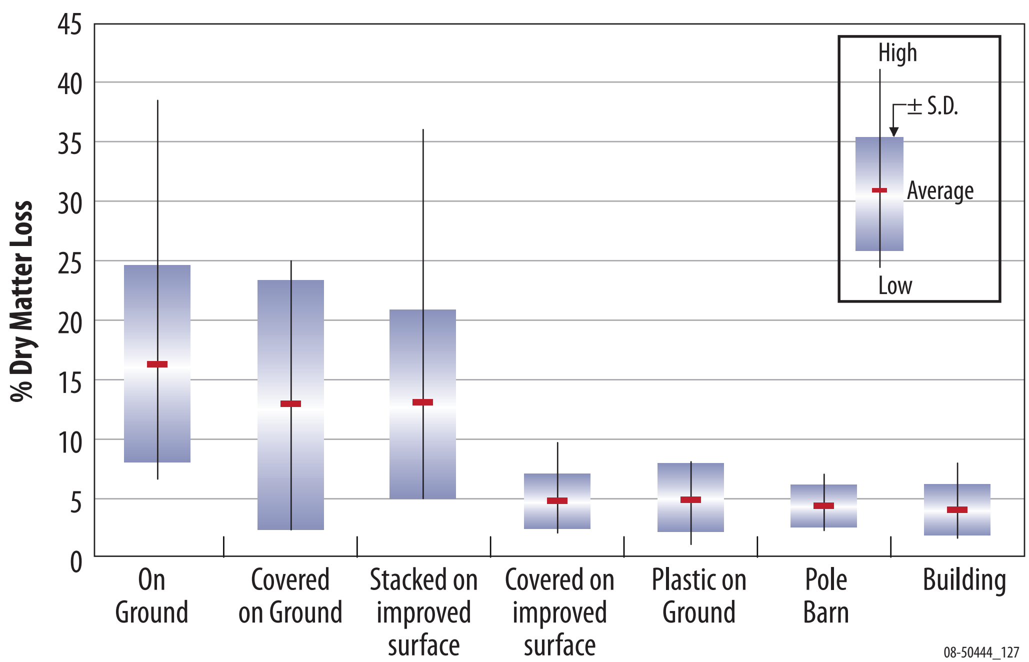


Figure 2-11. *Expected range of dry matter loss for different storage configurations in wet climates (Appendix A-5).*

Another issue that is often overlooked in biomass storage is that 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, survive 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 another 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.

When storing baled feedstocks it is important 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 be stored effectively as stacked bales.

2.2.1.1 Biomass Deconstruction, Fractionation, and Yield

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) during storage (Figure 2-13). Dry matter losses that occur in storage can be caused by microbial activity, mechanical loss during handling, or "apparent loss," which 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. Changes in the environment where biomass is stored can accelerate or arrest microbial activity that degrades 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 2-17). 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 ton dry basis (d.b.) of wheat straw and was stored uncovered in Idaho for 1 year. Sampling after 1 year revealed that moisture exposure caused varied levels of darkening of the straw. 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 2-17). 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.

In contrast to microbial dry matter losses, mechanical dry matter losses occur when loose material is scattered from bales that fall from stacks or fall apart. Recognizing and mitigating these losses is relatively easy 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

The storage format for the Conventional Bale design is large 4×4×8-ft square bales. 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 A-5). Another format consideration that can contribute to the cost of storage 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 (Tables 2-14 and 2-15).

This Conventional Bale design uses a stack configuration of one bale wide and two bales high (Tables 2-14 and 2-15). 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.), the two-bale-high stack configuration may not be feasible due to inefficient land area use. A more efficient land-area-usage stack configuration for 4×4×8-ft bales is four

Table 2-17. *Effects of various environmental conditions on baled wheat straw stored outdoors without protection for 1 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[b] ($/DM ton)
Pre-storage	Zero	Straw going into storage	64.7	$0
Dry	1 yr	Visibly undamaged	65.4	$0.90
Transiently Wet	1 yr	Visibly water stained, dry when sampled in spring	58.2	-$9.29
Continually Wet	1 yr	Dark brown, wet straw when sampled in spring	49.3	-$22.89

a. INL data, Hess et al. 2006.
b. Based on minimum ethanol selling price (MESP) of $1.07/gal (year 2000 $US). Calculations derived from Ruth and Thomas 2003.

bales high either in single or multiple adjacent rows (stack configuration in Figure 2-32). In an enclosed structure, the stack might be six to eight bales high to achieve the highest possible land area usage efficiency. Determining the best storage configuration requires balancing the storage system/configuration costs with the potential biomass dry matter losses of a particular configuration (Tables 2-14 and 2-15). Notice that the 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.

Another factor impacting storage decisions is distributed or centralized storage. 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 (Tables 2-14 and 2-15). 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 significant considerations 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 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 2-12).

Figure 2-12. *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 Processes 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.” A square bale is comprised of multiple flakes compressed together, which may allow water to channel into the bales and stacks. In contrast, round bales are not compressed into flakes, so they tend to resist water penetration better than square bales. The channeling in square bales can be observed even in very low precipitation areas (<10 in. annually) of the arid western United States (Figure 2-13). More precipitation would cause even greater infiltration and subsequent moisture damage. The total dry matter loss for the wheat straw bales shown in Figure 2-13 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.

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 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). The bales were stacked in five rows and three columns separated by Styrofoam-type insulation board. The stack number identifies the location of the tested bale in the stack.

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. 1999). 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" (aw) 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 aw measurement of 1.0 represents pure water that is unbound, while an aw 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 2-14). Figure 2-14 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.

Figure 2-13. *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.*

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

Moisture Content Range	**10–15%**		**15–20%**		**20–25%**		**25–30%**	
Stacks Monitored (quantity)	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

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 2-14 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 (2003, 2004).

Relative humidity, and thus water activity, can be 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 2-15, 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.

2.2.2 Conventional Bale Storage Equipment

The storage equipment in the Conventional Bale design is the same for both corn stover and switchgrass (Tables 2-14 and 2-15). 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). 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. For a more detailed discussion of equipment and specifications used for this model, see Appendix B-1.

2.2.2.1 Equipment Capacity and Operational Efficiency

Upon being moved to the side of the field with the self-propelled stacker, a telehandler 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 bale/hr (Appendix B-1, Table B-3). Based on manufacturer data, the field efficiency of the bale wrapper is modeled at 67%, leading to an operational capacity of 80 bale/hr, or 52.4 ton/hr. The telehandler system is capacity limited by the bale wrapper, and the stacking costs represent that drop in the telehandler's operational efficiency.

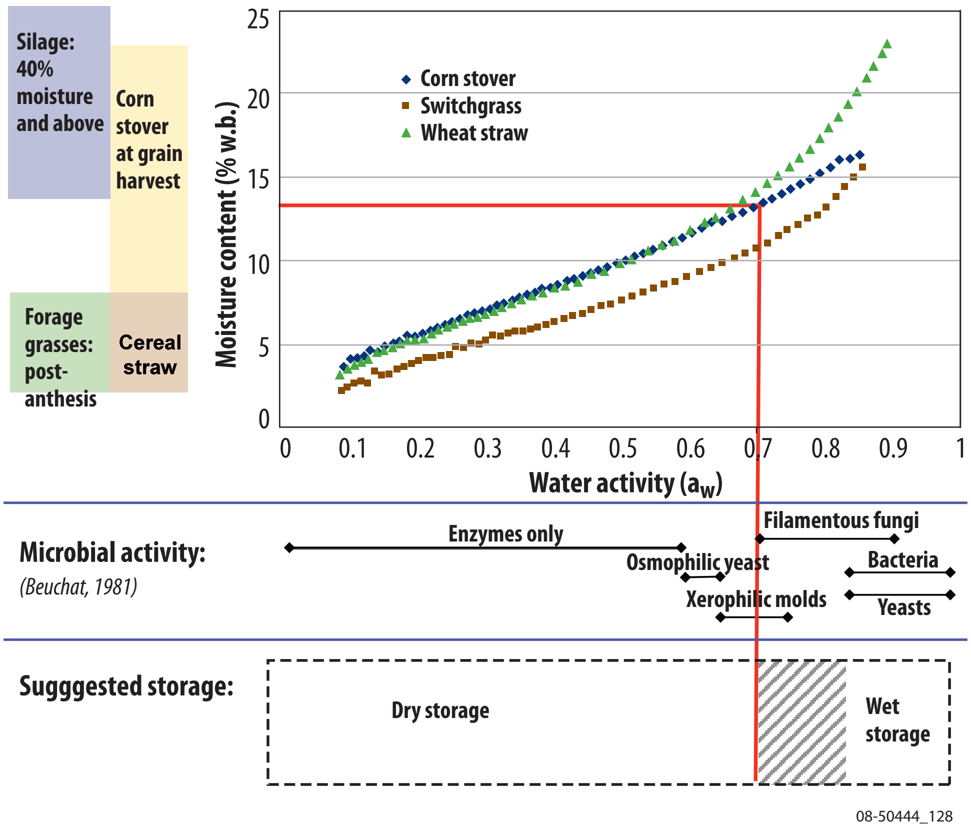


Figure 2-14. *The relationship of moisture content and water activity and the impact of water activity on storage of harvested biomass. The boxes on the left indicate the moisture content of various feedstocks.*

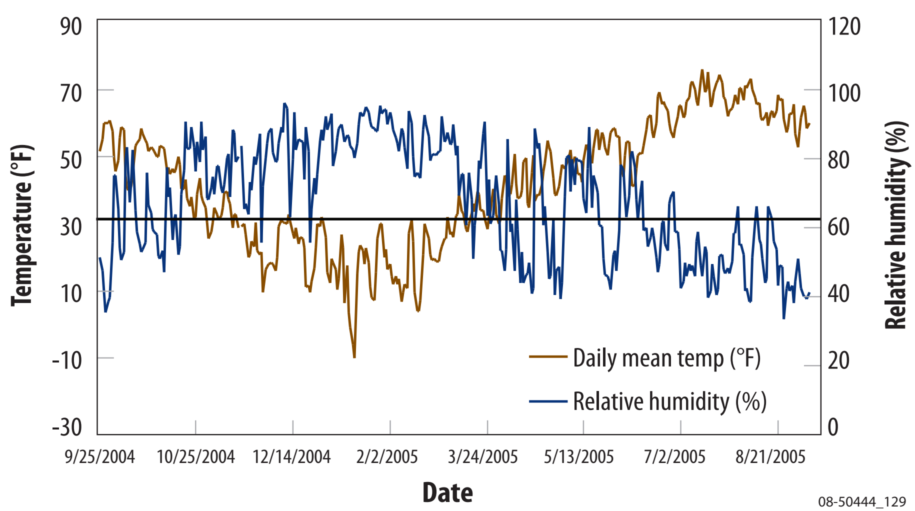


Figure 2-15. *The relationship of temperature and humidity over 1 year in a climate with cold winters and warm, dry summers. The black horizontal line represents a rough cutoff point where if both temperature and relative humidity fall above the line, conditions for rotting are prominent.*

The stack capacity is limited by international fire code, which allows a maximum of 100 ton/stack and requires 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 an annual repair and maintenance factor of 2%.

2.2.2.2 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 but does impact costs. At a cost of $0.69/ft^3 to build a gravel pad at the storage site (including 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 occurs at field-side, having an improved surface at the edge of the field is not practical, especially considering that the fields in which the stover is stored will rotate with corn production.

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 2-14. The resulting cost of a 5% dry matter loss in storage is $2.08/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 2-19). These costs are reported in terms of DM ton entering the storage process.

2.2.3.2 Cost Sensitivity Analysis

A histogram of the storage cost for corn stover (Figure 2-16) shows that with 90% confidence the cost of the operation ranges between $7.07 and $9.24/DM ton. Further, the mean and standard deviation of this range is $8.11 ± 0.66/DM ton. The mode value is $7.97/DM ton, which closely represents the result of the static model ($8.08/DM ton), since the defined value of the parameter distributions was set equal to the static value in the model.

Similarly, a histogram of the storage cost for switchgrass (Figure 2-17) shows with 90% confidence that the cost of the unit operation ranges between $6.25 and $7.95/DM ton with the mean and standard deviation of this range being $7.08 ± 0.52/DM ton. The mode value is $7.09/DM ton, which closely represents the result of the static model of $7.14/DM ton.

The overall costs associated with the Conventional Bale storage operation for both corn stover and switchgrass are provided in Table 2-20 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 2-19. *Static model costs ($U.S.) for major storage equipment in the Conventional Bale–Corn Stover and Switchgrass scenarios. (Corn stover data is shaded yellow and switchgrass data is shaded green.)*

	Stacking	Weather Protection	Storage
Equipment	**Loader**	**Wrapper**	**Insurance, Land Rent, Stack Maintenance**
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
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 $/annual DM ton capacity.
b. Ownership costs include depreciation, interest, taxes, insurance, and housing (Appendix A-3, Table A-7).
c. Operating costs include repairs, maintenance, fuel, lubrication labor, and consumable materials (Appendix A-3, Table A-7).

Table 2-20. *Storage cost summary for the Conventional Bale–Corn Stover and Switchgrass scenarios. (Corn stover data is shaded yellow and switchgrass data is shaded green.)*

Logistics Processes	Stacking	Weather Protection	Storage	Dry Matter Loss	Total Storage
Equipment	**Loader**	**Wrapper**	**Insurance, Land Rent, Stack Maintenance**		
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)
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.

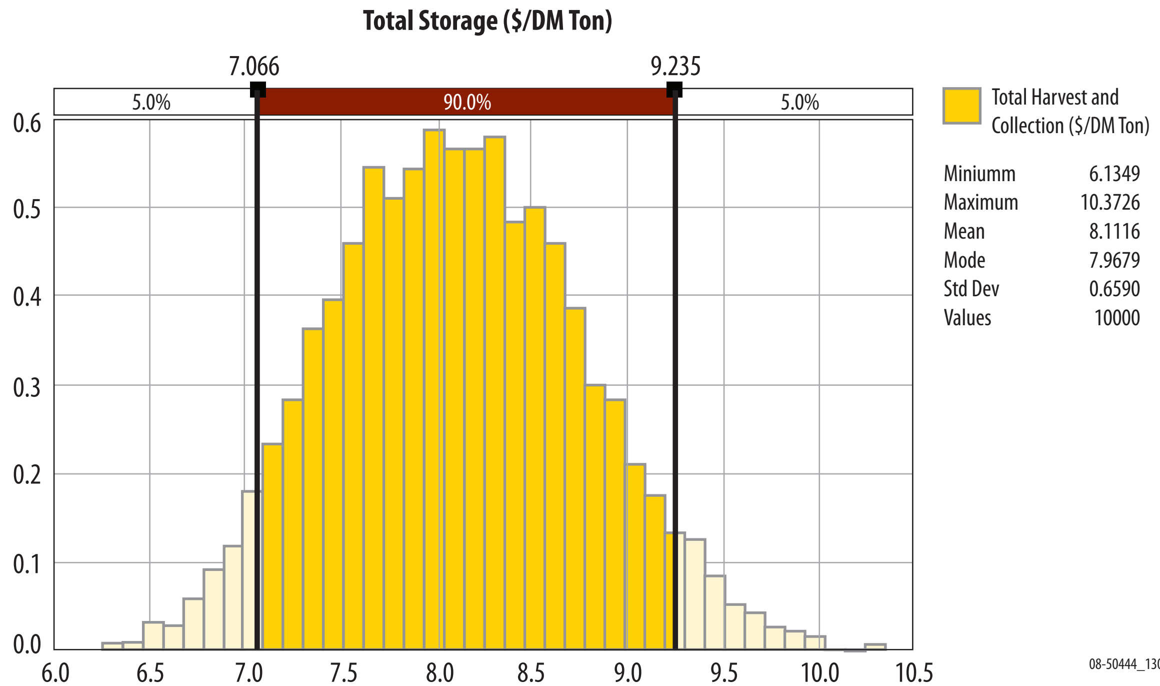


Figure 2-16. *Conventional Bale–Corn Stover storage cost distribution histogram from @Risk analysis.*

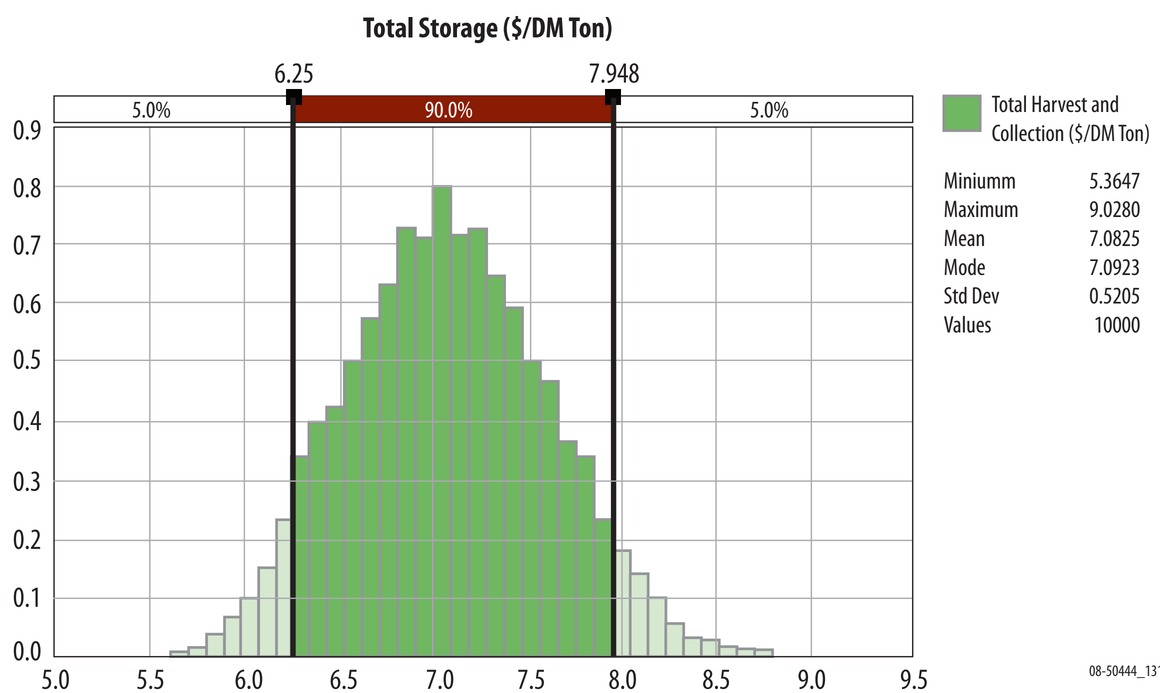


Figure 2-17. *Conventional Bale–Switchgrass storage cost distribution histogram from @Risk analysis.*

2.3 CONVENTIONAL BALE TRANSPORTATION AND HANDLING

The Conventional Bale transportation and handling operation centers around the movement of baled material from long-term, field-side storage to shorter-term, bale-yard storage at the biorefinery (Figure 2-18). 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 B-2, Table B-3).

Estimating the cost of the transportation and handling unit operation often focuses on just the transportation distance part of the system in terms of a $/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 transportation and handling 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 transportation and handling 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

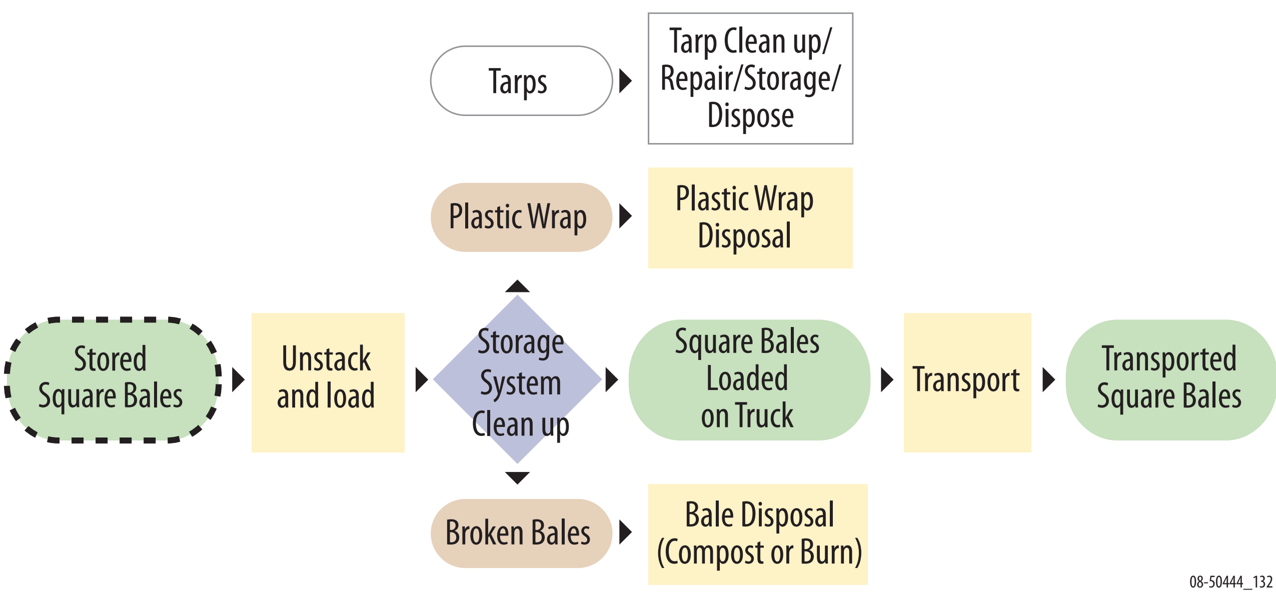


Figure 2-18. *Transportation and handling supply logistic processes and format intermediates. (Green ovals represent format intermediates, tan ovals represent potential waste streams, yellow rectangles represent processes modeled in this report, white rectangles represent processes not modeled in this report, and grey diamonds represent decision points.)*

at a time at a rate of 80 bale/hr using a self propelled loader (Section 2.2.2.1, Figure B-5). As shown in Figure 2-19, the fixed costs, totaling about $55/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/DM ton.

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 transportation and handling are discussed in the following subsections.

2.3.1 Conventional Bale Transportation and Handling Format Intermediates

The Conventional Bale transportation and handling 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 transportation and handling 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 2-21 and 2-22).

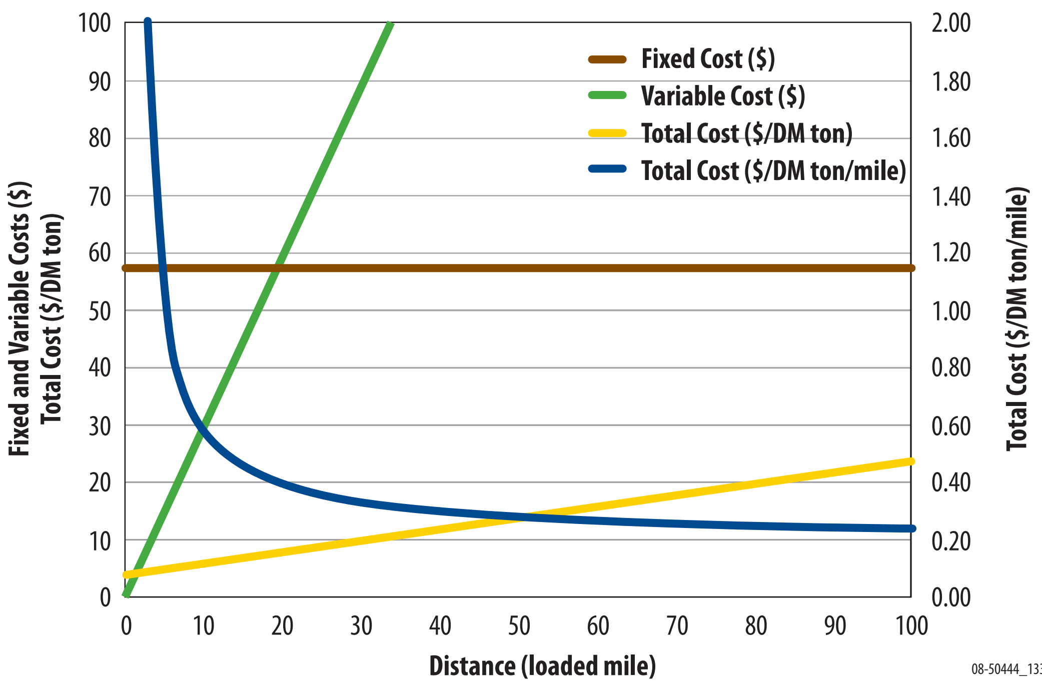


Figure 2-19. *Transportation costs for hauling larger square bales of corn stover with a semi-tractor trailer.*

Table 2-21. *Equipment and format intermediate attributes modeled for the Conventional Bale–Corn Stover transportation and handling operation and estimated costs.*

Logistics Processes	*Load Truck from Stack*	*Transport Load*	*Total Transportation & Handling Costs*
Equipment	**Self-propelled loader**	**3-axle day cab tractor with 53-ft flat bed trailer**	
Format Intermediates	4×4×8-ft unwrapped bales		
Biomass Description	Stalk, cob, and husk (collectively stover)		
Load Size (DM lb/load)	34,000 (26 bales)		
Bulk DM Density	8.55 (lb/ft^3)		
Moisture (w.b.)	12%		
Modeled Cost Totals[a] ($/DM ton)	0.84 ± 0.09	11.09 ± 1.22	11.93 ± 1.25

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

Table 2-22. *Equipment and format intermediate attributes modeled for the Conventional Bale Switchgrass transportation and handling operation and estimated costs.*

Logistics Processes	*Load Truck from Stack*	*Transport Load*	*Total Transportation & Handling Costs*
Equipment	**Self-propelled loader**	**3-axle day cab tractor with 53-ft flat bed trailer**	
Format Intermediates	4×4×8-ft unwrapped bales		
Biomass Description	Switchgrass		
Load Size (DM lb/load)	37,800 (26 bales)		
Bulk DM Density	10 (lb/ft^3)		
Moisture (w.b.)	12%		
Modeled Cost Totals[a] ($/DM ton)	0.76 ± 0.08 13.37 ± 1.40		14.13 ± 1.43

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

2.3.1.1 Biomass Deconstruction, Fractionation, and Physical Property Changes

The Conventional Bale transportation and handling 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 transportation and handling 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). Transportation and handling 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 2-18). 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 2-20. Again, as a reference, large 4×4×8-ft square bales of corn stover at 12% moisture typically weigh ~1,300 lb or have a DM bulk density of 9 lb/ft^3 (Table 2-21). 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 Bulk Density (DM lb/ft^3)
	Length (ft)	GVW (lb)	Max (lb)	Square 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,e]	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.
e. Overall truck length limit. Actual load length is 95 ft.

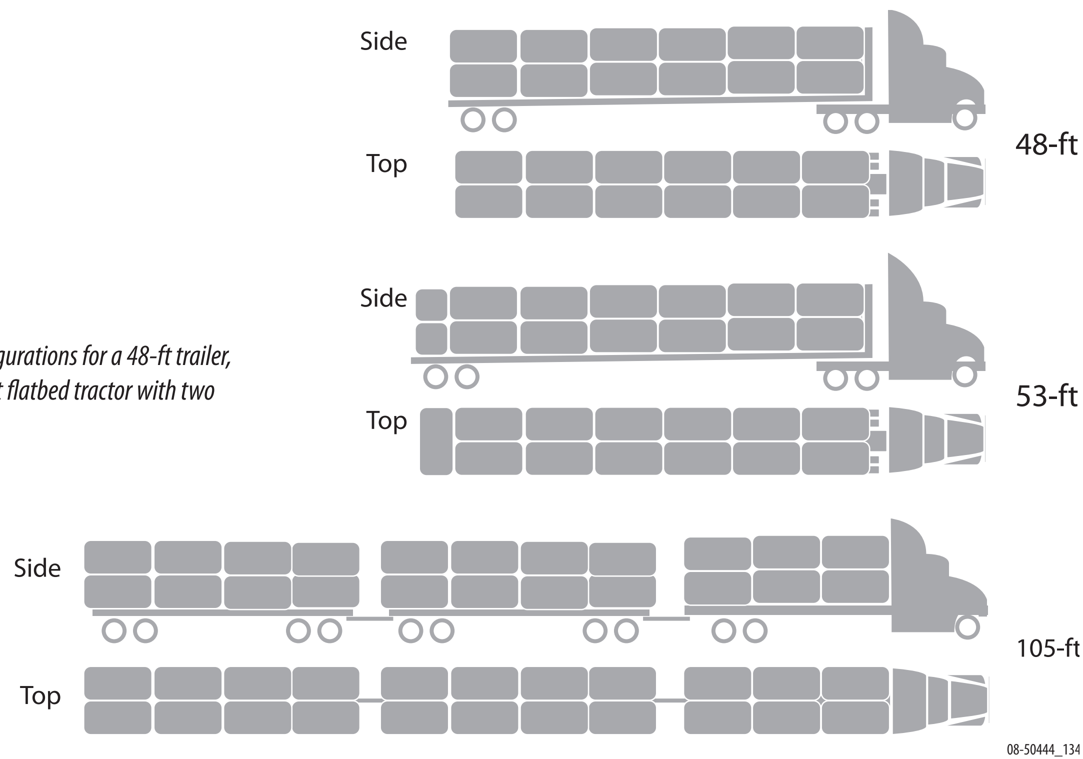


Figure 2-20. Truck configurations for a 48-ft trailer, a 53-ft trailer, and a 24-ft flatbed tractor with two 30 ft trailers.

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 2-20 for a 53-ft flatbed tractor-trailer unit hauling 26 (4×4×8-ft) bales. According to Table 2-24, 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 (Figure 2-21). 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.

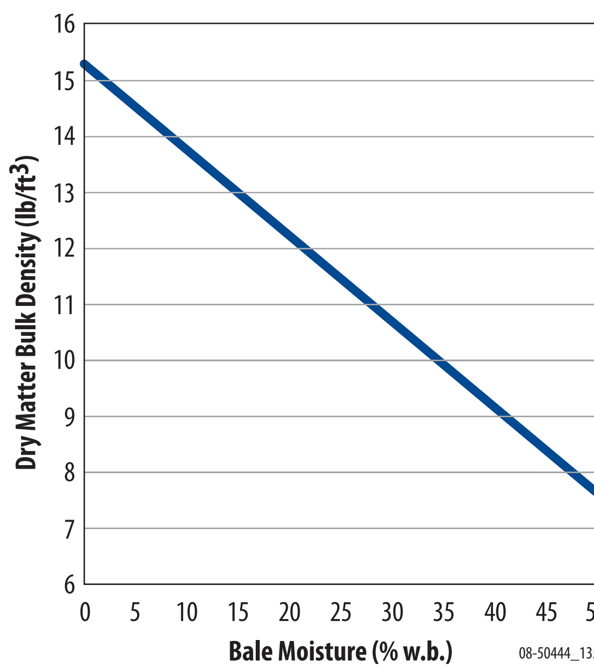


Figure 2-21. Effect of moisture on the bulk density of a 4×4×8-ft square bale needed to maximize truck load capacity. Example bale has a dry matter bulk density of 15.3 lb/ft^3, representative of a 53-ft flatbed tractor-trailer unit hauling 26 bales (Table 2-24).

2.3.2 Conventional Bale Transportation and Handling 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 field-side 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 (Tables 2-23 and 2-24). For a more detailed discussion of equipment and specifications used for this model, see Appendix B-1.

2.3.2.1 Equipment Capacity and Operational Efficiency

Transport and handling 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/hr, with an operational efficiency of 80% (Table B-3). The semi-tractor trailer is a 3-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/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 in Appendix A-5 to show their respective advantages and identify the variables that influence decisions to choose one system over the other

The variables of greatest impact on transportation and handling costs are the capacity of the transport container (variable cost contributor) and the efficiency of the handling equipment (fixed cost contributor) used to load the containers. The methodology in Appendix A-5 indicates that, in a comparison of semi-tractor trailer and rail car for transporting biomass, trucking has the lowest fixed costs but the highest variable costs of the two systems; thus, as the haul distance increases, maximizing transportation and handling processes and capacity is critical for keeping feedstock logistics costs down (Figure 2-22 and Table 2-24).

Table 2-24. *Transportation costs.*

Transportation Method	Cost ($/DM ton)
Truck	$\text{Cost} = 0.196 \times \text{Dist} + 4.33$
Rail[a]	$\text{Cost} = 0.034 \times \text{Dist} + 12.84$

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 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

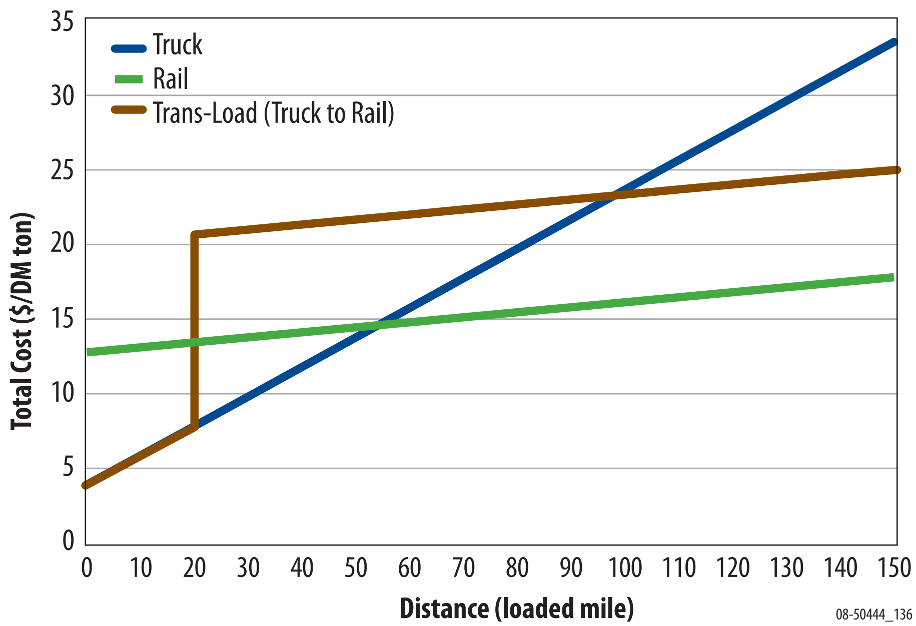


Figure 2-22. *Transportation cost comparison for truck and rail.*

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 2-25 illustrates the impacts on transportation cost for several truck configurations that accommodate different load limits. These same truck configurations are illustrated in Figure 2-20 for a visual comparison of their stacking arrangements.

Table 2-25. *Impacts on transportation cost for several truck configurations that accommodate different load limits.*

Truck Configuration	Load Limits: Length (ft)	Load Limits: GVW (lb)	Bale Count (ea)	Payload (lb)[a]	Transport Cost ($/loaded mile)	Transport Cost ($/DM ton)
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,e]	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.
e. Overall truck length limit. Actual load length is 95 ft.

2.3.2.2 Dry Matter Losses

Transportation and handling 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.

2.3.2.3 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-hr reserve supply in the bale yard as well as meeting the 24-hr/day supply demand of the preprocessing operation. With these constraints, the transportation and handling operations will run on an extended regular schedule of 14 hr/day, 6 day/wk, for a total of 350 day/yr. 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-hr 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 Transportation and Handling 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 2-26). These costs are reported in terms of DM tons entering the storage process.

2.3.3.2 Cost Sensitivity Analysis

A histogram of the transportation and handling cost (Figure 2-23) for corn stover shows with 90% confidence that the cost of the unit operation ranges between \$10.03 and \$14.16/DM ton. Further, the mean and standard deviation of this range is \$11.93 ± 1.25/DM ton. The mode value is \$11.95/DM ton, which closely represents the result of the static model (\$10.90/DM ton), since the defined value of the parameter distributions was set equal to the static value in the model.

Similarly, a histogram of the transportation and handling cost (Figure 2-24) for switchgrass shows with 90% confidence that the cost of the operation ranges between \$11.96 and \$16.61/DM ton, with the mean and standard deviation of this range being \$14.14 ± 1.43/DM ton. The mode value is \$13.51/DM ton, which closely represents the result of the static model of \$13.71/DM ton.

The overall costs associated with the Conventional Bale transportation and handling unit operation for both corn stover and switchgrass are provided in Table 2-27 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 2-26. *Static model costs for major Table 2-26. Static model costs for major transportation and handling equipment in the Conventional Bale–Corn Stover and Switchgrass scenarios.*

	Equipment	***Unstack/Unwrap, Load, and Clean-up*** ***Loader***	***Transport*** ***3-axle day cab with 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
	Dry Matter Loss Costs	N/A	N/A
	Energy Use (Mbtu/DM ton)	3.8	156

a. Installed capital costs are $/annual DM ton capacity.
b. Ownership costs include depreciation, interest, taxes, insurance, and housing (Appendix A-3, Table A-7).
c. Operating costs include repairs, maintenance, fuel, lubrication labor, and consumable materials (Appendix A-3, Table A-7).

Table 2-27. *Transportation and handling cost summary for the Conventional Bale–Corn Stover and Switchgrass scenarios.*

	Equipment	***Stacking***	***Transport***	***Total transportation and handling***
		Loader	***3-axle day cab with 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.

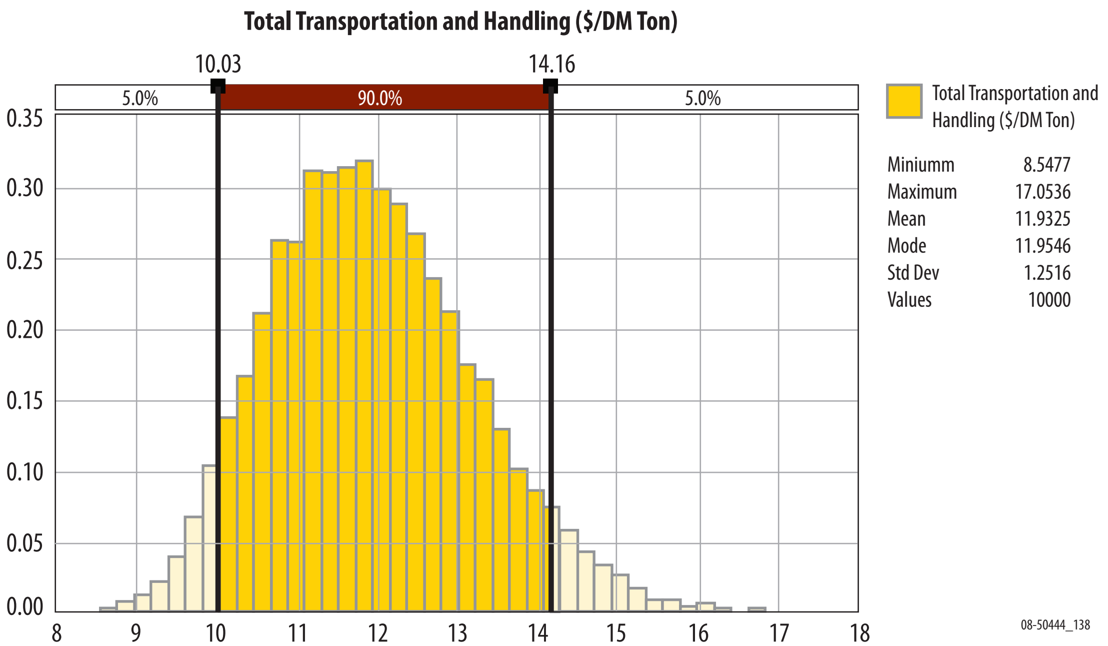


Figure 2-23. *Conventional Bale–Corn Stover transportation and handling cost distribution histogram from @Risk.*

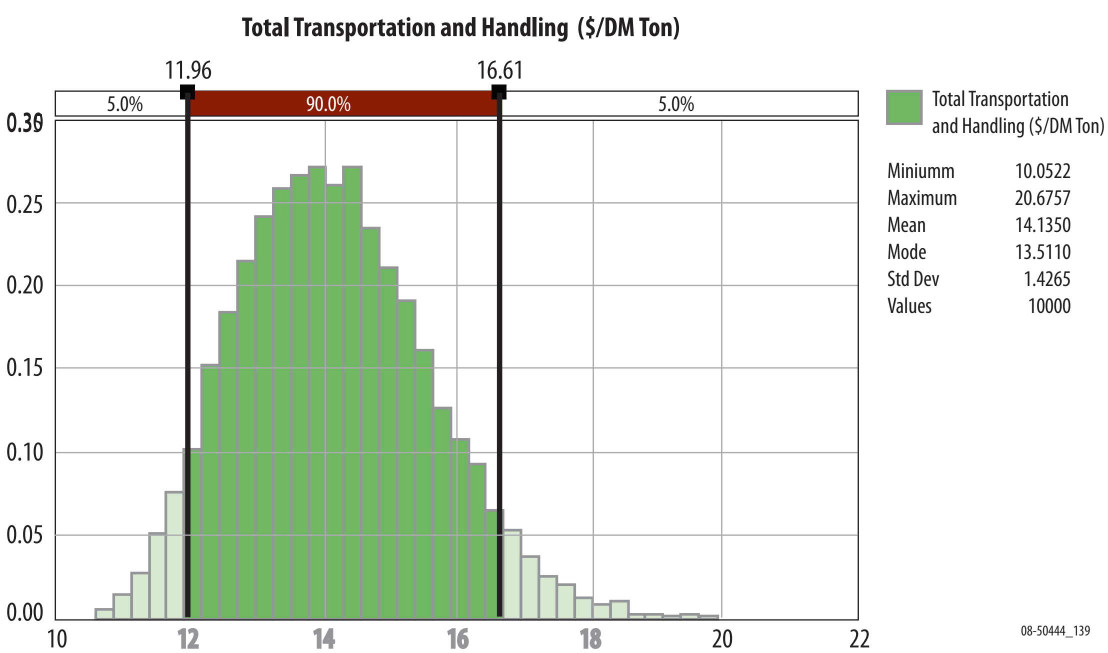


Figure 2-24*. Conventional Bale–Switchgrass transportation and handling cost distribution histogram from @Risk analysis.*

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 2-25). 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 2-25); 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 Section 3: Pioneer Implementation of the Uniform-Format Feedstock Supply System. 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. Equipment and format intermediate attributes modeled for the Conventional Bale corn stover and switchgrass scenarios are shown in Tables 2-28 and 2-29, respectively.

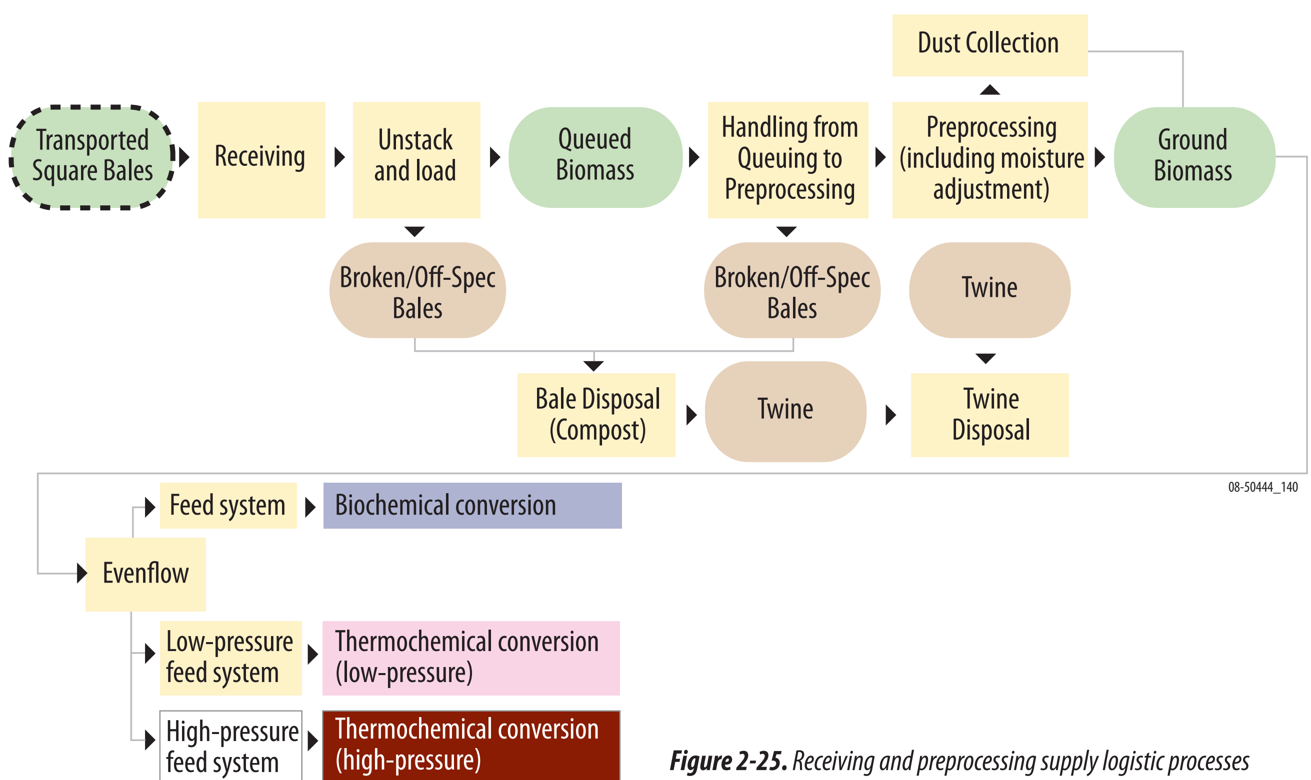


Figure 2-25. *Receiving and preprocessing supply logistic processes and biomass format intermediates. (Green ovals represent biomass format intermediates, tan ovals represent potential waste streams, yellow rectangles represent processes modeled in this report, and white rectangles represent processes not modeled in this report. The blue, pink, and red rectangles represent different conversion processes.)*

Table 2-28. *Equipment and format intermediate attributes modeled for the Conventional Bale–Corn Stover receiving, queuing, and preprocessing operation and estimated costs.*

Logistics Processes	***Receiving & Queuing***			***Preprocessing***				***Total Receiving & Preprocessing Costs***
Equipment	**Truck scales and asphalt storage**	**Self-propelled loader**	**Self-propelled loader**	**Grinder In-feed System**	**Horizontal Grinder**	**Dust Collection System**	**Surge Bin and Conveying Equipment**	
Format Intermediates	4×4×8-ft bales			Bulk (1.5-in. minus)				
Biomass Description	Stalk, cob, and husk (collectively stover)							
Capacity (DM ton/day)	2,600 (4,640 bales)[a]			2,600				
Bulk DM Density (lb/ft^3)	9			7.4				
Moisture (w.b.)	12%							
Modeled Cost Totals[b] ($/DM ton)	0.37 ± 0.01	0.84 ± 0.09	0.76 ± 0.04	1.54 ± 0.09	7.71 ± 0.96	1.76 ± 0.19	0.76 ± 0.05	13.74#± 1.31

a. Total tonnage and bale number for the bale-yard queue is the daily volume processed (24-hr period at 2,600 DM ton) multiplied by 3 days (72-hr queuing period), which equals a 7,800 DM ton queue-yard capacity, or about 14,000 bales.
b. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

Table 2-29. *Equipment and format intermediate attributes modeled for the Conventional Bale Switchgrass receiving, queuing, and preprocessing operation and estimated costs.*

Logistics Processes	***Receiving & Queuing***			***Preprocessing***				***Total Receiving & Preprocessing Costs***
Equipment	**Truck scales and asphalt storage**	**Self-propelled loader**	**Self-propelled loader**	**Grinder In-feed System**	**Horizontal Grinder**	**Dust Collection System**	**Surge Bin and Conveying Equipment**	
Format Intermediates	4×4×8-ft bales			Bulk (1.5-in. minus)				
Biomass Description	Switchgrass							
Capacity (DM ton/day)	2,600 (4,160 bales)[a]			2,600				
Bulk DM Density (lb/ft^3)	10				10.3	NA	10.3	
Moisture (w.b.)	12%			12%				
Modeled Cost Totals[b] ($/DM ton)	0.37 ± 0.01	0.76 ± 0.08	0.68 ± 0.04	1.54 ± 0.09	7.71 ± 0.95	1.76 ± 0.19	0.65 ± 0.04	13.47 ± 1.30

a. Total tonnage and bale number for the bale-yard queue is the daily volume processed (24-hr period at 2,600 DM ton) multiplied by 3 days (72-hr queuing period), which equals a 7,800 DM ton queue-yard capacity, or about 14,000 bales.
b. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

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 (Tables 2-29 and 2-30). 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 biorefinery. Just-in-time delivery minimizes the queuing capacity; nonetheless, a queuing system is 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 truckloads of 26 bales each will be received daily within a 14-hr operating window, and over the full 24-hr period, 4,000 to 5,000 bales will be removed from the bale-yard queue and preprocessed for conversion (Tables 2-29 and 2-30). 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-hr 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.

After the trucks arrive at the bale yard and are weighed, they are unloaded directly into a queue yard stack (Figure 2-26a). 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 ton (as received), and each stack is separated by a 20-ft clearance, as required by the International Fire Code (ICC 2003) (Figure 2-26b). 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

Figure 2-26. *Receiving and queuing 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.*

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 ton because stacks are built in multiples of 10 or 20 bales. (Note the difference in corn stover and switchgrass bale counts in Tables 2-29 and 2-30).

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 2-27). 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 2-31).

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 2-28).

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 significant issues 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).

Figure 2-27. *Images of corn stover and switchgrass feedstocks preprocessed through a nominal 1.5-in. minus grinder screen.*

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 2-29a). 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.

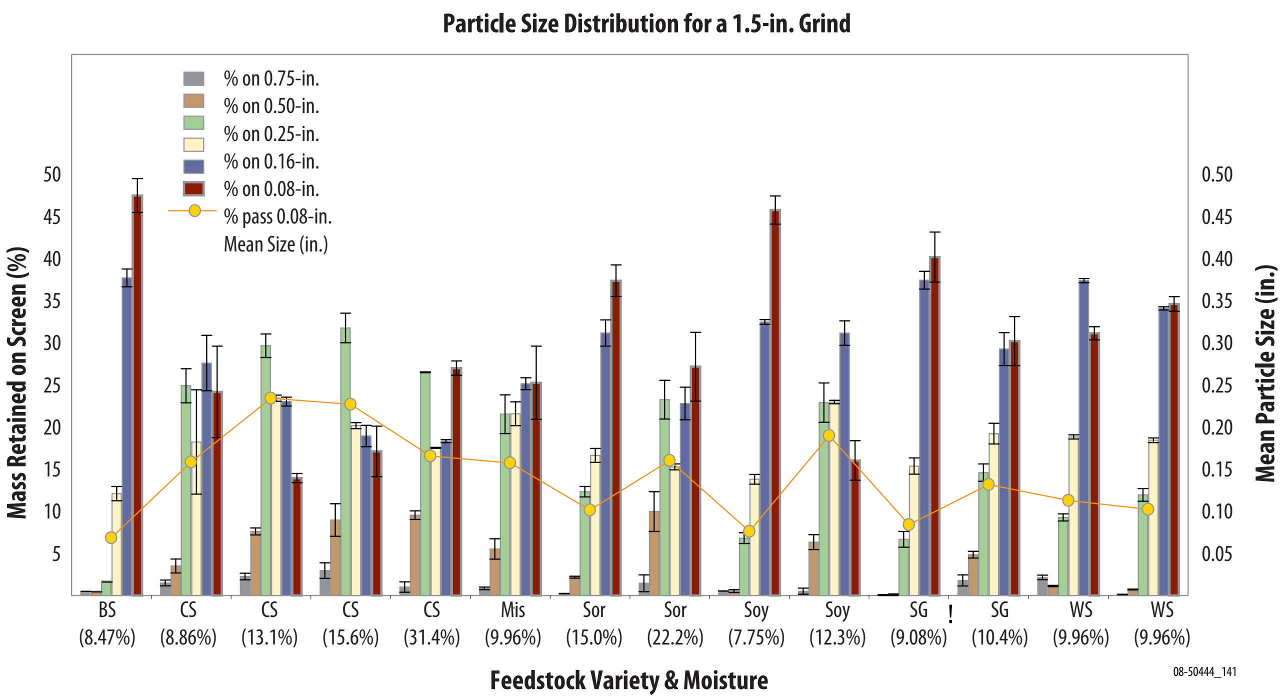


Figure 2-28. *Mean particle size and particle-size distribution for different feedstock varieties at different moistures (% w.b.). Feedstocks represented include barley straw (BS), corn stover (CS), miscanthus (Mis), grain sorghum stover (Sor), soybean stubble (Soy), switchgrass (SG), and wheat straw (WS). Mean particle size and distribution was determined using a forage particle separator ([ANSI/ASAE S424.2] ASABE 2007).*

Table 2-30. *Corn stover and switchgrass characterization after the Conventional Bale preprocessing operation.*

Feedstock (1.5-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 (lb/ft^3)	10.3 (lb/ft^3)
Compressibility (Δ% 0-500 lb/ft^2)	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 2-29b). 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 2-29).

Figure 2-29. *Corn stover (a) and switchgrass (b) ground with a tub grinder through a 1.5-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 2-30). 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.

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 2-31). 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 Implementation of the "Uniform-Format" Vision.

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 lb/ft^3, and after grinding, the feedstock bulk material bulk density declines to 7.4 lb/ft^3 (Tables 2-2 and 2-30). Switchgrass is received in a bale at a bulk density of 10 lb/ft^3, and after grinding to a bulk format, switchgrass remains at 10 lb/ft^3 (Tables 2-3 and 2-30). To get ground corn stover to exhibit similar bulk densities as switchgrass, additional preprocessing is required.

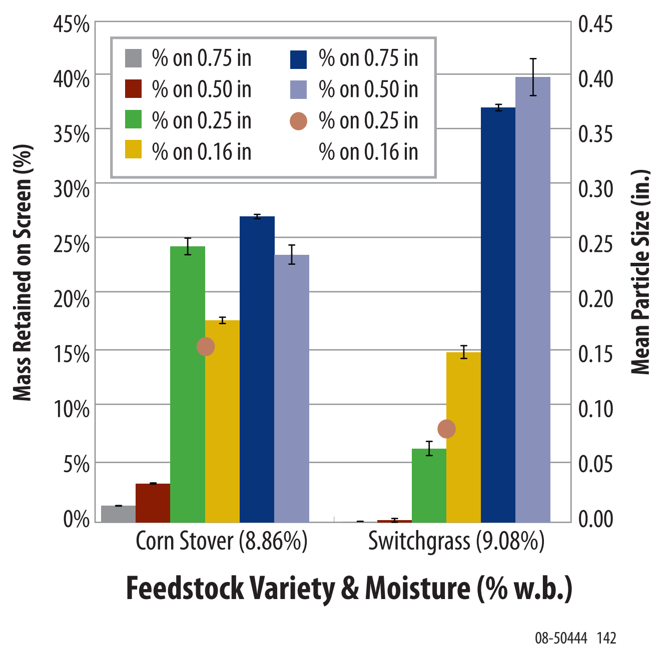


Figure 2-30. *Mean particle size and particle-size distribution for corn stover and switchgrass at the noted moisture (% w.b.). Mean particle size and distribution were determined using a forage particle separator ([ANSI/ASAE S424.1] ASABE 2007).*

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.

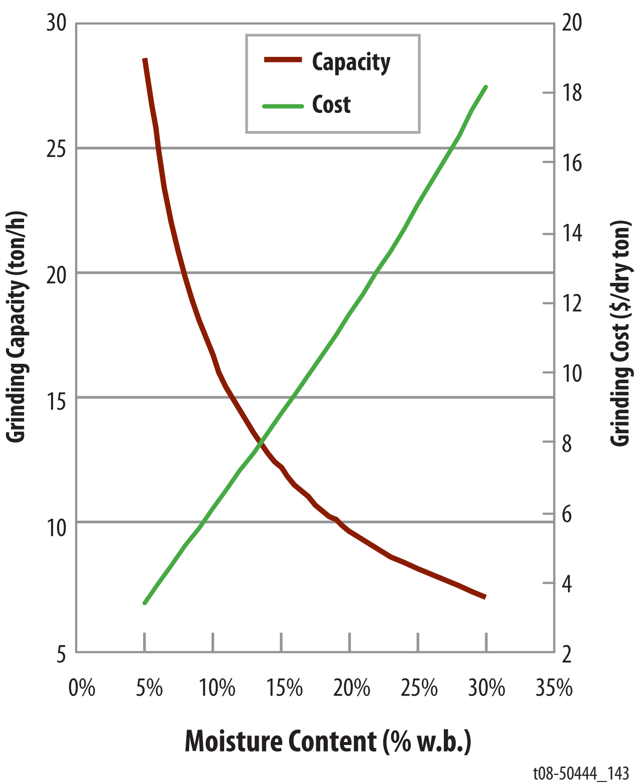


Figure 2-31. *Relationship between biomass moisture content at the time of grinding and both grinding capacity and grinding cost taken from the Chariton Valley Biomass Project (Antares 2008) data and the INL feedstock supply system model.*

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 (maximum 72 hr) 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 (Figure 2-31). 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 2-38). 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.

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.

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. For a more detailed discussion of equipment and specifications used for this model, see Appendix B-1.

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.

A telehandler 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 2-33. An important note with this particular layout is that it satisfies all current international fire

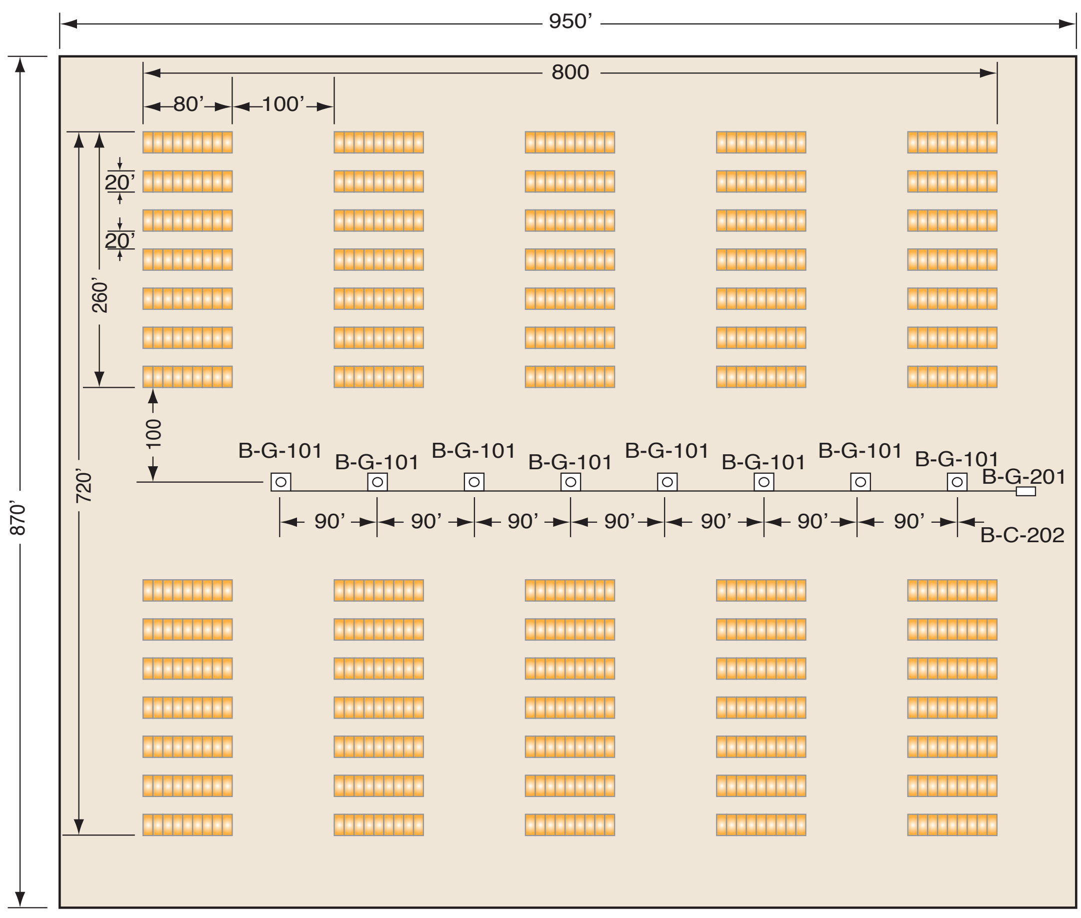


Figure 2-32. *Bale receiving layout.*

codes regulating aggregated biomass. Within this configuration, up to 7,000 tons of biomass can be stored at any given time.

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. For a more detailed discussion of equipment and specifications used for this model, see Appendix B-1.

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.).

Figure 2-33. *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).*

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 2-33). 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.

2.4.2.1 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 the efficiency of this design is broken bales. Altering the design to an 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 2-31).

Table 2-31. *Grinder capacities and power ratios for different types of feedstock varieties.*

	Capacity (DM ton/hr)	Capacity (DM ton/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

2.4.2.2 Dry Matter Losses

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 2-34). For the most part, the economic impact alone will require a mitigation strategy to be developed and implemented.

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 B-12). 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.

Figure 2-34. *Dust emissions as corn stover bales are preprocessed in a tub grinder.*

2.4.2.3 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 hr/day, 6 day/wk. This schedule will allow receiving to provide bales to the both the bale queuing yard to maintain the prescribed 72-hr 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 hr/day, 350 day/yr.

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 2-32). These costs are reported in terms of DM tons entering each process.

Table 2-32. *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**	**Loader**	**Grinder in-feed system**	**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 2-35) for corn stover shows with 90% confidence that the cost of the unit operation ranges between $11.90 and $16.13/DM ton. Further, the mean and standard deviation of this range is $13.74 ± 1.31/DM ton. The mode value of the receiving and preprocessing cost is $13.16/DM ton. This value closely represents the result of the static model, which is $12.95/DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

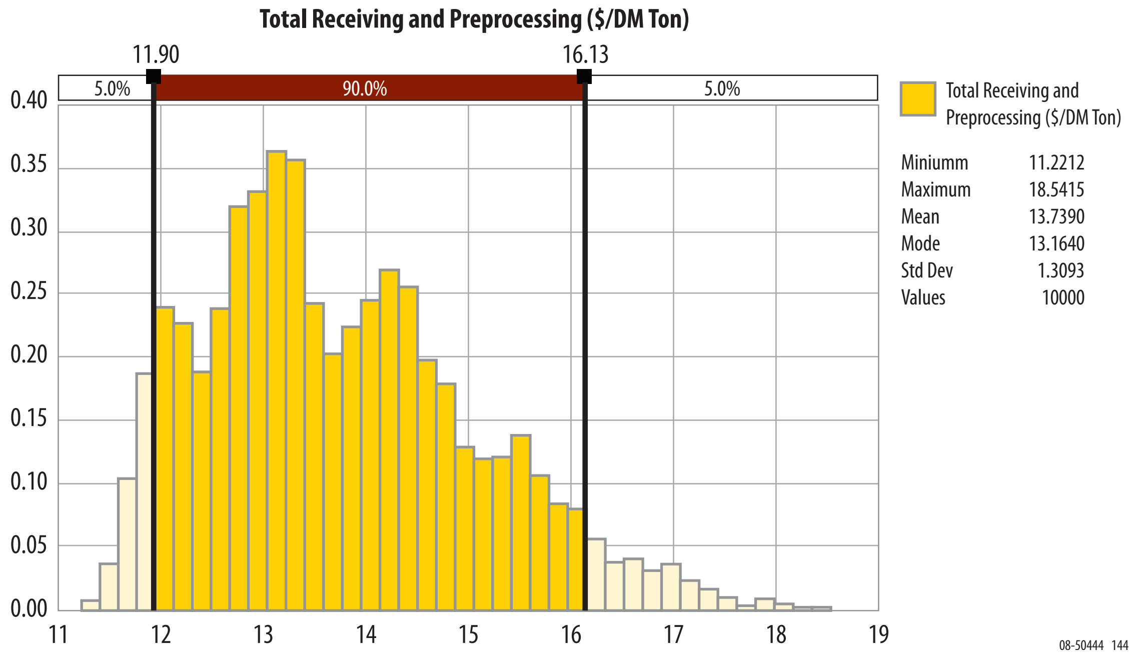


Figure 2-35. *Conventional Bale–Corn Stover receiving and preprocessing cost distribution histogram from @Risk analysis.*

Similarly, a histogram of the receiving and preprocessing cost (Figure 2-36) for switchgrass shows that with 90% confidence the cost of the unit operation ranges between $11.65 and $15.84/DM ton with the mean and standard deviation of this range being $13.47 ± 1.30/DM ton. The mode value of this cost range is $13.08/DM ton, which closely represents the result of the static model of $12.69/DM ton.

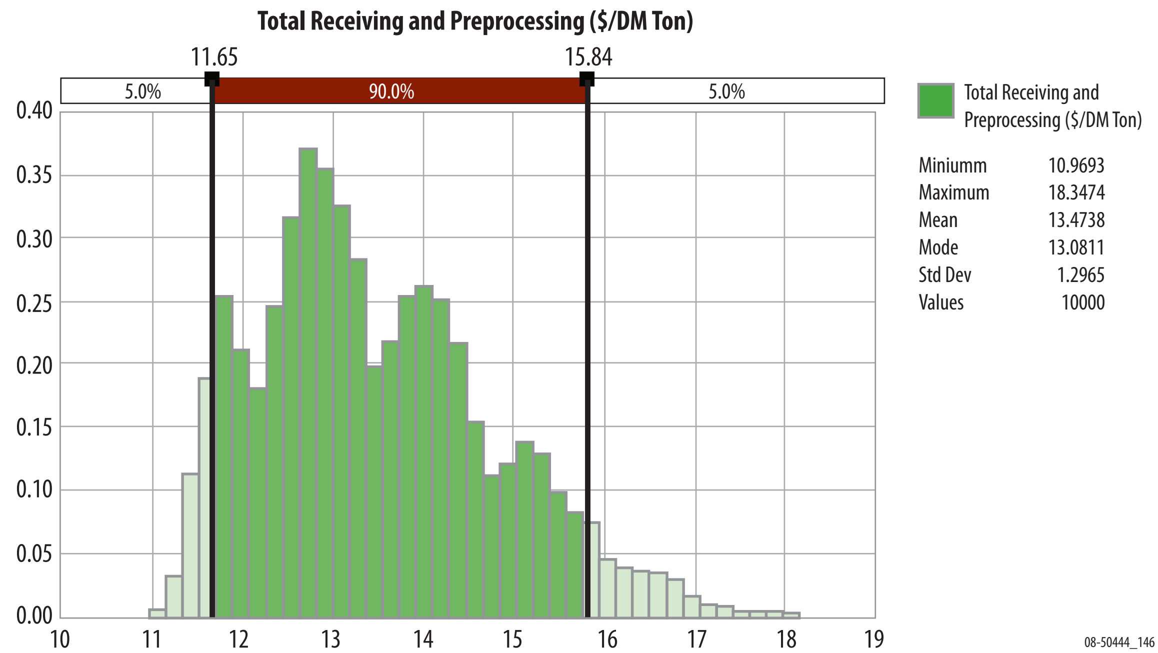


Figure 2-36. *Conventional Bale–Switchgrass receiving and preprocessing cost distribution histogram from @Risk analys.*

The overall costs associated with the Conventional Bale receiving and preprocessing unit operation for both corn stover and switchgrass are provided in Table 2-33 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 2-33. *Receiving and preprocessing modeled costs summary for the Conventional Bale–Corn Stover and Switchgrass scenarios.*

Receiving		***Preprocessing***				***Conversion Feed System***	***Total Receiving and Preprocessing***
Truck scales and asphalt storage	**Loader**	**Loader**	**Grinder in-feed system**	**Horizontal grinder**	**Dust collection system**	**Surge bin and conveying equipment**	
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)
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)

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 that 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 2-37, provide a ranking of input parameters according to the magnitude of their influence on the delivered feedstock cost.

Based on the ranking of input variables, resulting from the single-point sensitivity analysis, we then defined each parameter's uncertainty using a probability distribution. 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.

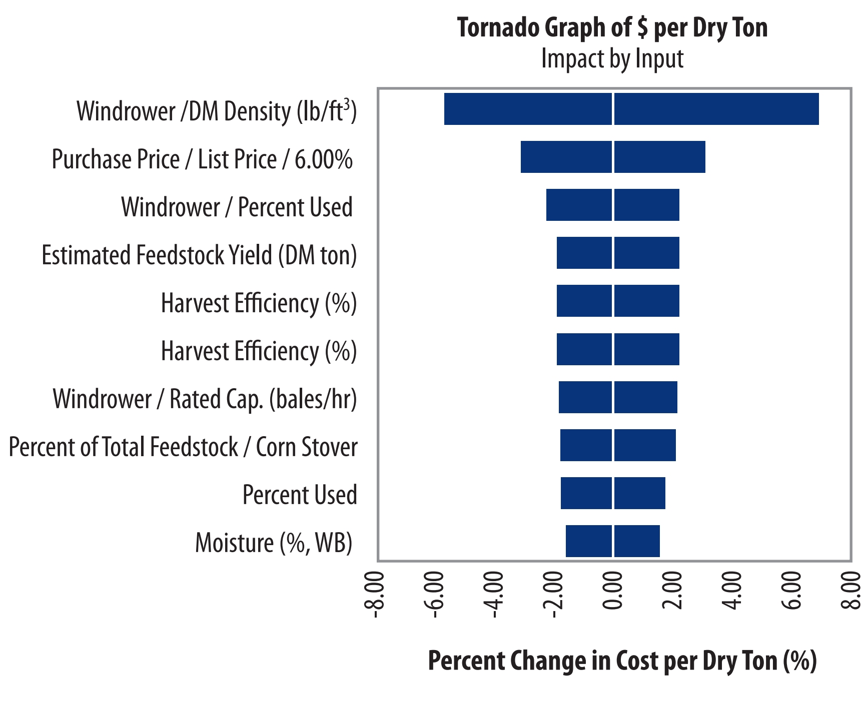


Figure 2-37. *Tornado chart of input parameters.*

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 (Table A-12), and the resulting total delivered feedstock cost as well as the incremental feedstock costs throughout each stage (five 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-4, "Sensitivity Analysis."

A histogram of the final cost for delivered corn stover to the throat of the conversion reactor at a biorefinery (Figure 2-38) shows with 90% confidence that the cost ranges between \$48.93 and \$62.94/DM ton. Further, the mean and standard deviation of this range is \$55.40 ± 4.31/DM ton. The mode value of the final cost is \$53.70/DM ton. This value closely represents the result of the static model, which is \$51.88/DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

Similarly, a histogram of the final cost for delivered switchgrass to the throat of the conversion reactor at a biorefinery (Figure 2-39) shows with 90% confidence that the cost ranges between \$44.59 and \$55.12/DM ton with the mean and standard deviation of this range being \$49.61 ± 3.20/DM ton. The mode value of the final cost is \$49.62/DM ton, closely representing the static model result of \$48.79/DM ton.

The probability curves of the total delivered feedstock cost (Figures 2-38 and 2-39) 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/DM ton.

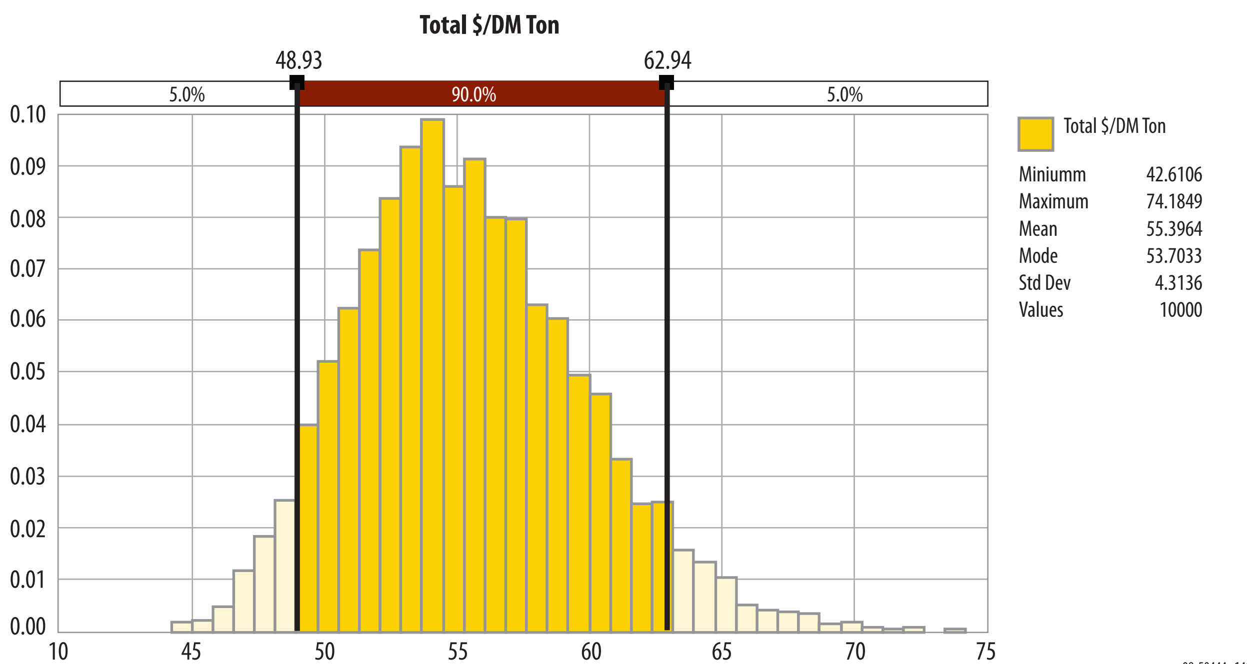


Figure 2-38. *Total Conventional Bale–Corn Stover supply system design cost distribution histogram from @Risk analysis.*

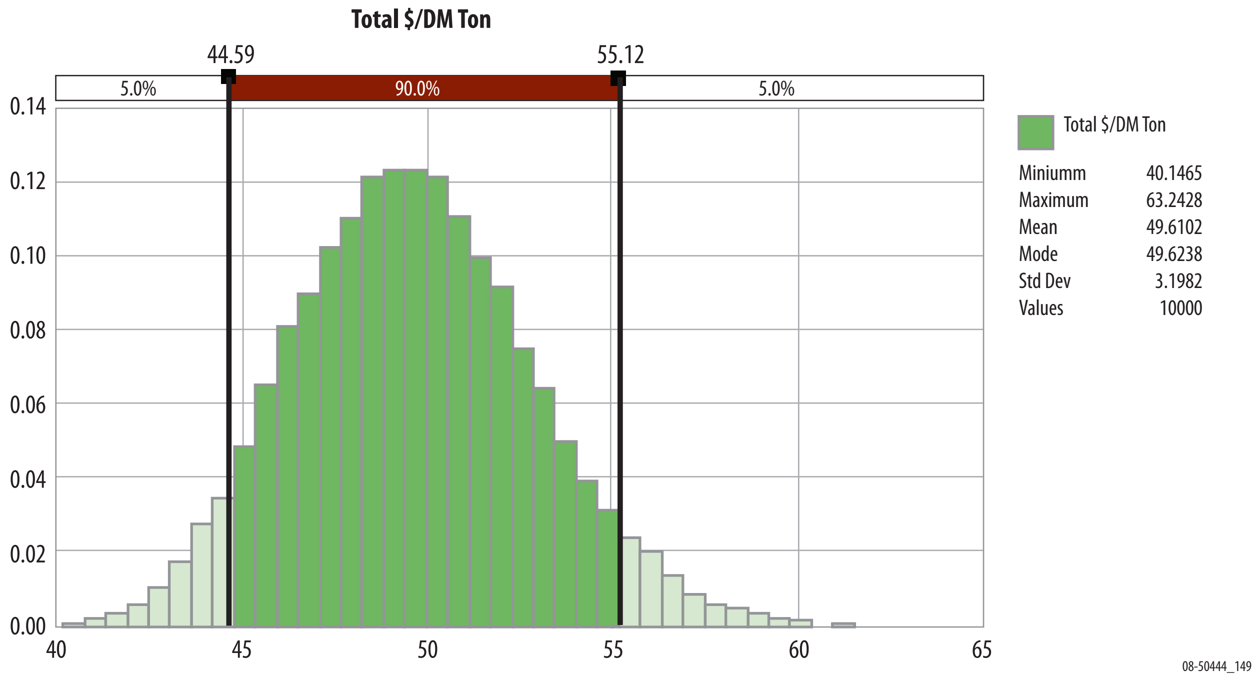


Figure 2-39. *Total Conventional Bale–Switchgrass supply system design cost distribution histogram from @Risk analysis.*

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 2-40, 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 2-40). 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.

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 2-41). 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 2-42).

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

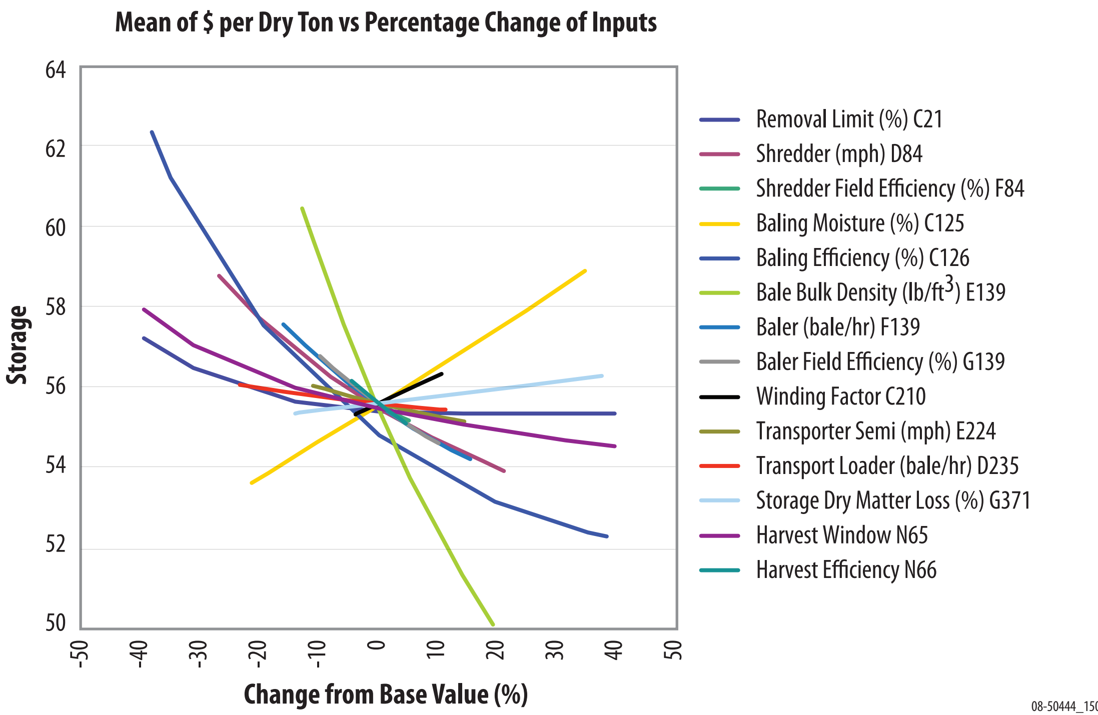


Figure 2-40. *Percent change of variable to output.*

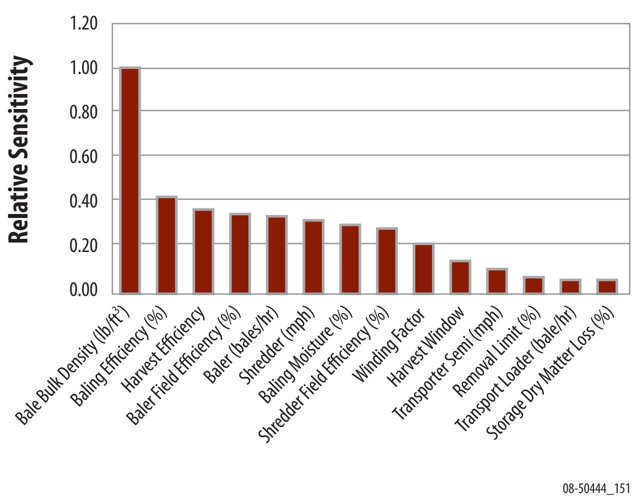


Figure 2-41. *Relative sensitivity of individual supply system parameters.*

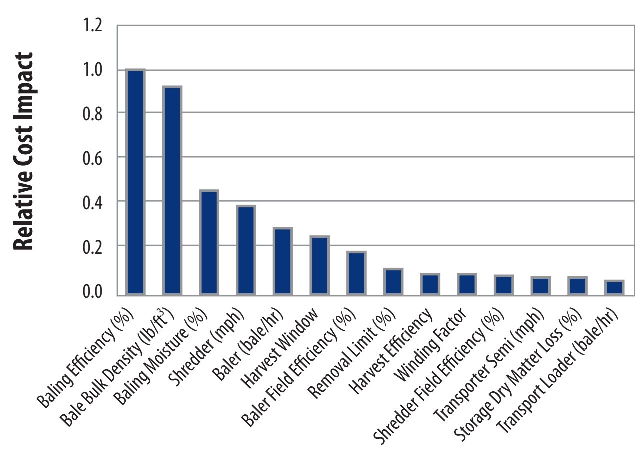


Figure 2-42. *Relative cost impact of individual supply system parameters.*

parameter in terms of its potential influence on feedstock cost (Figure 2-41), but it ranks among lowest (ninth in Figure 2-42) 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 2-41 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 2-42 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 2-43. The tornado chart shows that baler field losses, bale bulk density, and bale moisture are the top three parameters in order of decreasing uncertainty.

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 2-44), affecting harvest and collection, transportation and handling, 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 2-44). 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

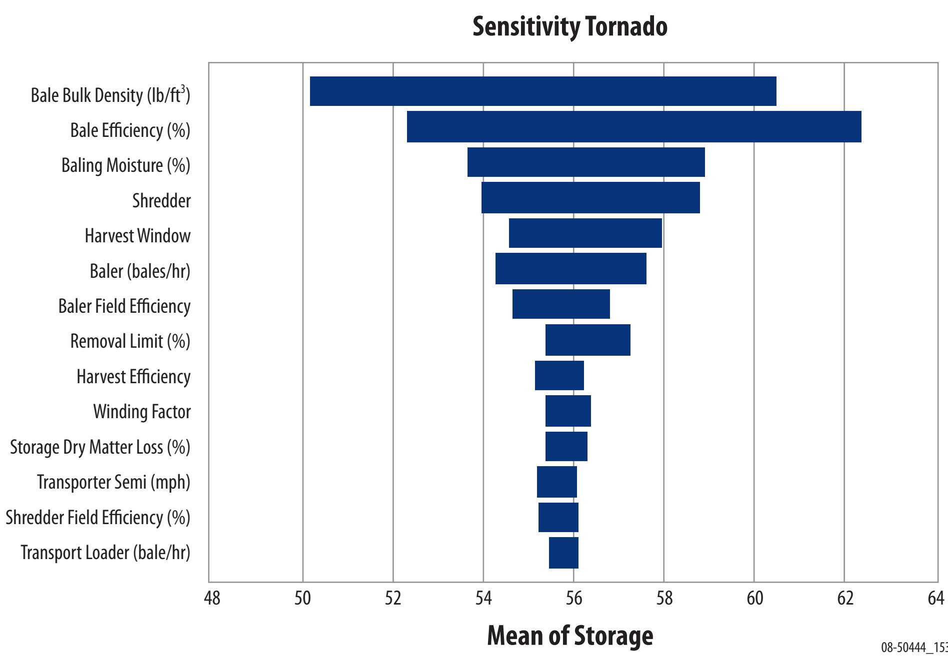


Figure 2-43. *Tornado chart reflecting the final cost in dollars according to the distribution ranges defined.*

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 2-31).
- 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.

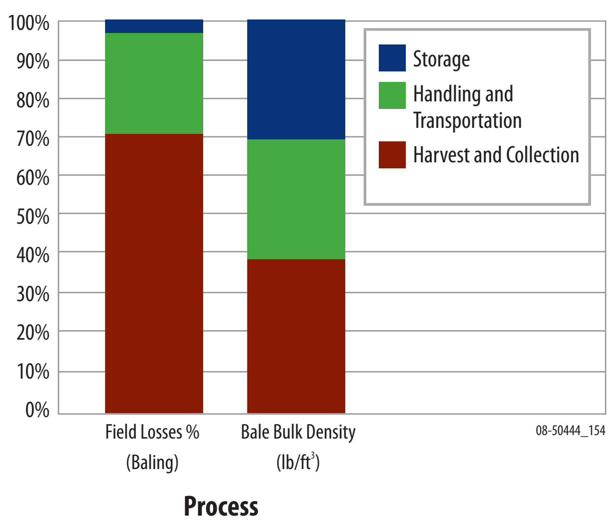


Figure 2-44. *Effect of baling efficiency on supply chain processes.*

2.6 CONCLUSIONS

The Conventional-Bale design represents feedstock supply system technologies, costs, and logistics that are achievable today for supplying lignocellulosic feedstocks to first generation biorefineries. The general architecture of these designs locates the preprocessing operation inside the biorefinery receiving gate (Figure 2.1). Since each biorefinery will be designed to accept a specific local feedstock(s), the burden of adapting to the diverse feedstock resources is assumed primarily by the biorefinery. The modeled feedstocks for this design 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. The parameters identified in this study as having the greatest impact on supply system costs and opportunities for optimization can be grouped into two general categories: Equipment Efficiency (shredder field speed, baler capacity, harvest window, and baling efficiency) and Material Properties (bulk density and moisture content). Each parameter influences processes throughout the supply system and provides opportunities for system improvement in each unit operation.

A sensitivity analysis was performed to determine variations of individual variables with respect to the entire integrated system (Section 2.5). This analysis was performed by uniformly varying all input variables by ±10% of the base value, and then identifying and ranking all input factors that affect the final delivered feedstock cost. Based on this ranking, the uncertainty of each parameter was defined using a probability distribution. The probability distribution represents either the inherent variability or the uncertainty of the respective input variables, as determined by the variability in collected field data, published data, or range of operating parameters suggested by skilled operators of the equipment. The benchmark values used in the Conventional Bale Stover model were derived from the most likely value included in each distribution. A more sophisticated Monte Carlo uncertainty analysis was then 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.

A key finding of this Monte Carlo analysis is that the Conventional Bale Stover supply system design is not able to achieve cost performance targets. Further analysis defined and ranked critically the supply system equipment and biomass material parameters that must be addressed to achieve cost targets. The simulation also produced a ranking of input parameters based on the statistical relationship between each parameter and the total supply chain logistics costs to determine the impact of each parameter individually, and capture the interdependence of each respective input parameter. Comparing the rankings of individual input parameters shows that although the feedstock cost may be highly sensitive to changes in the value of a specific variable (Figure 2-41), the uncertainty or variability of that parameter may be small, and the corresponding impact on cost is small as well (Figure 2-37). 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 2-42), but it ranks among the lowest (9th in Figure 2-42) 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 Stover design, the rankings in Figure 2-41 would be most relevant; however, if the objective of the sensitivity analysis of the Conventional Bale Stover design is to quantify the uncertainty in the design, the rankings shown in Figure 2-42 are most relevant. Finally, the cause-and-effect relationships of top cost impact parameters were examined (Figure 2-42). Baling efficiency had the largest influence on harvest and collection (Figure 2-44). This influence is fairly intuitive because it directly impacts the net biomass yield. As baling efficiency increases, net biomass yield increases. The effect of increasing biomass yield decreases per ton baling costs, as well as transportation cost. The change in per ton baling costs also has a cascading effect on the DM loss value of subsequent unit operations, and thus the impact shown in storage (Figure 2-44). Changes in bale bulk density demonstrated a near-equal impact on harvest and collection, storage, and transportation and handling (Figure 2-44).

Although the affect of bale moisture can be very significant throughout the feedstock supply system, the modeled assumption that the corn stover is able to field dry to 12% moisture limited the impact of moisture to grinding capacity in the preprocessing unit operation. Higher and larger variations in moisture cannot only impact supply system costs, but also increase the risk of catastrophic failures in supply systems (Hess et al. 2009). The next four parameters—shredder field speed, baler capacity, harvest window, and baler field efficiency—are all related to machine capacity, which is an obvious parameter affecting feedstock costs. Increasing machine productivity without a proportionate increase in machinery costs improves supply system cost performance. The uncertainty of the remaining parameters was not large enough to create significant cost impacts to the supply system. The Conventional Bale—Stover feedstock supply system is a design that can be implemented by a lignocellulosic biorefinery with little to no modifications to readily available forage equipment. Major opportunities to optimize conventional bale biomass feedstock supply systems for biorefining include improvements in equipment efficiency and capacity (Figure 2-44) and reduction of biomass losses in harvesting and collection and storage.

2.7 REFERENCES

Aden A, M Ruth, K Ibsen, J Jechura, K Neeves, J Sheehan, B Wallace, L Montague, A Slayton, J Lukas (2002) Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover, NREL/TP-510-32438, http://www.nrel.gov/docs/fy02osti/32438.pdf, verified January 17, 2008.

Adler PR, MA Sanderson, AA Boateng, PJ Weimer (2004) Harvest Management of Switchgrass in Pennsylvania for Yield and Biofuel Quality. Barnes TG, Kiesel LR, editors. Proceedings of the Fourth Eastern Native Grass Symposium, October 3-6, 2004, Lexington, Kentucky. 87-95.

Antares Group, Inc. (2008) Final Project Technical Report, Chariton Valley Biomass Project.

ASABE (American Society of Agricultural and Biological Engineers) (2004) Terminology for Combines and Grain Harvesting. ANSI/ASAE S343.3.

ASABE (American Society of Agricultural and Biological Engineers) (2006a) Agricultural Machinery Management. ASAE EP496.3.

ASABE (American Society of Agricultural and Biological Engineers) (2006b) Agricultural Machinery Management Data. ASAE D497.5.

ASABE (American Society of Agricultural and Biological Engineers) (2007) Method of Determining and Expressing Particle Size of Chopped Forage Materials by Screening. ANSI/ASAE S424.1 (March 1992, reaffirmed January 2007).

Beuchat LR (1983) Influence of Water Activity on Growth, Metabolic Activities, and Survival of Yeasts and Molds. Journal of Food Protection 46(2): 135-141.

Brady KC, P O'Kiely, PD Forristal, H Fuller (2005) Schizophyllum Commune on Big-Bale Grass Silage in Ireland. Mycologist, 19, 30-35.

Buckmaster DR, CA Rotz, RE Muck (1989) A Comprehensive Model of Forage Changes in the Silo. Transactions of the ASAE 32(4):1143-1152.

Clark S (1993) Silo and Hay Mow Fires on your Farm. Ministry of Agriculture, Ontario. http://www.omafra.gov.on.ca/english/engineer/facts/93-025.htm#Fire%20Danger%20Zone, verified April 1, 2010.

Cundiff JS, R Grisso, PP Ravula (2004) Management System for Biomass Delivery at a Plant Conversion. Paper No. 046169. 2004 ASAE/CSAE Annual International Meeting Sponsored by ASAE/CSAE Fairmont Chateau Laurier, The Westin, Government Centre Ottawa, Ontario, Canada.

De Lucca II AJ, TE Cleveland, DE Wedge (2005) Plant-derived antifungal proteins and peptides. Canadian Journal of Microbiology, 51:1001-1014.

Dien BS, HG Jung, KP Vogel, MD Casler, JF Lamb, LB Iten, R Mitchell, G Sarath (2006) Chemical composition and response to dilute-acid pretreatment and enzymatic saccharification of alfalfa, reed canarygrass, and switchgrass. Biomass and Bioenergy, 30:880-891.

Grant D (2003) Custom Baling and Transportation Rates and Straw Price Marketing Data for Jerome, Idaho Dairy Straw Market. Personal communication. Grant 4-D Farms, Rupert, Idaho.

Gray BF, JF Griffiths, SM Hasko (1984) Spontaneous Ignition Hazards in Stockpiles of Cellulosic Materials: Criteria for Safe Storage. J. Chem. Tech. Biotechnol, 34A:453-463.

Hess JR, KL Kenney, CT Wright, R Perlack, and A Turhollow (2009) Corn Stover Availability for Biomass Conversion: Situation Analysis. Cellulose, 16:599-619.

Hess JR, K Kenney, P Laney, D Muth, P Pryfogle, C Radtke, C Wright (2006) Feasibility of a Producer Owned Ground-Straw Feedstock Supply System for Bioethanol and Other Products, INL/EXT-06-11815.

Harwood DW, DJ Torbic, KR Richard, WD Glauz, L Elefteriadou (2003) National Cooperative Highway Research Program (NCHRP) Report 505, Review of Truck Characteristics as Factors in Roadway Design. Transportation Research Board (TRB) of the National Academies. Washington, D.C. http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_rpt_505.pdf, verified April 1, 2010

Hoskinson RL, DL Karlen, SJ Birrell, CW Radtke, WW Wilhelm (2007) Engineering, Nutrient Removal, and Feedstock Conversion Evaluations of Four Corn Stover Harvest Scenarios, Biomass and Bioenergy, Vol. 31, 126-136.

ICC (International Code Council) (2003) International Fire Code. International Code Council, Inc.

Kenney KL (2008) tech memo on review of cob harvest systems.

Knapp WR, DA Holt, VL Lechtenberg (1974) Anhydrous Ammonia and Propionic Acid as Hay Preservatives. Agronomy Journal 66, 823-824.

Knapp WR, DA Holt, VL Lechtenberg (1975) Hay Preservation and Quality Improvement by Anhydrous Ammonia Treatment. Agronomy Journal 67, 766-769.

Knapp WR, DA Holt, VL Lechtenberg (1976) Propionic Acid as Hay Preservative. Agronomy Journal 68, 120-123.

McDonald P, N Henderson, S Heron (1991) Microorganisms. The Biochemistry of Silage, 2nd ed. Chalcombe Publications, Marlow, Bucks GB.

NFPA (2006, 2007, 2008) http://www.nfpa.org/categoryList.asp?categoryID=124&URL=Codes%20&%20Standards. Accessed April 13, 2010.

ORNL (Oak Ridge National Laboratory) Bioenergy Conversion Factors. Oak Ridge National Laboratory Bioenergy Feedstock Development Program. http://bioenergy.ornl.gov/papers/misc/energy_conv.html, verified April 1, 2010.

Osbourn AE (1996) Preformed Antimicrobial Compounds and Plant Defense against Fungal Attack. The Plant Cell 8:1821-1831.

Phillips S, A Aden, J Jechura, D Dayton, T Eggeman (2007) Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass, NREL Technical Report, TP 510-41168, National Renewable Energy Laboratory, Golden, Colorado.

Pordesimo LO, S Sokhansanj, WC Edens (2004) Moisture and Yield of Corn Stover Fractions Before and After Grain Maturity. 2002 ASAE Annual Meeting, Chicago, Illinois, July 28-31, 2002. Transactions of the ASAE 47 (5).

Radtke C, DB Blackwelder, JR Hess (2005) Determine Optimum Storage Format in Terms of Cost, Shrinkage, and Feedstock Quality. INL-FY05-M7. Idaho National Laboratory.

Richey CB, JB Liljedahl, VL Lechtenberg (1982) Corn Stover Harvest for Energy Production. Transactions of the ASAE 1982 25(4):834–44.

Rider AR, SD Barr, AW Pauli (1993) Hay and Forage Harvesting. FMO Fundamentals of Machine Operation. 4th Ed. Illinois: Deere & Company.

Roberts CA (1995) Microbiology of Stored Forages. Post-Harvest Physiology and Preservation of Forages: Proceedings of a symposium sponsored by C-6 of the Crop Science Society of America. American Society of Agronomy, Madison, WI.

Rooney J (2008) Moisture Content Requirements for Contract Purchase of Wheat. General Mills, Inc. Procurement Division, Idaho Falls, Idaho. Personal Communication. October 14, 2008.

Rotz CA (2003) How to Maintain Forage Quality during Harvest and Storage. Advances in Dairy Technology 15, 227-239.

Rotz CA (2003) Presented at the Western Canadian Dairy Seminar.

Rotz CA (2004) Management to reduce nitrogen losses in animal production. J. Anim. Sci. 82:E119 E137.

Ruth MF, SR Thomas (2003) The Effect of Corn Stover Composition on Ethanol Process Economics, http://www1.eere.energy.gov/biomass/pdfs/34040.pdf, verified April 1, 2010, Golden, CO.

Searcy E and P Flynn (2008) The impact of biomass availability and processing cost on optimum size and processing technology selection, Applied Biochemistry Biotechnology, DOI 10.1007/s12010-008-8407-9.

Searcy E, P Flynn, E Ghafoori, A Kumar (2007) The Relative Cost of Biomass. Applied Biochemistry and Biotechnology. Vol 137-140.

Shinners KJ, BN Binversie (2007) Fractional Yield and Moisture of Corn Stover Biomass Produced in the Northern U.S. Corn Belt. Biomass and Bioenergy 31(8) doi:10.1016/j.biombioe.2007.02.002.

Shinners KJ, BN Binversie, RE Muck, PJ Weimer (2006a) Comparison of Wet and Dry Corn Stover Harvest and Storage, Biomass and Bioenergy 31: 211-221.

Shinners KJ, GC Boettcher, RE Muck, PJ Weimer, MD Casler (2006b) Drying, Harvesting, and Storage Characteristics of Perennial Grasses as Biomass Feedstocks, 2006 ASABE Annual International Meeting, Portland, Oregon, July 9-12, 2006, American Society of Agricultural and Biological Engineers, Paper number: 061012.

Sokhansanj S, LO Pordesimo (2002) Adaptation of forage handling systems for collecting biomass feedstock. ASAE 026060 paper presented at the ASAE International Meeting/CIGR XVth World Congress, Chicago, IL, MI:ASAE.

Troller JA, JHB Christian (1978) Water Activity: Basic Concepts. Water Activity and Food. New York: Academic Press. 1-12.

Ullrey DE (1997) Hay Quality Evaluation. Nutrition Advisory Group Handbook. Fact Sheet 001. www.nagonline.net/Technical%20Papers/NAGFS00197Hay-JONIFEB24,2002MODIFIED.pdf.

USDA-NASS (U.S. Department of Agriculture-National Agricultural Statistics Service) (2009). http://www.nass.usda.gov. Accessed December 15, 2009.

Venturi P, A Monti, I Piani, G Venturi (2004) Evaluation of harvesting and post harvesting techniques for energy destination of switchgrass. Proceedings of the 2nd Conference on Biomass for Energy, Industry, and Climate Protection, 10-14 May 2004, Rome. Editors: W.P.M. Van Swaaij et al. 234 236.

Vincelli P, DE Hershman (1997) Kentucky Plant Disease Management Guide for Corn and Sorghum. PPA-10a, University of Kentucky College of Agriculture. http://www.ca.uky.edu/agc/pubs/ppa/ppa10a/ppa10a.pdf, verified January 17, 2008.

Wilcke B, G Cuomo, C Fox (1999) Preserving the Value of Dry Stored Hay. Communication and Educational Technology Services, University of Minnesota Extension. FO-07404-GO. http://www.extension.umn.edu/distribution/cropsystems/DC7404.html.

Wright CT, PA Pryfogle, NA Stevens, ED Steffler, JR Hess, TH Ulrich (2005) Biomechanics of Wheat/Barley Straw and Corn Stover. Applied Biochemistry and Biotechnology 121-124 (Spring): 5 19.

3. PIONEER "UNIFORM-FORMAT" FEEDSTOCK SUPPLY SYSTEM

The Pioneer Uniform-Format (Pioneer Uniform) feedstock supply system design introduces forward-deployed preprocessing that occurs at distributed locations established by a group of growers, an independent business entity, or the biorefinery (Figure 3-1). These distributed preprocessing locations are referred to as depots and encompass a number of operations, including short- to medium-term storage; preprocessing activities such as size reduction, separation, and densification; biomass queuing; and loading of transportation systems.

The Pioneer Uniform supply system design addresses three fundamental constraints of the Conventional Bale supply system: (1) producers are limited to use of a particular biomass bale format and/or biomass resources that can be baled; (2) there are inefficiencies in handling and transport of biomass of multiple sizes, shapes, and bulk densities; and (3) multiple, capital-intensive feed systems at the front end of the biorefinery limit the transferability of biorefinery designs from one location to another. The Pioneer Uniform feedstock supply system design models five scenarios (Table 3-1):

Similar to the discussions presented in the Conventional Bale supply system (Section 2), the following section describes the impact of feedstock format intermediates and machinery on each unit operation in the order it occurs within the Pioneer Uniform supply system (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 square bale harvest and collection unit operation does not include details on format intermediates or machinery already discussed in the Conventional Bale supply system (Section 2). Alternatively, a 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 the Appendix.

Table 3-1. *Pioneer Uniform supply system scenarios included in this feedstock supply system design.*

Feedstock	Format	Scenario Name
Corn Stover	Square Bale	"Stover Square"
Corn Stover	Round Bale	"Stover Round"
Switchgrass	Square Bale	"Switchgrass Square"
Switchgrass	Round Bale	"Switchgrass Round"
Corn Stover Cob	Bulk	"Cob"

Like the Conventional Bale system, the Pioneer Uniform feedstock supply system is also designed to supply a biorefining facility with 800,000 DM tons of biomass annually (Table 3-2). This Pioneer Uniform supply system design would be appropriate for supplying biomass to 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.

Delivered feedstock costs for the Pioneer Uniform—Stover Square and Round, Switchgrass Square and Round, and Cob scenarios were calculated by the model and are summarized in Table 3-3. These are static costs and do not represent the impact that variables within each operation can have on the performance of both the unit operation and the overall supply system. Each unit operation is impacted by the performance of another, so each operation section of this report is concluded a summary analysis of cost, performance, and logistics based on stated format intermediate attributes and equipment operational assumptions.

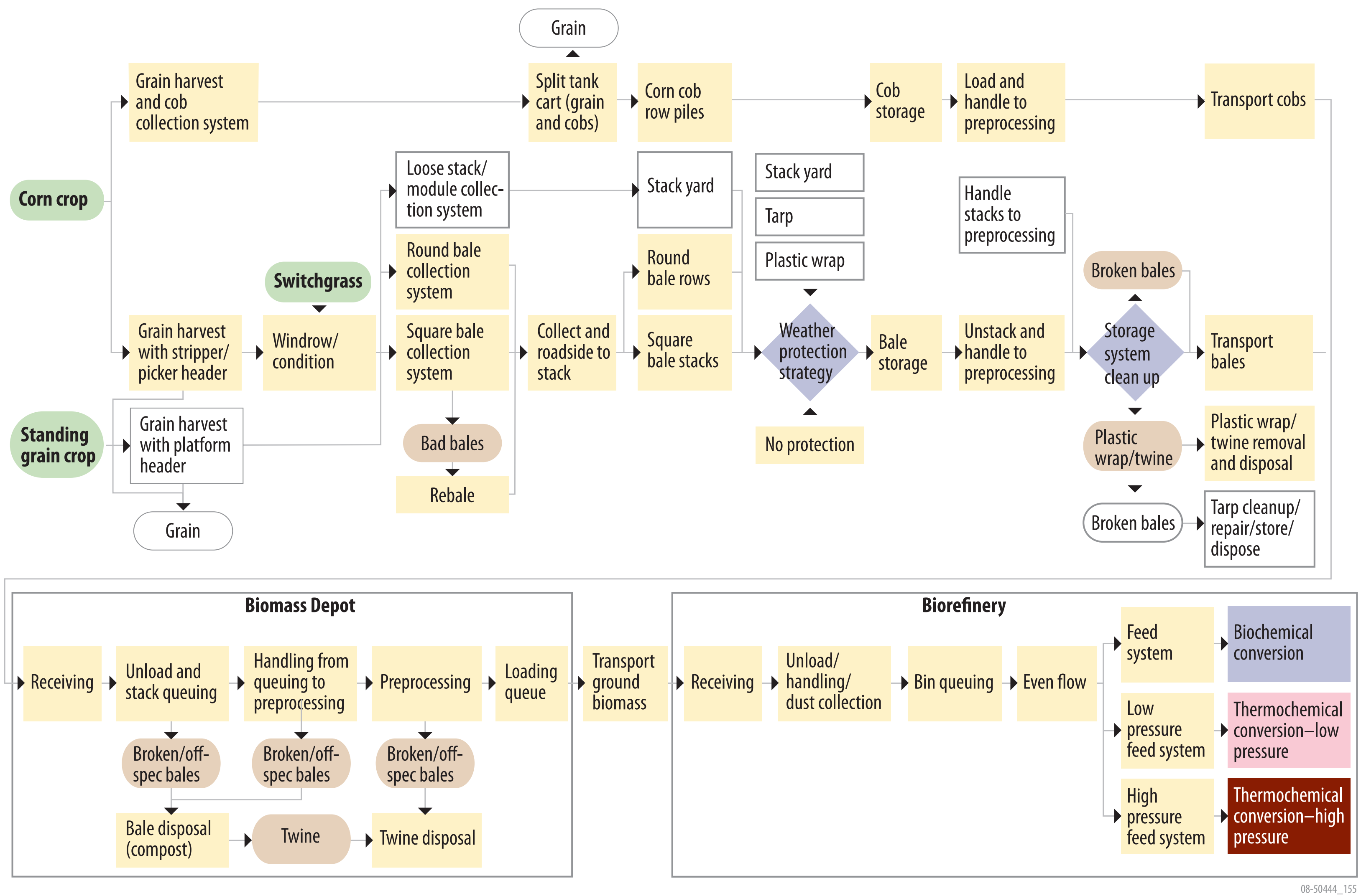


Figure 3-1. Order of unit operations in the Pioneer Uniform feedstock supply system. Preprocessing is relocated from the biorefinery to distributed depots at or near biomass storage locations.

(Note: 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.

Table 3-2. *Design size annual capacity assumptions for the Pioneer Uniform–Stover Round and Switchgrass Round supply system scenarios.*

	Stover	Switchgrass
Plant Operation Size (delivered tons[a])	800,000 DM ton/yr	800,000 DM ton/yr
Feedstock Harvested Annually[b]	860,000 DM ton	860,000 DM ton
Cultivated Acres	2,107,000	4,248,000
Acres Available for Contract	1,054,000	212,000
Participating Acres	50%	100%
Acres Harvested Annually	527,000	212,000
Feedstock Supply 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.

3.1 PIONEER UNIFORM HARVEST AND COLLECTION

The Pioneer Uniform design expands upon the Conventional Bale design and adds round-bale collection systems for corn stover and switchgrass (Table 3-1 and Figure 3-2). This design also introduces a single-pass corn residue harvest system that collects corn cobs along with selected fractions of the corn stalk, leaves, and husks. This corn cob harvest system represents a first implementation of a bulk harvest and collection approach for crop residues. Additionally, selective harvest of specific corn stover residue fraction(s) has potential sustainability and feedstock logistics/conversion advantages ranging from bulk density to conversion recalcitrance to soil amendment value. Finally, and possibly the most prominent feature of this design, is that the Pioneer Uniform system is tolerant of diverse alternate collection formats (e.g., square bale, round bale, bulk corn cob), thus giving the producer flexibility to choose harvesting and collection systems that are most economical and practical for their respective operations (Figure 3-2).

3.1.1 Pioneer Uniform Harvest and Collection Format Intermediates

The Pioneer Uniform harvest and collection unit operation removes corn stover and switchgrass from the field in both large square bale and round bale formats. For corn stover and switchgrass, the

Table 3-3. *Total delivered feedstock cost summary for Pioneer Uniform–Stover Square and Round, Switchgrass Square and Round, and Cob scenarios.*

Logistics Unit Operations	Harvest & Collection	Storage	Preprocessing	Transportation	Receiving & Handling	Total
Stover Square ($/DM ton)[b]	$20.21 ± 1.90	$8.03 ± 0.61	$14.75 ± 1.64	$11.88 ± 0.73	2.91 ± 0.01	57.78 ± 3.72
Stover Round ($/DM ton)[b]	$25.12 ± 3.16	$1.57 ± 0.41	$14.75 ± 1.64	$16.78 ± 1.01	$3.04 ± 0.01	61.27 ± 4.57
Switchgrass Square ($/DM ton)[b]	$14.80 ± 1.34	$7.06 ± 0.49	$15.72 ± 2.24	$ 11.14 ± 0.72	2.86 ± 0.01	51.58 ± 3.79
Switchgrass Round ($/DM ton)[b]	$22.45 ± 2.86	$1.41 ± 0.36	$15.72 ± 2.23	$ 15.56 ± 0.92	$1.98 ± 0.01	57.12 ± 4.92
Cob ($/DM ton)[b]	$24.68 ± 1.01	$4.38 ±0.41	$18.96 ± 3.04	$13.03 ± 1.05	7.86 ± 0.62	68.91 ± 4.11

a. Cost is in 2008$ and represents the weighted average of U.S. regional costs (Hess et al. 2009).
b. Costs are in 2008$ and represent the mean and standard deviations of 10,000 model iterations for the simulated scenarios (Tables 2-3 through 2-6).

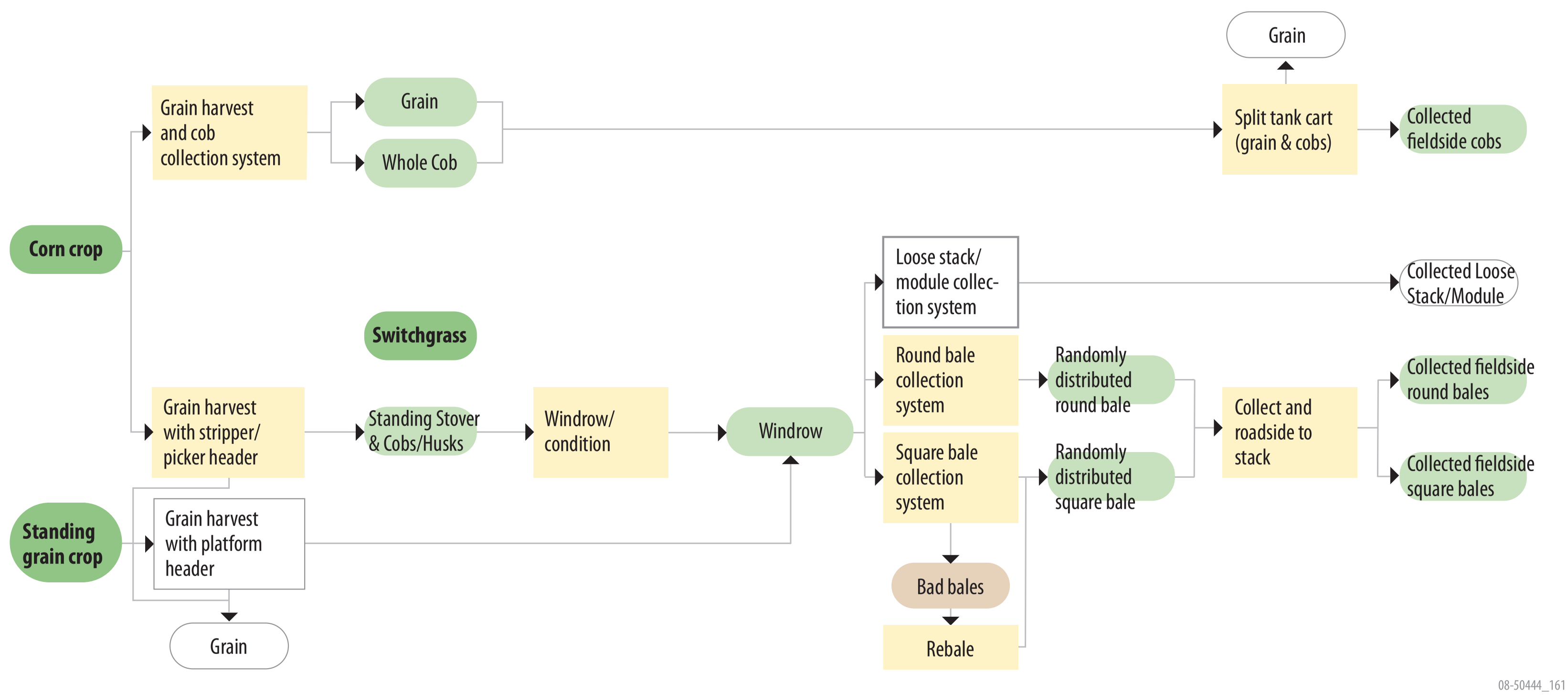


Figure 3-2. Pioneer Uniform harvest and collection supply logistics processes and format intermediates.

(Note: Green ovals represent biomass format intermediates, tan ovals represent potential waste streams, and yellow rectangles represent processes modeled in this report. White rectangles represent alternative processes not modeled.)

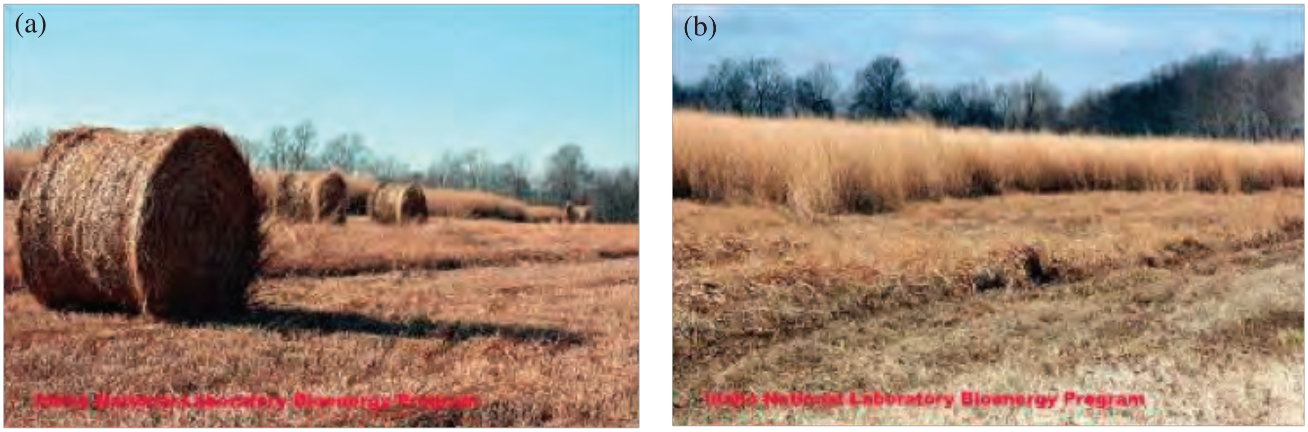


Figure 3-3. Switchgrass (a) standing in the field (background, right), and after harvest and windrowed with a mower/conditioner (foreground); and (b) baled in a round format.

production, harvesting, windrowing/conditioning, field drying, and large square baling processes are the same as those presented in the Conventional Bale design (Section 2.1.1), and that information is not repeated in this section of the report. For bulk corn cob, the production process is the same as for that presented in the Conventional Bale design (Section 2.1.1), and that information is not repeated in this section of the report. The processes of baling, collecting, and roadsiding include both large square bale (Section 2.1.1) and round bale formats (Table 3-4). “Roadsiding” refers to the process of moving the collected biomass to a location that is generally next to a road that borders the field or is nearby.

For the Pioneer Uniform round bale scenarios, the corn stover and switchgrass are allowed to dry in the windrow to 12% moisture content and then are baled into 5.5-ft diameter × 4-ft wide round bales. The biomass field drying and 12% moisture input assumptions discussed in Section 2.1.1 for square baling are also applied to round baling, even though it is recognized that optimum biomass moistures for round and square bale equipment are not always the same. When the biomass moisture drops below 10–12%, some round baler designs will not work effectively, and baling operations may need to be suspended until evening or nighttime after the dew comes on (Grant 2003). Conversely, round bales have a greater baling and storage tolerance than square bales for biomass moistures above 12–15% (Shinners 2007). Similar to square baling in the Conventional Bale design, the round baling operation in this design drops the bales in the field as they are formed (Figure 3-3). The bales are then collected and roadsided. The harvest and collection unit operation is complete once the bales are delivered to the field side and placed into a storage stack.

The Pioneer Uniform—Cob scenario harvesting process is a single-pass operation in which the grain and cob are collected simultaneously (Table 3-5). This process does not produce a biomass windrow behind the harvester that must be collected with a subsequent process. The two most common cob harvest systems are the (1) grain and cob mix (often referred to as “CCM” for “corn and cob mix”) and (2) cob separation and collection into a second cob collection bin. The grain and cob mix harvest process collects both the grain and cob together in the harvester grain tank, and separation of the grain and cob is performed in a later process. (For an overview of the grain and mix process, see Kenney 2008 and Christiansen 2009.)

The Pioneer Uniform—Cob collection system separates and maintains the grain and cob as distinct product streams from the point of harvest (Figure 3-4). Single-pass cob harvest systems provide no opportunity for field drying, so the grain and cob are both removed from the field at their respective harvest moisture levels. The modeled harvest moisture level for grain is targeted at 15%. Based on the grain moisture, the relative cob moisture is assumed to be

***Table 3-4**. Pioneer Uniform–Stover Round and Switchgrass Round: Equipment and format intermediate attributes and estimated costs of the harvest and collection operation.*

	Logistics Processes	Baling	Collect & Roadside	Dry Matter Loss	Total Costs
STOVER ROUND	Equipment	105 hp tractor and large round baler	Self-propelled stacker		
	Format Intermediates	Randomly distributed 5.5×4-ft round bales[a]	Stacked 5.5×4-ft round bales[a]		
	Biomass description	Stalk, cob, and husk (collectively stover)			
	Yield (DM ton/acre)[b]	1.63 (3.9 bale/acre)	N/A		
	Bulk DM Density	9.0 lb/ft3 (829 DM lb/bale)[b]			
	Moisture (w.b.)[e]	12%			
	Modeled Costs[f] ($/DM ton)				
	Modeled Costs[f] ($/acre)				
SWITCHGRASS ROUND	Equipment	105 hp tractor and large round baler	Self-propelled stacker		
	Format Intermediates	Randomly distributed 5.5×4-ft round bales[a]	Stacked 5.5×4-ft round bales[a]		
	Biomass description	Whole crop less stubble (switchgrass)			
	Yield (DM ton/acre)[b]	4.1 (9.4 bale/acre)	N/A		
	Bulk DM Density	9.4 lb/ft3 (or 865 DM lb/bale)[c]			
	Moisture (w.b.)[e]	12%			
	Modeled Costs[f] ($/DM ton)				
	Modeled Costs[f] ($/acre)				

a. See machinery capacity and efficiency calculations (Appendix A-3)
b. Stover based on Richey et al. 1982; Switchgrass based on INL test data, switchgrass, and Miscanthus harvest in Illinois, January 2008. Harvest efficiency = 1-DM _Loss.
a. The Conventional Bale Stover supply system is based on the 4×4×8-ft bale, though other large square bale formats are available, including 3×4×8-ft low- and high-density formats.
b. Process output yield calculations based on equipment dry matter loss: grain harvest 1:1 residue-to-grain ratio, or harvest index of .5; condition and windrow collection efficiency of 71%; baling collection efficiency of 54%; and collect and roadside collection efficiency of 100%.
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 and Binversie 2007.
e. Hoskinson et al. 2007.
f. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.
g. Harvest costs associated with grain are not included in the cost of the feedstock since they are born by the grain industry.

Table 3-5. *Pioneer Uniform–Cob: Equipment and format intermediate attributes and estimated costs of harvest and collection operation.*

Logistics Processes	Single-Pass grain and cob harvest		Cob transferred to roadside	Dry Matter Loss	Total Costs
Equipment	Combine with 8 Row Corn Header, towing cob wagon	Vermeer Corp. CCX770 Cob Harvester	Sunflower 8210 Dump Wagon		
Format Intermediates	Grain	Whole cob (90%) and some attached husk	Collected in field-side piles		
Biomass description	Corn grain	Whole cob	Whole cob		
Yield (DM ton/acre)b	4.26 (180 bu/acre corn)	0.77	N/A		
Bulk DM Density	52 (lb/bu)b	8.0 (lb/ft^3)[c]			
Moisture (%w.b.)[e]	15[d]	34[d]			
Modeled Costs[f] ($/DM ton)					
Modeled Costs[f] ($/acre)					

a. Process output yield calculations based on equipment dry matter loss (Table 3-6).
b. The standard grain bulk density is 56 lb/bu at 15% moisture (Bern and Brumm 2009) Grain Bulk Density.
c. Corn cob bulk density, based on 90% whole cob purity (Foley 1978).
d. Grain moisture at harvest (Shinners et al. 2007).

Figure 3-4. Single-pass grain and cob harvest: (a) harvested grain unloaded from the combine grain tank, and (b) harvested cob, plus some attached husk, unloaded from a second tank attached to or pulled behind the combine.

34% (Table 3-5).

While single-pass harvesting processes eliminate biomass field drying opportunities that may present moisture management issues for downstream storage and handling unit operations, they also provide advantages because cobs are not returned to the ground. By eliminating the windrow, single-pass harvest and collection systems have the benefits of reduced collection costs and soil compaction. Product quality is also improved because cobs are not left in the field, eliminating the risk of adverse weather exposure or contamination with soil that can result during field drying and subsequent collection operations. Once the cobs are harvested, separated, and collected, they are transferred to a field-side location and dumped into a pile (Figure 3-5).

3.1.1.1 Biomass Deconstruction, Fractionation, and Yield

The biomass deconstruction, fractionation, and yield issues for corn stover and switchgrass are the same as those described in the Conventional Bale design (Section 2.1.1.1). However, the Pioneer Uniform design includes whole cob harvesting, which presents several new plant deconstruction and separation/ fractionation challenges. Separating the grain from the cob is well understood and a fundamental function of modern grain combines. However, separating the cob from the remainder of the corn stover residue presents separation challenges, particularly with regard to husk material attached at the cob base

Figure 3-5. Harvested corn cobs being dumped into a field-side cob pile.

(Figure 3-4b). Cob purity is the focus of cob harvester development programs being conducted by John Deere, Vermeer, CNH, and others. Having the husk or other stover material present in the whole cob product stream is not a concern for biorefineries tooled to convert whole stover, but the husk material reduces the bulk of the cob product stream and may impact preprocessing and other material handling processes in the supply chain. Since the husk is physically connected to the cob base, the engineering challenge is the development of threshing/chopping mechanisms as part of existing combine harvester systems that can detach the husk from the cob and keep the cob whole (Birrell 2008).

The grain and cob mix harvest system is more successful at achieving higher cob purities because the cob is broken up and the husk is detached in the harvester threshing process (Kenney 2008). However, this process breaks the cob into small pieces that co-mingle with the grain and require subsequent specialized handling and separation processes. The purpose of the whole cob harvest system is to collect a cob product stream that is not chopped up and co-mingled with the grain, thereby maintaining the integrity of the corn grain product stream and producing a durable whole cob product for subsequent feedstock logistics and biorefining operations. As such, the development of harvester threshing and separation technologies is essential for producing high-purity whole-cob product streams.

3.1.1.2 Format and Bulk Density Impact on Supply System Processes

Although the square bale format discussed in Section 2.1.1.2 does not share the same storage benefits as the round bale format (Section 3.2), square bales do have distinct handling, transportation, and storage footprint advantages. Square bales can be handled two or three at a time for 4×4×8-ft and 3×4×8-ft sizes, respectively (Figure 3-6a). They also rapidly stack together on trucks and can be automatically stacked, making the handling and stacking operations rapid and efficient (Figures 2-10 and 2-21). Round bales must be handled one at a time, which causes handling and stacking operations to be slower and less efficient (Figure 3-6b). Loading a 53-ft semi trailer with square bales can be accomplished in less than 30 minutes (80 bales/hr, Table 3-22), whereas loading the same trailer with round bales takes nearly 1 hr (40

Figure 3-6. Biomass bales being loaded onto haul trailers: (a) large square bales can be handled two at a time, while (b) round bales can only be handled one at a time for proper orientation of the trailer.

bales/hr, Table 3-25).

Similar to the square bale format, different crops baled in the round bale format result in different densities, which impacts the number of bales per acre at the respective crop yield for each design scenario. Even with round bales, cereal straw residues produce some of the lowest bale densities, resulting in relatively high bale counts per ton of biomass (Table 3-6). The cost to handle each bale is essentially the same, irrespective of bale density or size; thus, using plant material or engineering configurations that produce fewer bales per ton of biomass will improve bale collection and handling efficiencies. Regardless of the selected biomass handling format, bale density is a key factor in collection and handling efficiencies, capacity, and ultimately costs.

Unlike stover or switchgrass, cobs in this design are handled as a bulk solid material from the point of harvest. With the whole cob harvest system modeled herein, the cob biomass is not compacted into a higher density package. The whole cob harvest and logistic system takes advantage of the inherent density of the cob. A pure cob product will have a dry matter density of 9–10 lb/ft3 and an assumed moisture content of 30% at the time of harvest (Smith et al. 1983). Compared to bulk stover, which is about 1 lb/ft3, cob is nearly 10 times more dense (Table 3-6). For this reason, any contamination of the whole cob stream with other stover materials can greatly reduce the bulk density of whole cobs. Depending on the amount of husks that remain attached to the cob, the density will be reduced to 6–8 lb/ft3. Assuming 90% cob purity, the dry matter density of a whole cob product stream would be approximately 8 lb/ft3 (Foley 1978).

Cob purity ranges from 80–90% on a weight percentage basis. The impurities consist primarily of husks. Many of the husks are attached to the base of the cob, and corn variety appears to influence how much husk is attached.f Usually the husks either remain attached to the shank or to the cob when the ear is picked from the stalk during harvesting. If it remains attached to the shank, the husk stays with the stalk and does not pass through the combine. Otherwise, the husk enters the combine with the cob. The husk may be removed from the cob during the process of shelling the corn in the combine threshing cylinder/rotor. In this case, the cleaning system of the cob wagon can effectively separate cob and husk.

A cob purity of 80% seems acceptable for subsequent cob handling and storage operations, and the main issue with cob purity is bulk density. Assuming cobs have a density of 9 lb/ft3 and husks have a density of 0.5 lb/ft3, a cob purity of 80% reduces bulk density to about 7 lb/ft3, which adds more than $1 per dry ton to a 25-mile haul. The grinding behavior of husks as compared to cobs is also different, and changes in the cob/husk ratio can affect grinder performance (e.g., more husks makes it more difficult to grind).

Table 3-6. *Yield and bulk density data for round bales of various biomass feedstocks and corn cobs.*

	Crop Yield (baled DM ton/acre)	Bale/Pile Wet Bulk Density (lb/ft^3)	Bale/Pile DM Bulk Density (lb/ft^3)	Round Bales/Acre
Corn Stover	1.6[a]	10.2[b]	9.0[b]	3.9
Corn Cob[c]	0.77	10.4–11.7	6.8–8.7	N/A
Cereal Strawd	1.1	7.3–9.4	6.6–8.5	3.3–4.2
Switchgrass[e]	4.0	10.7	9.4	9.4
Miscanthuse	5.1	9.4–11.4	8.5–10.3	12.6–15.3

a. INL data, modeled scenario (Table 2-3).
b. Shinners (2007).
c. Based on INL field test data, corncobs harvested in Iowa and Minnesota, November 2008.
d. INL test data, wheat straw harvest in Colorado and Idaho, July to August 2007.

3.1.1.3 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. Like the Conventional Bale design (Section 2.1.1.3), the Pioneer Uniform Round scenarios require wet biomass to be field-dried prior to baling. Section 2.1.1.3 discusses typical moisture levels at harvest for corn stover, cereal grains, and dedicated energy crops that are collected and stored in bales. If high-moisture biomass cannot be dried in the field, it is unsuitable to be baled and stored with this Pioneer Uniform design, which has no wet storage processing system. Without a wet storage system to stabilize the biomass in the presence of water (e.g., ensiling), or an active moisture mitigation system to remove the water at some later point in the supply system (e.g., Section 4, Advanced Uniform-Format Supply System), other alternate moisture management strategies may be employed to handle high-moisture biomass in the Pioneer Uniform design. The first, and likely simplest, strategy is to eliminate storage and go to just-in-time delivery, preprocessing, and conversion of the biomass. This would require the crops and environment that allow a year-round green harvest, much like the sugar cane feedstock supply system, and is certainly a viable option in many of the southern areas of the United States. A second option would be to selectively harvest only the plant parts that have an acceptable moisture level. The cob harvest system presented in this Pioneer Uniform design is an example of such a selective harvest system.

Selective harvest provides an effective approach for dealing with high-moisture biomass. Because a portion of crop residues may be required to be left in the field during harvest to sustain soil health, selectively removing the low-moisture portions while leaving the high-moisture portions would satisfy agronomic sustainability. This would also provide biomass that may have more desirable bulk density and moisture levels (e.g., corn cobs). Studies performed by Hoskinson et al. (2007) and Shinners et al. (2006a) provide the basis for moisture-based selective harvest. Hoskinson et al. (2007) evaluated an actual harvest scenario in Ames, Iowa, using a modified grain combine, whereas Shinners et al. (2006a) manually collected whole-plant samples from Arlington Agricultural Research Station (AARS) in Wisconsin, with subsequent anatomical separation performed in a laboratory (Table 3-7).

***Table 3-7**. Results of stover yield and moisture tests.*

	Hoskinson et al. 2007	Shinners et al. 2006
Bottom stalk	64%	>70%
100% of stover	34%	48–64%
Top stalk + ear	20%	34–48%
% of potential stover in material other than grain (MOG) fractions	55%	40%
Grain moisture	<12%	<30%

Both studies found that the lower portion of the corn stalk exhibited the highest moisture content (>60%) at the time of grain harvest (Table 3-7). The top stalk and ear fractions of the stover were considerably dryer than the bottom stalk. The entire composite stover moisture (including all stover fractions) ranged from 48–64% for the 3-year Shinners et al. (2006) study. These stover moisture levels were considerably higher than those reported by Hoskinson et al. (2007). The difference appears to be largely attributed to the timing of grain harvest. The Shinners et al. (2006) harvest occurred when the grain moisture dropped below 30%, whereas the Hoskinson et al. (2007) study delayed harvest until the grain moisture was below 12%. Another possible contributing factor in the moisture discrepancy is that Shinners et al. (2006) collected whole plants, while Hoskinson et al. (2007) cut the plants with a combine at 10 cm above the ground. Both studies reported similar bottom stock moistures, so the amount of bottom stalk in the composite stover measurement may have been greater in the Shinners et al. (2006) study than in the Hoskinson et al. (2007). Further efforts to understand this discrepancy are important, since harvest timing combined with selective removal could be a very effective moisture management strategy.

In this design, the dry stover fractions (the MOG), which include about 40% of the available stover mass, including all the cobs and husk, and 50% each of the leaf and top stalk, pass through the combine (Table 3-7). These results are of particular interest to single-pass harvester development because they suggest that as much as 40–55% of the available stover fractions may be harvested as a dry product (<20% w.b.), depending on a number of variables including growing conditions, harvest conditions, and timing of harvest. However, whether the crop is standing in the field or lying in a windrow, decisions to delay harvest to allow for field drying must be balanced with the risk of crop loss.

Cob harvest and stability are also affected by moisture content at the time of grain harvest. In a study of individual corn stover component dry down, cobs retained less moisture than whole stover at grain harvest (Pordesimo et al. 2004)—from 40–50% versus 50–60% for the whole stover. Additionally, cobs reached equilibrium moisture content sooner than the whole stover and suffered fewer dry matter losses after grain harvest. These trends were observed in both standing plants and on-ground residues.

Selective cob harvest may provide a benefit during unusually wet harvest seasons or when grain storage space is limited. Cob moisture content was lower than that of whole stover, and whole plants could be left standing in the field until suitable conditions permitted later grain and cob harvests. Cob dry matter content was essentially constant from 128–213 days after planting; whole stover dry matter content decreased over this time, primarily due to the loss of leaves and husks (Pordesimo et al. 2004). In addition to its merit as a bulk-handled feedstock, selective cob harvest could be an attractive moisture management strategy during off-normal corn and stover harvest conditions.

3.1.2 Pioneer Uniform Harvest and Collection Equipment

The Pioneer Uniform design differs from the Conventional Bale design by allowing multiple harvest and collection systems to supply biomass though a common feedstock supply system. In the Conventional Bale design, only one harvest and collection system was used (Section 2.1). In this Pioneer Uniform design, harvesting machinery for corn stover and switchgrass is the same as the Conventional Bale design (Section 2.1.2). However, for these crops, the Pioneer Uniform design allows the use of multiple collection systems. The collection systems modeled here are the large square bale (Table 2-3) and the round bale (Table 3-4).

In addition to accepting biomass in various bale formats, the Pioneer Uniform design can accept biomass collected and handled with bulk harvesting systems. In this case, the modeled system is whole corn cobs harvested and collected with single-pass equipment (Table 3-5).

3.1.2.1 Equipment Used in Pioneer Uniform Design Model

The harvesting and collection equipment for large square bales is presented in Section 2.1.2, and the description of that equipment will not be repeated in this section. Because the round bale collection system relies on the same harvest systems as square bales, only the baling and collection/roadsiding equipment that is unique to the Pioneer Uniform design is presented here. The whole corn cob harvest and collection system, which is new to the Pioneer Uniform design, and the equipment of this system are presented in their entirety.

Baling

The round baling equipment selected for this design is pulled behind a tractor, and the baler's mechanical systems are powered by the tractor's power take off (PTO) drive. The round baler has a pickup system to lift a windrow of biomass and feed it into the baling mechanism. The baling mechanisms of the round and square balers are quite different. Biomass in square balers is stuffed and pressed into the bale (Section 2.1.1), whereas biomass in a round baler is rolled into a bale. A round baler rolls the biomass with a series of rotating belts (or in some designs, a single large belt). This design uses a Vermeer 604 Super M large round baler that forms 5.5×4-ft round bales (Figure 3-7a). Round bale width is set by the baler model, but bale diameter can be adjusted on most models. The 5.5-ft diameter size maximizes the number of bales that can fit on a semi-tractor flatbed for transport to the biomass depot.

Bale compaction in a round baler is achieved with

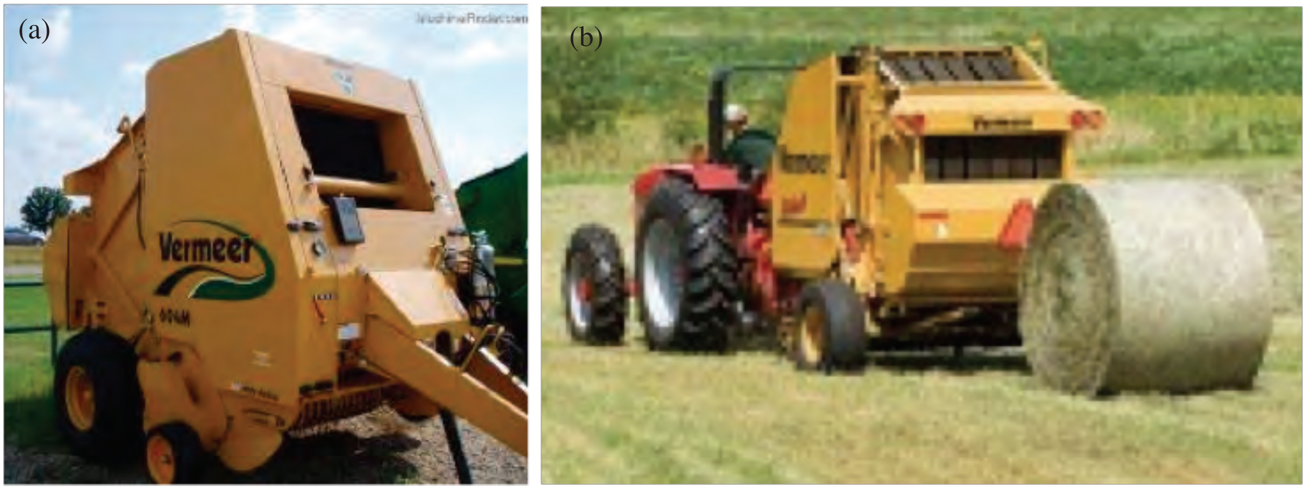


Figure 3-7. Round baler: (a) Vermeer 604 Super M Large Round 5.5×4-ft round baler (b) pulled by a 115 hp mechanical front-wheel-drive tractor with a round bale that has just been discharged from the baler.

a belt tension mechanism that tightens the belts around the rolling biomass. As the bale grows in size, the belt tension mechanism adjusts to maintain an appropriate compaction pressure to form the bale. Once the bale has reached the cut-off diameter, the tractor/baler operator is notified by an indicator light/buzzer. The operator stops the tractor, which stops biomass from feeding into the baler. The bale wrapping and discharge cycle is then activated. As the bale continues rolling in the bale chamber, the baler then wraps it with twine or a net wrap material to prevent it from unrolling. Once the bale is wrapped, hydraulics open the bale chamber and discharge the bale (Figure 3-7b). The bale chamber closes, the operator is notified to proceed, and the process begins again. The round baler in this design is pulled/powered by a 115 hp Massey Ferguson tractor (Figure 3-7b), which is 160 hp smaller than that required to pull a large square baler (Section 2.1.2).

Collection and Roadsiding

Collection and roadsiding for the Pioneer Uniform design is similar to the Conventional Bale design (Section 2.1.2). Randomly distributed round bales are collected from the field and transported to the field-side storage location using a self-propelled Stinger Stacker 5500 (Figure 3-8). This 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 round bale into the pickup mechanism, just like the Conventional square bale operation (Section 2.1.2). Once the Stacker is loaded with bales, it is driven to the field-side location for the bale drop. Bales are dropped by the Stinger's stacking rack gate being released while the machine is in motion, allowing the bales to simply slide off the bale deck onto the ground at the unload point. Because this modeled design uses 4-ft wide bales and a loader to organize the bales in the field-side stack, the Stinger's stacking deck can transport nine bales instead of seven (as shown in Figure 3-8) to the unloading point during each collection cycle. Round bales are generally not stacked on end, so the Stinger Stacker self-stacking mechanism is not used with round bales.

Cob Harvesting and Collection

Figure 3-8. Stinger Stacker 5500 loaded with round bales.

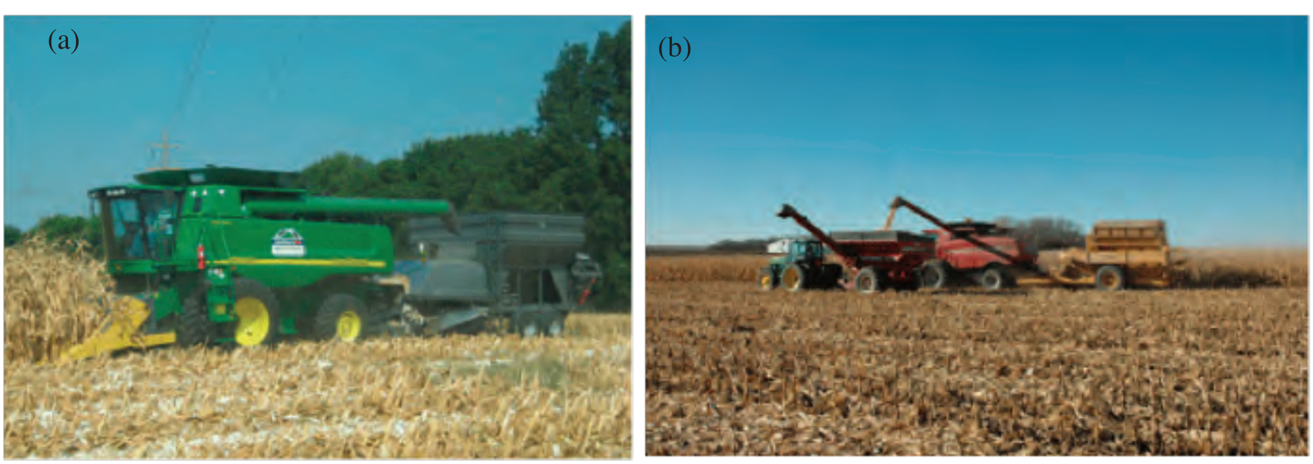
There are currently four different machinery options for harvesting corn cobs. All of the systems collect the MOG that passes through the combine, use an air-based cleaning system to remove the material other than cob (MOC), and transport the clean cobs to a collection tank. The differences in these systems are (1) single-stream grain and cob mix or a two-stream harvester and (2) cob collection in an onboard collection tank or in a separate wagon or cart that is towed behind the combine or pulled alongside the combine by a tractor. This design uses the whole cob collection system, which uses a cob wagon pulled behind a grain combine harvester (Table 3-5).

The grain harvesting operation of the whole cob system functions just like the corn stover system (Section 2.1.2). The combine header strips the ear of corn from the stalk and passes the ear through a threshing mechanism. The shelled corn is cleaned and then conveyed to an onboard grain tank (Table 3 5). A John Deere 9670 STS combine using a John Deere 608C 8-Row Header is the modeled grain harvesting equipment in this design (Figure 2-5). The cobs pass through the combine with the MOG stream, but instead of being discharged back onto the ground with the rest of the MOG, the cob and MOC are discharged into the hopper of a pull-behind cob wagon (Figure 3-9). The cob wagon has an onboard air cleaning system to separate the cobs from the MOC. The cobs are then conveyed to the wagon holding tank, and the MOC is discharged back to the field.

Several agricultural manufacturers are currently developing a cob wagon type of system, including Vermeer, CNH, and Redekop. An advantage of the cob wagon is that it is minimally intrusive to the combine design and function (Figure 3-10). This is an important consideration, because most farmers will use their combines to harvest soybeans, small grains, and sometimes other crops in addition to corn during a typical harvest season. The ability to install or uninstall the cob harvesting system with a simple hitch pin maintains the combine's rapid versatility. One drawback to that system is that towing a wagon reduces the maneuverability of the combine when backing up, when moving around obstacles in the

Figure 3-10. A dual tank grain/cob cart for collecting grain from the combine and cobs from the cob wagons of single-pass harvest systems, Dethmers Manufacturing Co. (Demco) dual-cart 2-SKU Cob Cart.

Figure 3-9. Harvesting both grain and cobs; (a) CNH combine pulling a Vermeer cob wagon in a corn field near Holloway, Minn., during the Chippewa Valley Ethanol harvesting demonstration Oct. 28, 2008;h (b) John Deere combine pulling a Redekop Manufacturing cob wagon (Source: Redekop Manufacturing)



field, or when harvesting the head rows to open up the field for harvest. The wagon may also pose problems when harvesting on side hills or going up and down hills.

Ideally, the combine grain tank and the wagon cob tank are sized to relatively equal proportions. When the grain and cob tanks are full, they are unloaded into a tractor-drawn wagon that moves the harvested products to trucks waiting at a field-side location (Figure 3-11).

Both the CNH and Redekop cob wagons have the ability to unload on-the-go, with the former using a belt conveyor and the latter using an auger to move cobs from the wagon to receiving cart or truck. In contrast, the Vermeer cob wagon, which is modeled in this design, is a high-dump wagon. This wagon is capable of unloading at a faster rate than the CNH or Redekop systems, but it requires the harvest operation to be stopped for unloading (Figure 3-11). The CNH system is powered by the combine hydraulic system, and the Vermeer system is powered by its own dedicated on-board engine.

In addition to the cob wagon harvest systems, CCM grain and cob collection systems, integrated combine-cob collection systems, and single-pass harvesters with rear cob separation are all being developed. Each of these systems has advantages and disadvantages over the cob wagon systems.

The CCM harvest system collects corn and cobs into the existing combine harvester grain tank as a mixture of corn grain and chopped cob. This process reduces the cleaning efficiency of a combine, so that the cobs pass through the grain cleaning system with the grain rather than being deposited on the ground behind the combine. While this can be achieved to some degree by appropriate combine adjustments, CCM kits have been developed by combine manufacturers to improve cob collection. As the cob is mixed with the grain, unloading of the cobs occurs at the same time as unloading of the corn grain (they are mixed together and separated later). However, CCM has lower flowability than grain, so the grain carts will likely need to be equipped with large augers to handle this material. Further, a separator is needed to separate the cob and grain after harvest.

Figure 3-11. With a truck positioned beside the cob wagon, the harvest operation is temporarily stopped to dump the cob wagon bin. Vermeer Corp. CCX770 Cob Harvester.

The cob collection systems that are integrated with the combine are functionally the same as the cob wagon system, except that the cob separator and cob holding tank are installed directly onto the combine. One of these integrated cob collection systems, the Ceres Residue Recovery System, is easily differentiated from its competitors by the residue tank that sits atop the grain tank on the combine. After the MOC is removed by the Ceres cleaning system, the cobs are blown into the cob tank above the grain tank. The Ceres cob system has the advantages of an onboard collection system like CCM, the two-stream advantages of the wagon systems, and is capable of unloading on-the-go using a drag-chain system in the cob tank. However, compared to cob wagon systems, these integrated cob collection systems require modifications and installation of additional after-market components onto the combine.

Another cob harvesting system is offered by John Deere and is based on a single-pass harvester developed by Deere and Iowa State University. This harvester has been under development for the last several years with a focus on single-pass stover harvest, but more recently the focus has included cob-only harvest. As such, this harvesting system is fundamentally a bulk residue harvester that can collect everything from whole stover to cob only. The cob harvesting settings operate similarly to the Ceres system in that the cob cleaning system and a blower are positioned at the rear of the combine to collect the MOG that passes through the combine, remove the MOC, and blow the clean cobs into a collection tank. The chopper, blower, and separator at the rear of the combine differentiate this harvester from a regular grain combine.

One of the primary criteria in evaluating these systems is the impact the added cob systems have on grain harvest, with the basic rule that anything that reduces the efficiency and rate of grain harvest is unfavorable. Thus some of the features that must be evaluated include the ability to unload the cobs from the combine without stopping; logistical issues such as the amount of additional time needed, labor and equipment needed to collect cobs, installation and combine modifications required of the cob harvesting system, and cob purity. Both CCM and two-stream cob harvesting systems will likely play a role in the cob harvesting market. Smaller farmers who may not be able to afford the capital investment of the more efficient systems and do not have the acreage and thus the time-constraint of harvesting large acreage in a limited harvest window may be able and willing to accept delays in grain harvest associated with the CCM approach. Alternatively, large farms that are able to afford the higher capital investment of a two-stream harvester may adopt this method because of the improved logistics.

3.1.2.2 Equipment Capacity and Operational Efficiency (field efficiency)

Machine field capacity, field efficiency, yield, and field speed are the same for the Pioneer Uniform and Conventional Bale designs for combining, shredding, windrowing, and raking, and are described in Section 2.1.2.1 and in Tables 2-8 and 2-9. Table 3-8 shows the range and typical values of field speed and field efficiency for round baler equipment (ASABE D497.5 2006b) and cob harvesting equipment. These values were used in the modeling of the design scenarios, with the exception of the field speeds noted in the “Model” column of Table 3-8.

Field capacities of cob and round baler equipment used in the Pioneer Uniform harvest and collection operation of crop residues and herbaceous energy crops are shown in Table 3-9. The grain combine is the same machine as that used in the Conventional Bale design, and as such has the same rated capacity (Tables 2-9 and 3-9). However, the same combine towing a cob wagon only has a field capacity of 8.6 tons of cob/hr (1,425 ft3/hr) because of the reduced maneuverability due to towing the cob wagon and the additional logistics of managing the second cob product stream (Table 3-9). Factors such as needing to unload two product tanks (i.e., grain and cob) that may have mismatched or variable fill rates, or needing to stop harvesting to unload one or both tanks, result in stand-alone combine field efficiency reductions from 70% (Table 2-8) to 67% when pulling a cob wagon (Table 3-8).

Table 3-8. *Typical field speeds and field efficiencies for corn cob and round baler equipment.*

Machine/Equipment	Field Speed (mph)			Field Efficiency (%)	
	Range	Typical	Model[a]	Range	Typical
Corn combine towing cob wagon[b]	2.0–5.0	3.0	3.8	65–80	67
Cob wagon[b]	N/A	N/A	10	N/A	57b
Round baler[c]	3.0–8.0	5.0	3.6	55–75	65

a. Based on INL 2007 harvest field data.
b. Model assumes that cob wagon services three cob harvesters.
c. ASABE D497.5 2006b.

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

Machine/Equipment	***Yield***		***Capacity***		
	Value	Units per acre	Rated[a]	Field[b]	Units per hour
Corn combine towing cob wagon[c]	180	bushels	2,000	1,340	bushels
Cob wagon[d]	0.77	DM tons	8.6	5.7	tons
Corn stover round baler[e]	1.6[f]	Baled (DM ton/acre)	25.6	20.5	bales

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. Vermeer Corp. CCX770 cob harvester.
e. Baler: round baler, 5.5×4-ft, 8.5 lb/ft3.
f. Baler yield is based on 3.0 DM ton/acre in the windrow with 71% harvest efficiency.

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 downtime for crop unloading. Dealing with present-day cob wagons and any other cob harvesting add-ons increases unproductive operational time. Solutions to improved field capacities and efficiencies while harvesting a second product stream (i.e., cobs) will come as a combination of new technologies, additional pieces of equipment, and management.

The smaller size and horsepower requirements of round balers make round bale equipment less expensive to purchase and operate than square bale equipment, but the capacity of square balers is greater than round balers (compare Table 2-9 to Table 3-9). This document does not attempt to determine which system is better, but it does identify different advantages and disadvantages of each. When considering the overall supply system costs per ton, the larger capacity square bale system will report the lower costs per ton (compare Tables 2-12 and 2-13 to Table 3-10). However, feedstock supply systems are collections of many producer enterprises that supply many markets. As such, the optimization drivers for these independent enterprises might be different than the overall biomass supply system for biorefining. As an example, smaller, diversified producers who may not benefit from the increased capacity of large square bale systems, and may not need the handling advantage of square bales, may opt for the lower cost round bale systems for their respective enterprises. This is a key feature of the Uniform-Format supply system design. This design allows for a high-volume "standardized" biomass supply system to couple to a diversity of independently optimized production enterprises without imposing suboptimal requirements on either system. For example, the Pioneer Uniform supply system does not have to handle round bales into the biorefinery, nor do producers have to have the more expensive square bale harvest and collection equipment of the Conventional Bale design. In fact, the Uniform-Format design allows each enterprise to choose what is best to optimize the capacity and efficiency for their respective operations.

3.1.2.3 Operational Dry Matter Losses (complement of loss = harvest efficiency)

Dry matter loss in harvesting and collection systems (the complement of harvest loss [1-DM_harvest loss] is referred to as harvest efficiency) can be one of the biggest cost factors in both the Conventional Bale and Pioneer Uniform supply system designs (compare Tables 2-12 and 2-13 to Table 3-10). For harvesting and windrowing operations with corn stover and switchgrass, the factors affecting losses in the Pioneer Uniform design are as described for the Conventional Bale design in Section 2.1.2.2. In baling systems, harvest efficiency is a combination of many factors, including but not limited to biomass material size and physical properties, moisture content, and baler design. While it is not possible here to discuss every material-loss-inducing combination, a short discussion of some of the more frequently encountered effects is presented.

Baler design presents the greatest near-term opportunity for improving total harvest efficiency, but it is the interactions between baler design and the biomass material being baled that dictates the effectiveness of a design to control losses. For example, both square and round bale harvest and collection systems have a harvest efficiency of 38% (71% harvesting, 54% baling) in corn stover and 81% (90% harvesting, 90% baling) in switchgrass (compare Table 2-7 to Table 3-5).

These differential losses are the result of how biomass materials can perform differently in the various baler designs. Corn stover that has been in part passed through a combine and a shredding operation has been chopped and conditioned to the point that much of the anatomical structure of the plant has been broken up, resulting in many friable and detached small plant pieces. These smaller, more friable tissues do not readily mat onto the surface of the forming bale, and the rolling action of the round baler further disintegrates and separates these materials from the forming bale. These fine materials that do not mat to the bale surface create a pile of material inside the bale chamber that sifts through the baling belt gaps and is lost back to the field.

The harvesting process for switchgrass crushes the grass stems to accelerate drying, but does not severely destroy the plant structure. The more intact condition of the switchgrass (i.e., friable tissues are still connected to long stems) mats all of the material to the forming bale surface, thereby greatly reducing losses. The moisture content of the corn stover and switchgrass at the time of baling can also greatly affect losses. In the arid western states, baling is often suspended in the heat of the day when the biomass is at its lowest moisture levels to reduce baling losses (Grant 2003).

Conversely, large square bale systems have very little, if any, losses once the biomass material is in the baling chamber regardless of the material (i.e., corn stover or switchgrass) being baled. In a square baler, the biomass is stuffed into the baling chamber, and a 4×4-ft plunger compresses the material into a large "flake" to form a bale. This process does not rely on a matting process, and the square baler design provides no opportunity for material loss once the biomass is inside the baler.

The single-pass corn cob harvest system does not return the cob to the ground after grain harvest like in the Conventional Bale and Pioneer Uniform corn stover harvest systems. This single-pass system eliminates opportunity for field losses resulting from multiple harvest and collection processes. As such, cob losses are the result of threshing and separation processes within the single-pass harvesting system. Corn cob losses are generally the results of a tradeoff between whole cob purity and cob yield. Producing a higher purity cob stream will have the tendency to break up the cobs. Broken cob is not a problem in the CCM system, since those systems, by design, chop the cob. However, for the whole cob system modeled here, broken cob pieces can be lost in the cob separation system and returned to the field along with the MOC.

3.1.2.4 Operational Window

The operational window for harvesting and collection is the same for the Conventional Bale and Pioneer Uniform designs. See Section 2.1.2.3, which includes information on the harvest window and daily hours of operation.

3.1.3 Pioneer Uniform Harvest and Collection Cost and Sensitivity Analysis

3.1.3.1 Static Model Cost Summary

A breakdown 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 (Tables 3-10 and 3-11). These costs are reported in terms of DM tons entering each process respectively.

3.1.3.2 Cost Sensitivity Analysis

Histograms of the harvest and collection cost were produced for the scenarios shown in Table 3-12, and a sample histogram for the Pioneer Uniform—Stover Round scenario is shown in Figure 3-12.

The overall costs associated with the Pioneer Uniform harvest and collection unit operation for corn stover, switchgrass, and corn cobs are provided in Tables 3-13 and 3-14, on a per-DM-ton, per-bale, and per-acre basis. These costs, reported as a mean and

Table 3-10. *Static model costs for major harvest and collection equipment in the Pioneer Uniform—Switchgrass Round scenario. Costs are expressed in $/DM ton unless otherwise noted.*

Equipment	***Condition and Windrow Switchgrass***	***Baling***	***Move to Field side (Roadsiding)***
	Windrower with disc header	Large round baler	Stacker
Installed equipment quantities	49	208	45
Installed capitala	6.41	8.71	7.43
Ownership costsb	1.10	2.23	1.09
Operating costsc	1.71	10.53	0.99
Labor	0.32	1.49	0.28
Non-labor	1.40	9.04	0.71
DM loss costs	N/A	0.59	N/A
Energy use (Mbtu/DM ton)	30.6	31.0	20.1

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.

Table 3-11. *Static model costs for major harvest and collection equipment in the Pioneer Uniform—Cob scenario. Costs are expressed in $/DM ton unless otherwise noted.*

Equipment	Single-Pass Grain and Cob Harvest	Cob Transferred to Roadside	
	Combine with Corn Header, towing cob wagon	Cob Harvester	Dump Wagon with Tractor
Installed Equipment Quantities	365	365	122
Installed Capital[a]	129.34	31.76	14.66
Ownership Costs[b]	3.23	4.74	2.19
Operating Costs[c]	3.09	6.88	4.59
Labor	0.35	N/A	0.77
Non-Labor	2.73	6.88	3.82
Dry Matter Loss Costs	N/A	N/A	N/A
Energy Use (Mbtu/DM ton)	364.1	59.7	84.5

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.

***Table 3-12**. Summary of sensitivity analysis for harvest and collection. Values are presented in $/DM ton.*

	Mean ± Std Dev	Mode	90% Confidence Range	Static Model Value
Stover Round	$25.12 ± 3.16	$25.00	$20.29–$30.67	$23.31
Stover Square	$20.21 ± 1.90	$19.82	$17.36–$23.52	$20.12
Switchgrass Round	$22.45 ± 2.86	$20.55	$18.05–$27.45	$21.59
Switchgrass Square	$14.80 ± 1.34	$14.98	$12.72–$17.11	$14.99
Cob	$24.68 ± 1.01	$23.99	$23.17–$26.48	$24.71

Figure 3-12. Pioneer Uniform—Stover (Round) harvest and collection cost distribution histogram from @Risk analysis.

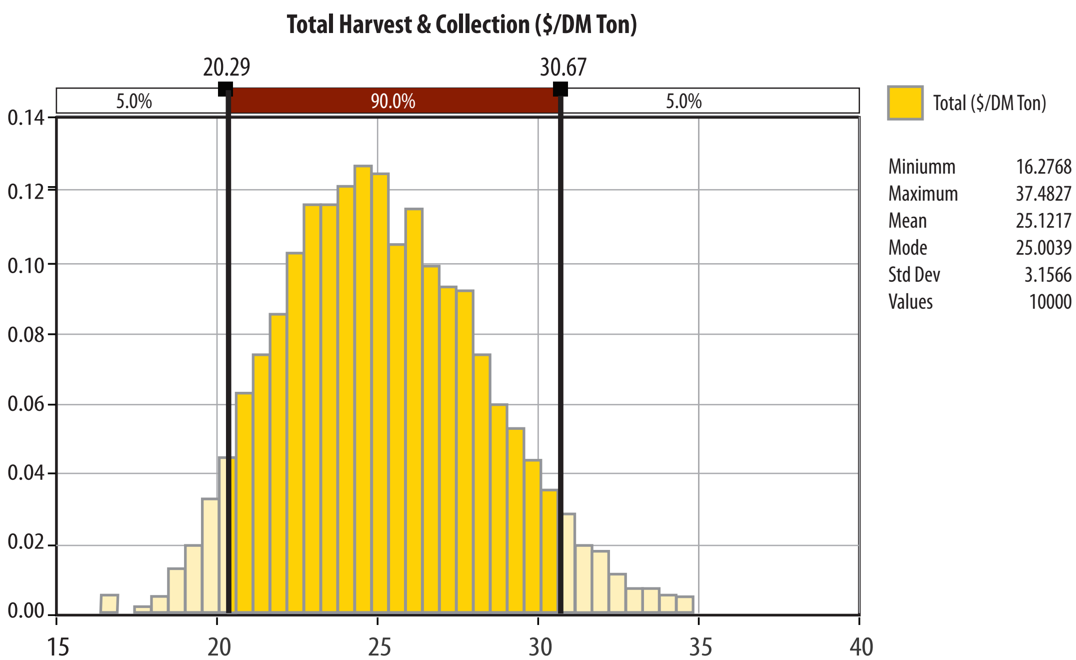


Table 3-13. Harvest and collection cost summary for the Pioneer Uniform corn stover, switchgrass, and corn cob scenarios.

Logistics Processes	***Grain Harvest Only***[a]	***Condition/ Windrow***	***Baling***				
Roadside	Dry Matter Loss	Total Harvest & Collection Round	Total Harvest & Collection Square				
STOVER							
Equipment	Combine with 8-row corn header	15-ft flail shredder with windrowing pulled by 180 tractor	Super M large round 5.5×4-ft	Stacker	–	–	–
Modeled Cost Totalsb	No Cost	3.90 ± 0.61 ($/DMton)	14.17 ± 2.72 ($/DM ton)	2.57 ± 0.33 ($/DM ton)	3.65 ± 1.07 ($/DM ton)	25.12 ± 3.16 ($/DM ton)	20.21 ± 1.90 ($/DM ton)
	No Cost		5.96 ±1.08 ($/bale)	1.08 ± 0.12 ($/bale)		7.39 ± 1.08 ($/bale)	7.40 ± 0.51 ($/bale)
	No Cost	11.49 ± 1.43 ($/acre)	22.07 ± 5.38 ($/acre)	3.99 ± 0.78 ($/acre)	5.48 ± 0.97 ($/acre)	43.03 ± 5.90 ($/acre)	36.67 ± 3.66 ($/acre)
SWITCHGRASS							
Equipment	–	Windrower with disc header	Super M Large round 5.5×4-ft	Stacker	–	–	–
Modeled Cost Totalsb	–	5.71 ± 1.20 ($/DM ton)	12.77 ± 2.42 ($/DM ton)	2.31 ± 0.29 ($/DM ton)	0.90 ± 0.29 ($/DM ton)	22.45 ± 2.86 ($/DM ton)	14.80 ± 1.34 ($/DM ton)
	–		5.96 ± 1.08 ($/bale)	1.08 ± 0.12 ($/bale)		7.39 ± 1.08 ($/bale)	7.40 ± 0.51 ($/bale)
	–	22.48 ± 1.99 ($/acre)	45.00 ± 12.09 ($/acre)	8.15 ± 1.84 ($/acre)	3.03 ± 0.69 ($/acre)	78.67 ± 13.46 ($/acre)	53.26 ± 8.57 ($/acre)

Table 3-14. *Harvest and collection cost summary for the Pioneer Uniform—Cob scenario.*

Logistics Processes		Single-Pass Grain/ Cob Harvest	Single-Pass Grain/ Cob Harvest	Roadside	Dry Matter Loss	Total Harvest and Collection
COB						
Equipment	–	Combine with 8-Row Corn Header, towing cob wagon	Cob Harvester	180 hp MFD Dump Wagon	–	–
Modeled Cost Totals[b]	–	6.16 ± ($/DM ton)	11.58 ± 0.62 ($/DM ton)	5.40 ± 0.29 ($/DM ton)	N/A	24.68 ± 1.01 ($/DM ton)
	–	0.02 ± 0.00 ($/unit)	0.05 ± 0.00 ($/ton)	0.02 ± 0.00 ($/ton)	N/A	0.09 ± 0.01 ($/unit)
	–	4.68 ± 0.21($/acre)		4.10 ± 0.13 ($/acre)	N/A	17.54 ± 0.29 ($/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

standard deviation, come as a result of 10,000 model iterations of the simulated Pioneer Uniform feedstock supply system.

3.2 PIONEER UNIFORM 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 3-13). Just as in the Conventional Bale design, the Pioneer Uniform storage design does not include biomass material stabilization (i.e., drying or ensiling) for corn stover or switchgrass, because stabilization of the biomass material occurs with the field drying process in the harvest and collection unit operation.

The storage configuration for the Pioneer Uniform design is field-side, plastic-wrapped, one-bale-wide by two-bale-high stacks for square bales (Section 2.2.1) and net-wrapped round bales set field side in rows one-bale high (Figure 3-14). A major advantage of round bales over square bales is that they do not require a shelter for storage, as the shape allows water to shed (Cundiff and Marsh 1995). The selection of the best storage protection strategy depends on 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 3-13).

Storage requirements for the Pioneer Uniform—Square scenarios are identical to the Conventional Bale system. For this reason, Section 2.2 in the Conventional Bale supply system applies to the Pioneer Uniform system as well. Additional storage requirements are necessary for the round bales and corn cobs and to interface with preprocessing equipment.

For corn cobs, field-side or near field-side piles are used for storage in this design (Figure 3-15). These are not massive 100-ft, 10,000-ton cob piles that are occasionally built by large-scale cob-product manufacturers, but rather they are small windrow-type piles, about 14×200-ft, and 300 tons total (depending on the amount of husks mixed in with the cobs), formed by dumping the cobs directly from the cob cart along the edge of the field. The design does not use a loader to make the piles taller than the cart dump height. The size of each pile is equivalent to the yield of cob from a harvest area of about 350 acres, assuming a cob dry matter yield of 0.77 ton/acre (for 180 bu/acre grain). Unlike the stover and switchgrass designs, the single-pass harvest operation for cobs does not allow for field drying, so some change in cob moisture content will occur in storage.

(Note: 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 3-14. Row of round bales wrapped with plastic with a modified baler to bind the bale rather than using twine.

Figure 3-15. On-farm corn cob storage pile located at or near field side.

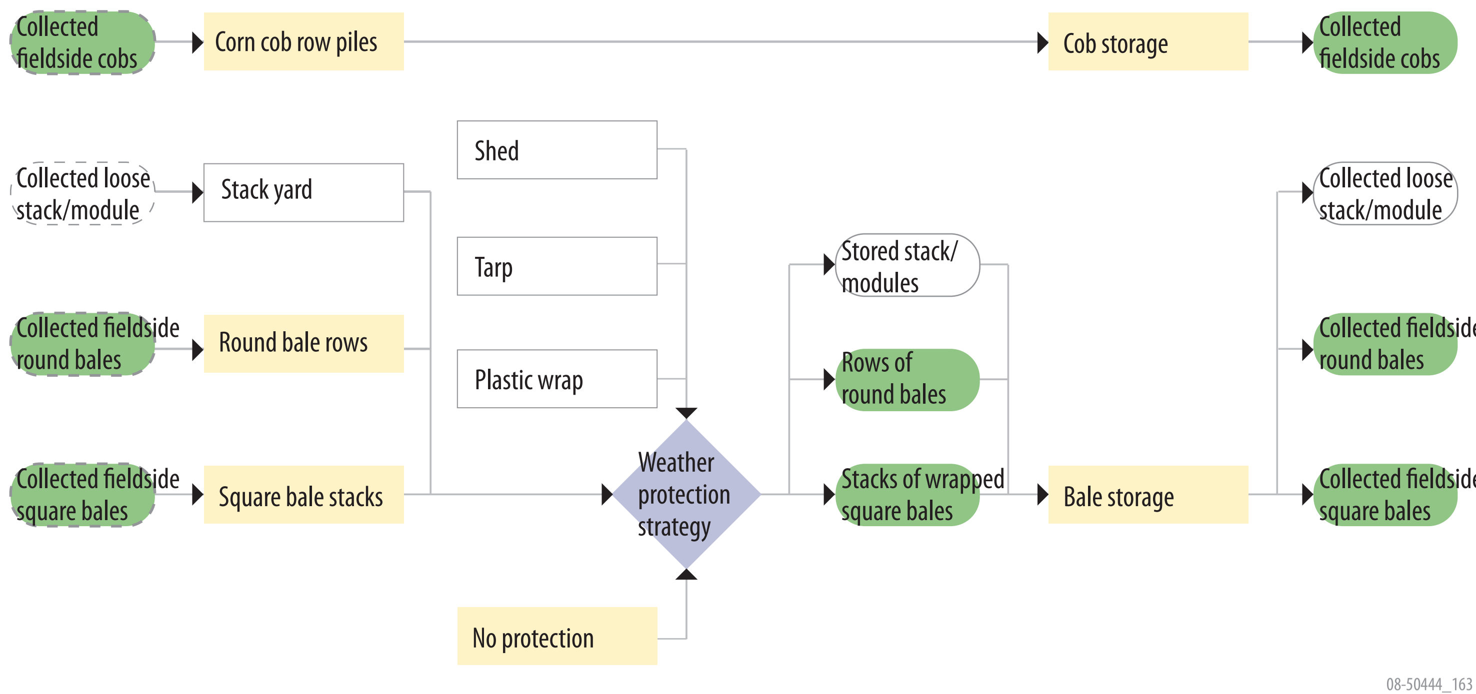


Figure 3-13. Storage supply logistic processes and format intermediates.

3.2.1 Pioneer Uniform Storage Format Intermediates

As with the Conventional Bale design storage system, the objective of the Pioneer Uniform storage system is to maintain the original biomass properties throughout the duration of storage. However, in practice, there will always be some change resulting in biomass loss during storage, often referred to as shrinkage. The mechanism of biological impacts and moisture content increases would be similar for round and square bales (Section 2.2.1), although different in magnitude. Unlike square bales, round bales are formed such that moisture does not penetrate to the center of the bale, so they are not plastic wrapped. Figure 2-11 illustrates the expected range of round bale shrinkage for different storage configurations in wet climates. Pioneer Uniform—Stover Round scenario storage attributes are influenced by the fact that the round bales are net wrapped for long-term storage, rather than plastic wrapped. Table 3-15 outlines the attributes of round bales and cob piles during storage. Shinners et al. 2006 showed that the net-wrapped round bales had about 60–70% lower DM losses than bales wrapped with sisal twine and 25–30% lower DM losses than bales wrapped with plastic twine.

Feedstock Variety

Feedstock type in bulk dry storage shares many commonalities with the bale storage mentioned in the Conventional Bale design (Section 2.2). The composition of feedstock types in bulk dry storage will depend greatly on geographical location, as the crops that are available in a given area will determine what will be stored. This will create a wide range of macronutrient and soluble sugar levels in bulk storage structures across the country.

Geographical location will also determine how often a storage structure is used, depending on whether a location employs a single harvest or multiple harvests throughout the year. The capital investment cost of storage structures are typically amortized over 20 years, and the cost per ton is based on the number of times that a structure can be used throughout the year. Therefore, a structure used only once a year will be twice as expensive (on a per ton basis) as a structure used twice a year.

Environmental and Human Health

Bulk storage of dry cellulosic materials such as cobs poses a fire hazard, which is a low-probability but high-cost risk. Sources of ignition include, but are not limited to, equipment failures resulting in sparks,

Table 3-15. *Attributes of storage format intermediates for corn stover, a crop residue, and switchgrass, a dedicated energy crop.*

	Stacked Bales	***Stored Bales***	***Stored Cobs***	***Stacked Bales***	***Stored Bales***
Biomass Output	Stover	Stover	Cobs	Switchgrass	Switchgrass
Yielda (DM tons/stack)	200	190	277 (ton/pile)	200	190
Format Output	Rows of round bales, stacked 1 bale wide and 1 bale high at field side	Rows of round bales, stacked 1 bale wide and 1 bale high at field side	Loose cobs, piled 14-ft high at field side	Rows of stacked round bales at field side, 1 bale wide × 1 bale high	Rows of stacked round bales at field side, 1 bale wide × 1 bale high
Bulk DM Density Output	9.0 lb/ft^3 stack[b] (0.13 acres/stack)	9.0(lb/ft^3) stack[b] (0.13 acres/stack)	8.0 (lb/ft^3)	9.4(lb/ft^3) stack[b] (0.11 acres/stack)	9.4(lb/ft^3) stack[t] (0.11 acres/stack)
Output Moisture (% w.b.)	12%	12%	34%	12%	12%

a. Model assumes 5% shrinkage of yielding DM tons during storage for stored bales (i.e., loss of original biomass DM); actual wet tons may be equal to or greater than starting tonnage (Table 2-7). Model assumes 16% shrinkage of yielding DM tons during storage for stored cobs.
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.

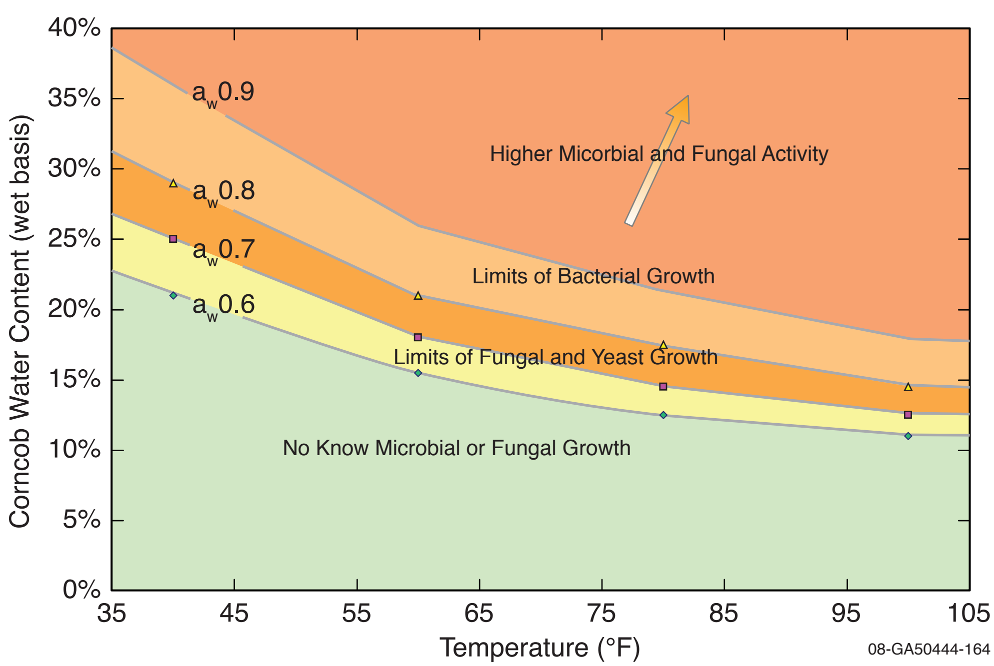
sparks or embers from nearby controlled burns (weeds or other refuse), lightning strikes, malicious acts such as arson, and spontaneous ignition (similar to bale and silo fires). The latter is the most complicated and least understood risk (Buggeln and Rynk 2002) and is therefore difficult to quantify.

Spontaneous heating to the point of combustion occurs rarely and is generally associated with the storage of densely packed natural materials in the range of 30–80% water content (Buggeln and Rynk 2002, Nelson et al. 2007, Li et al. 2006, Festenstein 1971, and OMAFRA 1993). Stover moisture content at the time of grain harvest is typically 40–66% (w.b.), and cobs are reported to be approximately 10% less (Pordesimo et al. 2004). Spontaneous heating in biomass occurs as a result of cellular respiration by either the freshly harvested plant matter or the bacteria and fungi associated with it and occurs in the range of 30–80°C (80 to 180°F), sometimes referred to as biological self-heating. Biological self-heating is self-limiting, as most enzymatic reactions responsible for biological activity stop before temperatures reach 80°C, and increased evaporation rates have greatly reduced the water necessary for biological activity. Figure 3-16 demonstrates the effect of microbial activity—the primary cause of dry matter and structural sugar loss in storage—with increasing water content in cobs.

Spontaneous combustion requires: (1) an initial heat source (often provided by biological self-heating), (2) insulation to trap heat and permit temperatures to rise to the point of ignition, and (3) the proper mix of reactive materials to support combustion (Buggeln and Rynk 2002). Factors implicated in spontaneous combustion include moisture content, packing density, heat loss, air circulation in pile, pile size, and time in storage (Buggeln and Runk 2002). However, there is no simple relationship among these factors that allows the construction of a general model for predicting spontaneous combustion risks (Li et al. 2006).

Reports suggest that cob pile size is an important factor that affects heat loss and air circulation; additionally, large piles are often stored for longer periods of time (Buggeln and Rynk 2002). For example, a fire which started on December 27, 2008 in a 10-story high, 17,000-ton pile at the Anderson

Figure 3-16. Corn cob water content and relative microbial activity over a range of temperatures, based upon water activity to water content data taken from Foley 1978.



Grain in Delphi, Indiana, (DuBose 2008), burned for nearly 2 weeks before it was brought under control. An earlier fire at the same plant in December 1989 burned within a 35,000-ton pile for 9 days before being extinguished. No cause for either fire has been reported.

As a result of the uncertainties surrounding spontaneous combustion in stored cobs and the association of fires with large pile size, pile dimensions in this design were kept small to allow for heat dissipation and reduce the risk of injury to workers and the surrounding community and avoid catastrophic feedstock loss.

Mold spores are another major human health concern, and biomass that has more than the moisture threshold for dry storage could be at high risk of mold growth. Mold would be a factor in bulk storage as the high amount of surface area would increase human exposure concerns. Most exposure from the mold spores would occur during the movement of biomass from storage to transportation. Dust is also an issue in the handling of bulk stored biomass, and mitigation techniques for mold and dust handling would need to be in place.

See Section 2.2.1 for further discussion of the environmental and human health considerations when storing large amounts of biomass.

3.2.1.1 Biomass Deconstruction, Fractionation, and Yield Losses

Deconstruction, fractionation, and yield losses relating to round bales are similar to that of square bales discussed in the Conventional Bale design (Section 2.2.1.1), thus they are not repeated here.

3.2.1.2 Format and Bulk Density Impact on Supply System Processes

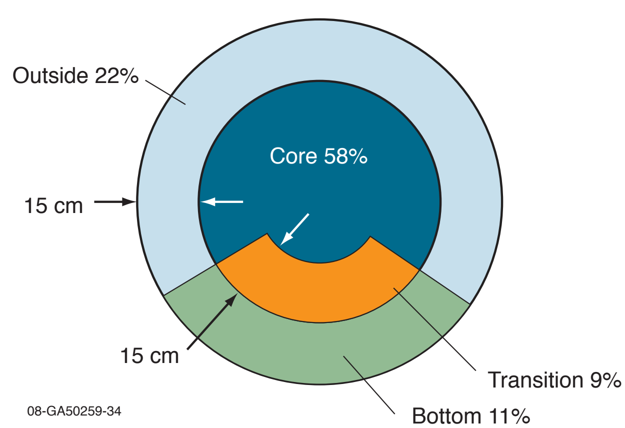
Round bales can be difficult to store because they do not stack well. It is recommended to store round bales in a shed to keep them as dry as possible. If this is not possible, the bales must be stored on a well-drained surface (preferably on crushed rocks) with space between the bales to allow for the free shedding of rainwater. Rider et al. (1979) classified different portions of a round bale according to susceptibility of each portion to deterioration (Figure 3-17). As a round bale settles, approximately 33% of its circumference contacts the ground. A substantial amount of moisture can be absorbed through this contact area, resulting in spoilage as far as 12 in. (30 cm) into the bale. If the weather affects the outer 6 in. (15 cm) of the round bale that is not in contact with the ground, plus an additional 6 in. at the bottom, as much as 42% of the total bale volume can be affected. Assuming a uniform bale density, the outer 6 in. of a round bale accounts for more than 20% of the total mass of the bale for a 5.5-ft diameter × 4-ft long bale.

The Pioneer Uniform storage system incorporates square bales, 5.5-ft diameter × 4-ft long round bales, and cobs. As mentioned in Section 2.2.1.2, various factors can influence the negative impacts of storage systems including bale or pile size, stack configuration, bulk density, moisture content, and whether storage is on a well-draining surface.

The round bale design lays net-wrapped round bales horizontally, end-to-end in a row. This configuration does not minimize the stack footprint; however, it reflects common practice for optimizing their water shedding ability. If land use is inexpensive and available, as this design assumes, this configuration is a cost-effective storage solution.

The large round bales are transported to the field side and generally placed in a well-drained environment.

Figure 3-17. Division of a round bale (adapted from Rider et al. [1979]). Weather impacts were shown to affect the outer 6 in. (15 cm) of the bale in a 5-ft diameter × 4-ft thick bale.



The bales are placed back-to-back in long cylindrical rows to minimize the trapping or channeling of moisture between bales and separate rows of bales. Round bales are less prone to water penetration than are square bales, and net wrapping helps round bales shed water. The specific impacts of moisture on storage stability for round bales in comparison to square bales are discussed in Section 2.2.1.3.

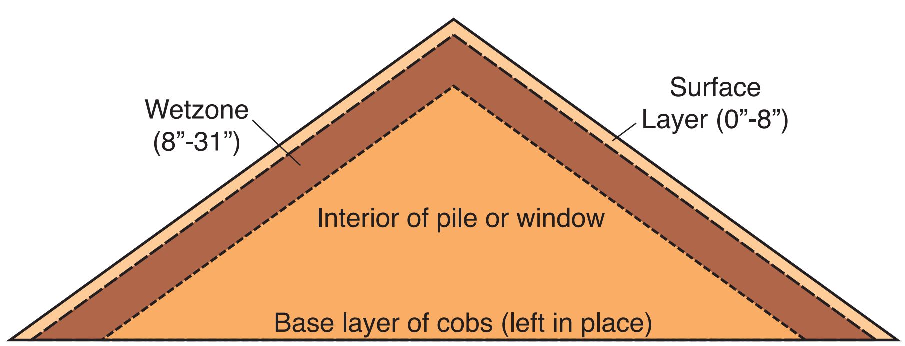
3.2.1.3 Biomass Moisture Impact on Supply System Process and Material Stability

Cobs are stored directly on the ground in unventilated field-side piles. Moisture contents within the outdoor-stored cob piles have been found to increase in annual storage (Dunning et al. 1948, Smith et al. 1985), primarily in the outer 1–3 ft, resulting in a subsequent loss in dry matter and structural sugars over time (Smith et al. 1985). Ventilating the piles reduced dry matter losses from ~33–20%. Changes of greater than 1,000 ton have been observed in farm-scale piles such as employed in this design and in industrial-scale piles (Smith et al. 1985). Regardless of scale, the inner-most region of the cob piles exhibits less change relative to the starting materials. However, due to the dramatic increase in moisture content in the outer-most regions, the bulk moisture content of the cob pile tends to increase. The depth of the outer wetted layer is independent of pile size, and as a result the larger surface-area-to-volume ratio is a key contributor to moisture and composition changes in storage. Thus, bulk moisture content of larger piles is expected to be lower than that of smaller piles stored under identical conditions. Additionally, increased dry matter loss and degradation of the structural sugars was associated with the wet regions (Smith et al. 1985). Despite this result, distributed storage of smaller piles and windrows onsite was selected for the Pioneer Uniform design for logistic (transportation by cob cart to the local pile) and safety (fire risk) reasons.

The results from Smith et al. (1985) were used to construct a geometric model to predict final bulk moisture contents and dry matter loss in outdoor cob piles (Figure 3-18). Using this model, small piles and windrows up to 300 ft are estimated to be within the range of 40–45% moisture content when storing cobs with 34% moisture content for one year. Bulk moisture contents are predicted to be only 29% in 100-ft piles. Increasing pile size to 100 ft results in predicted dry matter loss of only 12% compared to the 18–21% predicted in the smaller piles and windrows, but increases the material handling and transportation costs by placing a large receiving facility between the field and the biorefinery.

Cundiff and Marsh (1995) studied the impact of dry matter loss from round bales of switchgrass stored outdoors. In general, higher initial moisture content and longer storage times caused increased dry matter loss. Also, ground storage on a well-draining surface reduces dry matter losses. Johnson et al. (1991) found that storing bales on rock decreased dry matter loss. Heslop and Bilanski (1986) reported that in Western

Figure 3-18. Modeled moisture zones of cob pile stored outdoors. The thickness of the outer surface layer is independent of pile size, and therefore fewer large piles would encourage dry matter preservation.



Canada the loss of dry matter in round bales, as a result of outdoor storage, was 4–8%. Wrapping bales is a commonly used method of reducing moisture infiltration, and therefore reduces dry matter loss.

3.2.2 Pioneer Uniform Storage Equipment

Storage equipment in the Pioneer Uniform design is the same for both corn stover and switchgrass scenarios (Table 3-16). The stacking is operationally coupled to the roadsiding process in harvest and collection. The bale collection equipment brings the biomass to the field-side storage site (which has a 200 ton/site capacity) and drops the bales on the ground. Table 3-16 shows the storage equipment specifications for the Pioneer Uniform design.

TThe Stinger Stacker 5500 is used for square-bale handling in this design scenario and is described in Section 2.2.2. Round bales are handled using a Stinger 5500 (without the stacker). Cobs are placed in a roadside pile directly from the Sunflower 8210 Dump Wagon (Figure 3-19).

3.2.2.1 Equipment Capacity and Operational Efficiency

Cobs are placed in a roadside pile directly from the Sunflower 8210 Dump Wagon onto the ground (Figure 3-19). After being moved to the field side, a two-wheel-drive John Deere tractor loader JD 6115D, 115 hp (95PTO) with spear loader is used to arrange the round bales in a row. The bales were net wrapped during harvest and collection to reduce dry matter losses. The stack capacity is limited by international fire code, which allows a maximum 100 ton/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 depreciated over 20 years with a repair and maintenance factor of 2% of initial costs annually.

3.2.2.2 Dry Matter Losses (Shrinkage)

Placing bales on an improved surface that moves drainage away from the bales (for example, gravel) helps reduce losses. However, as discussed in Section 2.2.2.2, the losses would have to be in excess of 16% to cover the cost of the improved site, and construction of the surface is likely not practical.

Table 3-17 shows a comparison of dry matter losses in various scenarios and the estimated ownership costs of improvements and dry matter loss.

From Table 3-18, dry matter losses were estimated to range between $0.4 and $4.30/DM ton, and were higher in wet climates than in dry climates. In many cases, the cost of improving the site to reduce dry

Table 3-16. *Storage equipment specifications for the Pioneer Uniform design.*

	Square Bale Stack	Square Bale Plastic Wrapper	Round Bale Stack	Storage
Equipment	Telehandler	Cube-Line Wrapper	Tractor with Spear Loader	None
Rated Capacity (ton/acre)	80 bales/hr	80 bales/hr	110.8 bales/hr	N/A
Operational Efficiency (%)a	80%	67	100%	N/A
Dry Matter Loss (%)				
0%	5[c]	5%	7%	
Operational Window				
hr/day	12	12	12	24
day/year	36	36	36	365

a. Estimate of the space utilization efficiency relative to corn grain.
b. Loss without protection in a semi-arid environment.
c. Loss with the identified protection in a moderate environment.

Figure 3-19. Sunflower 8210 dump wagon.

matter losses was found to be higher than the cost of the dry matter loss. For dry climates, the ownership costs were lower than the dry matter loss for stacking on the ground with and without an improved surface. When considering a wet climate, it was also more economic to cover the stack on the ground than to accept the material loss.

3.2.2.3 Operational Window

The storage operation begins at the point of roadsiding; therefore, there is no limitation on the operational window that may impact subsequent operations.

Table 3-17. 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).
b. Multiple data sources; (Appendix A-2).
c. Ownership costs are based on a structure to accommodate 100 DM tons, property tax of $300/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/ft2 and concrete hardstand at $3.00/ft2. (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).

Table 3-18. *Static model costs for major storage equipment in the Pioneer Uniform corn stover and switchgrass scenarios. (Values are expressed in $/DM ton unless otherwise noted.)*

	Equipment	***Square Bale Stack***	***Square Bale Plastic Wrapper***	***Round Bale Stack***	***Storage***
		Telehandler	***Stinger Wrapper***	***Tractor loader with Spear Loader***	***Insurance, Land Rent, Stack Maintenance***
Corn Stove	Installed Equipment Quantity	43	43	47	N/A
Corn Stove	Installed Capital[a]	3.55	2.04	12.83	N/A
Corn Stove	Ownership Costs[b]	0.47	0.30	0.25	0.28
Corn Stove	Operating Costs[c]	0.42	5.41	0.62	N/A
Corn Stove	Labor	0.29	0.29	0.29	N/A
Corn Stove	Non-Labor	0.14	5.12	0.33	N/A
Corn Stove	Dry Matter Loss Costs	N/A	N/A	N/A	1.24
Corn Stove	Energy Use (Mbtu/DM ton)	4.5	3.0	6.0	N/A
Switchgrass	Installed Equipment Quantity	39	39		45
Switchgrass	Installed Capitala	3.22	1.85	11.86	N/A
Switchgrass	Ownership Costs[b]	0.42	0.27	0.24	0.27
Switchgrass	Operating Costs[c]	0.38	4.87	0.59	N/A
Switchgrass	Labor	0.26	0.26	0.28	N/A
Switchgrass	Non-Labor	0.12	4.61	0.32	N/A
Switchgrass	Dry Matter Loss Costs	N/A	N/A	N/A	1.15
Switchgrass	Energy Use (Mbtu/DM ton)	4.0	2.7	5.7	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).

Table 3-19. *Summary of sensitivity analyses for storage using static model. Values are presented in $/DM ton.*

	Mean ± Std Dev	Mode	90% Confidence Range	Static Model Value
Round Bale Stover	$1.57 ± 0.41	$1.62	$0.93–$2.26	$1.52
Square Bale Stover	$8.03 ± 0.61	$7.97	$7.03–$9.06	$8.12
Round Bale Switchgrass	$1.41 ± 0.36	$1.31	$0.84–$2.03	$1.42
Square Bale Switchgrass	$7.06 ± 0.49	$7.00	$6.27–$7.89	$7.16
Corn Cob	$4.38 ±0.41	$4.30	$3.72–$5.08	$4.58

3.2.3 Pioneer Uniform Storage Cost and Sensitivity Analysis

3.2.3.1 Static Model Cost Summary

A breakdown 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 3-18). These costs are reported in terms of DM tons entering the storage process.

3.2.3.2 Cost Sensitivity Analysis

Histograms of the storage cost were produced for the scenarios shown in Table 3-19, and a sample histogram for the round bale corn stover scenario is shown in Figure 3-20 (histograms for all scenarios are

Table 3-20. *Storage cost summary for the Pioneer Uniform corn stover and switchgrass scenarios.*

	Equipment	Square Bale Stack	Square Bale Plastic Wrapper	Dry Matter Loss (Square Bale)	Round Bale Stack	Storage (Round Bale and Cob Pile)	Dry Matter Loss (Round Bale or Cob Pile)	Total Round Bale or Cob Pile Storage	Total Square Bale Storage
		Telehandler	Stinger Wrapper		Tractor loader with Spear Loader	Insurance, Land Rent, Stack Maintenance			
Corn Stover	Modeled Cost Totals[a]	0.90 ± 0.08 ($/DM ton)	5.65 ± 0.34 ($/DM ton)	1.37 ± 0.41 ($/DM ton)	0.83 ± 0.05 ($/DM ton)	1.57± 0.41 ($/DM ton)	1.30 ± 0.41 ($/DM ton)	1.57 ± 0.41 ($/DM ton)	8.03 ± 0.61 ($/DM ton)
		0.52 ± 0.03 ($/bale)	3.30 ± 0.03 ($/bale)	0.80 ± 0.24 ($/bale)	0.35 ± 0.002 ($/bale)		0.55 ± 0.17 ($/bale)	0.66 ± 0.17 ($/bale)	4.69 ± 0.24 ($/bale)
Switchgrass	Modeled Cost Totals[a]	0.81 ± 0.07 ($/DM ton)	5.09 ± 0.28 ($/DM ton)	1.06 ± 0.31 ($/DM ton)	0.75 ± 0.04 ($/DM ton)	1.41 ± 0.36 ($/DM ton)	1.16 ± 0.36 ($/DM ton)	1.41 ± 0.36 ($/DM ton)	7.06 ± 0.49 ($/DM ton)
		0.53 ± 0.03 ($/bale)	3.30 ± 0.03 ($/bale)	0.69 ± 0.20 ($/bale)	0.35 ± 0.002 ($/bale)		0.54 ± 0.17 ($/bale)	0.66 ± 0.17 ($/bale)	4.58 ± 0.21 ($/bale)
Corn Cobs	Modeled Cost Totals[a]	N/A	N/A	N/A	± $/DM ton	4.38 ± 0.41 ($/DM ton)	4.29 ± 0.41 ($/DM ton)	4.38 ± 0.41 ($/DM ton)	
						525.11 ± 275.28 ($/pile)		525.11 ± 275.28 ($/pile)	

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

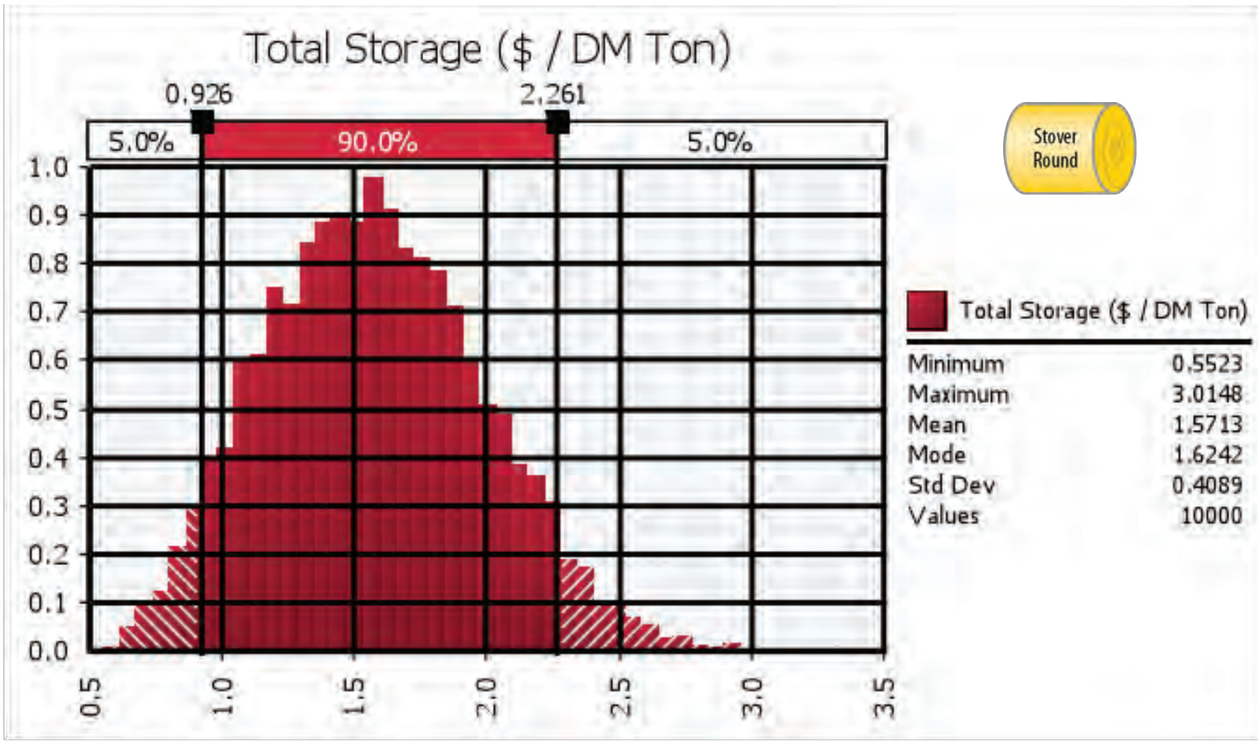


Figure 3-20. Pioneer Uniform—Corn Stover (Round) storage cost distribution histogram from @Risk analysis.

presented in Appendix 3).

The overall costs associated with the Pioneer Uniform storage unit operation for corn stover, switchgrass, and corn cobs are provided in Table 3-20 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.

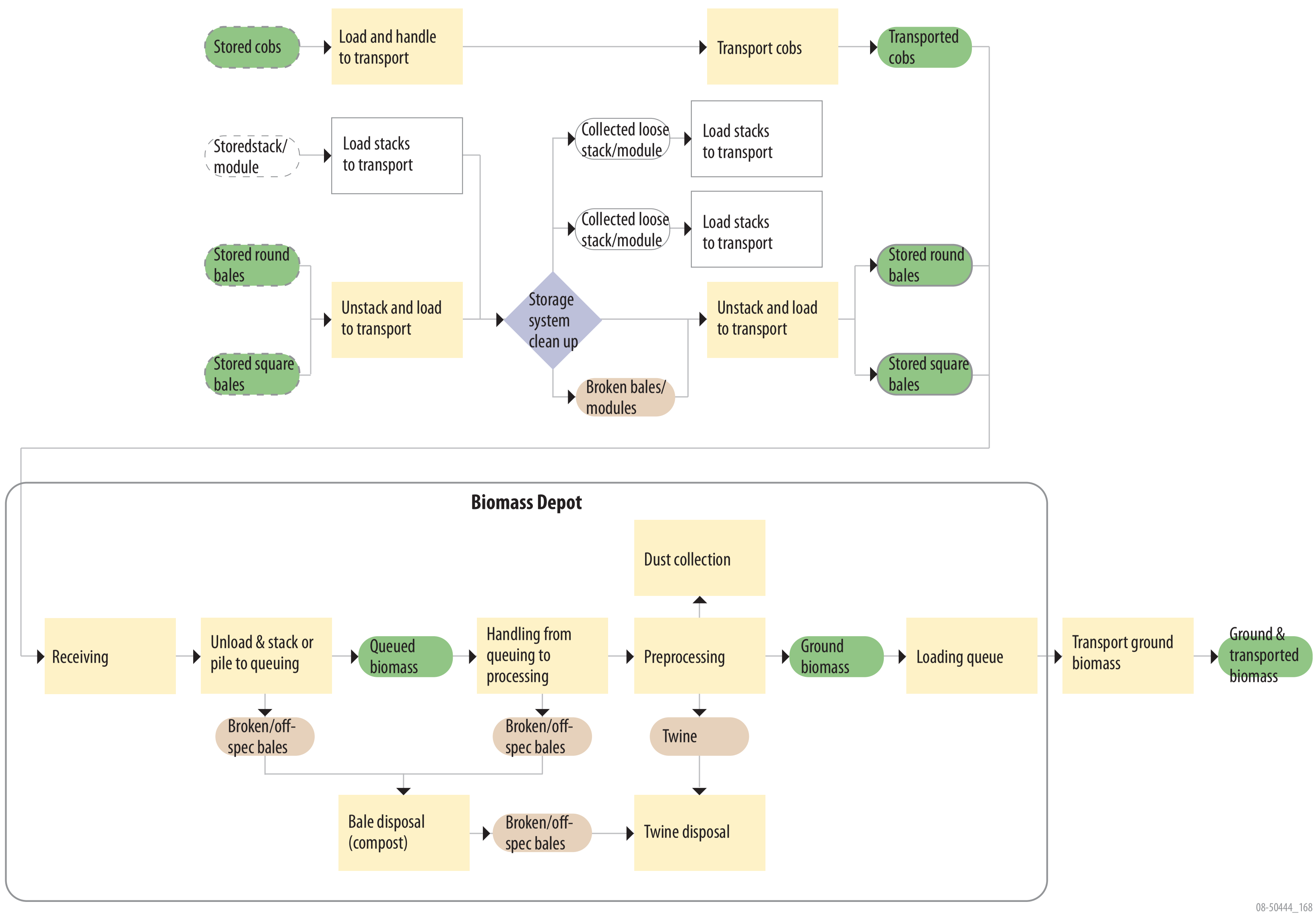


Figure 3-21. Preprocessing and transportation supply logistic processes and format intermediates.

(Note: 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.)

3.3 PIONEER UNIFORM PREPROCESSING AND TRANSPORTATION

Distributed preprocessing (grinding) is established as part of the Pioneer Uniform design to manage feedstock diversity upstream of the biorefinery and allow receiving and handling systems at the biorefinery to be reduced to a specific uniform feedstock format. This design minimizes capital costs at a biorefinery by eliminating the need for multiple receiving lines necessary to accept various feedstock formats such as square bales, round bales, loose bulk material, etc. Thus, the preprocessing operation is moved forward in the supply system from just before the conversion process to just after field-side storage (Figure 3-21). In general, the forward-deployed preprocessing unit will match the preprocessing operation modeled in the Conventional Bale design in terms of equipment, operating parameters, and operating time. The primary advantage of a forward-deployed preprocessing unit (referred to in this report as a Biomass Depot) is its ability to accept and process any feedstock format, including square or round bales, broken bales, loose material, and unprocessed bulk material (i.e., corn cobs) and deliver a uniform-format feedstock to the biorefinery.

Locating the biomass depot as early in the supply system as possible provides an opportunity to add value to the biomass and other unit operations to improve the overall efficiency and capacity of the system. This is done by putting the biomass into a bulk-flowable format early in the supply system, such that handling and transportation logistics and costs are significantly reduced. In addition, the biomass depot provides a distributed queuing system that reduces the quantity of feedstock and the associated capital to queue at the biorefinery. Thus, the biomass depot is a key component in the Pioneer Uniform design in that it provides flexibility in feedstock format, improves the efficiency and capacity of downstream operations, and reduces capital investment at the biorefinery.

Since transportation distance is still a key factor in the cost of moving feedstocks from the field to the biorefinery, the biomass depot is located such that it minimizes the overall handling and transportation cost primarily as a function of feedstock bulk density. Thus, the biomass depot is located closer to the biomass production site than the biorefinery because the bulk density of baled or loose bulk feedstocks leaving the fields is increased through preprocessing at the biomass depot. The shorter distance between the biomass depot and the production site allows lower density feedstocks to be cost competitive with higher density feedstocks in this design. As a result, the biomass depot is particularly advantageous for accepting round bales that, due to higher transportation costs, may be cost prohibitive in a centralized grinding design (i.e., at the biorefinery) such as the Conventional Bale design. The specific logistics and cost components of handling and transporting baled feedstocks is the same as discussed in Section 2.3 of the Conventional Bale design. Additional information on handling, transporting, and preprocessing bulk material (i.e., corn cobs) is presented in the following sections.

3.3.1 Pioneer Uniform Preprocessing and Transportation Format Intermediates

The same feedstock attributes that affected preprocessing in the Conventional Bale design affect preprocessing in the Pioneer Uniform design. Some minor changes are discussed that account for improvements in the material format to help optimize adjacent unit operations (Table 3-21). Of primary consideration are the handling and transportation processes, which occur directly after preprocessing. Unlike at the biorefinery, preprocessing must at the very least achieve bulk densities comparable to baled material, but ideally be much higher to allow for optimization of the handling and transportation system. Thus, the new bulk density requirement for preprocessing is the bulk density required to put the maximum amount of weight on a tractor-trailer unit within the given state road limits (Section 2.2.2.2).

Preprocessing must also adhere to more stringent bulk-flowability requirements because the material must be handled within the transportation, receiving, and biorefinery queuing systems and not just the metering bins before the conversion process, as discussed in the Conventional Bale design. A discussion of bulk density attributes is presented in this section of the report, and a discussion of

Table 3-21. *Attributes of preprocessing and transportation format intermediates for corn stover and corn cobs (crop residues) and switchgrass (a dedicated energy crop).*

Operation	Load/Unload Bale Transport	Transport to Depot	Bale/Bulk Queue for Preprocessing	Bulk Queue for Transport	Transport to Biorefinery
Stover Round					
Yield (DM ton/day)	2,600 (34 bales/truck)	2,600 (34 bales/ truck)	2,600		2,600
Format Output	Unwrapped round bales loaded on flatbed trailer	Round bales on bale conveyor	Bulk (1.5-in. minus)	Bulk (1.5-in. minus)	Bulk (1.5-in. minus)
Bulk DM Density Output	9.0 (lb/ft^3)	9.0 (lb/ft^3)	7.4 (lb/ft^3)	7.4 (lb/ft^3)	7.4 (lb/ft^3)
Output Moisture (% w.b.)	12	12	12	12	12
Switchgrass Round					
Yield (DM ton/day)	2,600 (34 bales/truck)	2,600 (34 bales/ truck)	2,600		2,600
Format Output	Unwrapped round bales loaded on flatbed trailer	Round bales on bale conveyor	Bulk (1.5-in. minus)	Bulk (1.5-in. minus)	Bulk (1.5-in. minus)
Bulk DM Density Output	9.4 (lb/ft^3)	9.4 (lb/ft^3)	10.3 (lb/ft^3)	10.3 (lb/ft^3)	10.3 (lb/ft^3)
Output Moisture (% w.b.)	12	12	12	12	12
Cob					
Yield (DM tons/day)	–	2,600	2,600		2,600
Format Output	–	Cobs with some husks	Bulk (1.5-in. minus)	Bulk (1.5-in. minus)	Bulk (1.5-in. minus)
Bulk DM Density Output	–	8 (lb/ft^3)	14 (lb/ft^3)	14 (lb/ft^3)	14 (lb/ft^3)
Output Moisture (% w.b.)	–	34	12	12	12

flowability attributes is presented in Section 3.4.2, Receiving and Handling.

Based on the two baled feedstock formats modeled in the Pioneer Uniform design (square and round), trucks arriving at the biomass depot are weighed and unloaded into either a very short-term queuing yard (~200 tons) or directly into the preprocessing system. Since the grinding units used in this design are the same as those used in the Conventional Bale design, the feedstock characteristics discussed in Section 2.4.1 still apply. The ground feedstock coming out of the preprocessing system is queued in evenflow metering bins that feed the bulk transport system. The short-term queuing yard and queuing bins at the biomass depots provide the biorefinery with a distributed queuing system (~2300 ton, or a 1-day supply), which minimizes some risks due to weather delays, field conditions, or other feedstock security issues. The bale and bulk queuing systems are still subject to fire code constraints as discussed in Section 2.4.1.

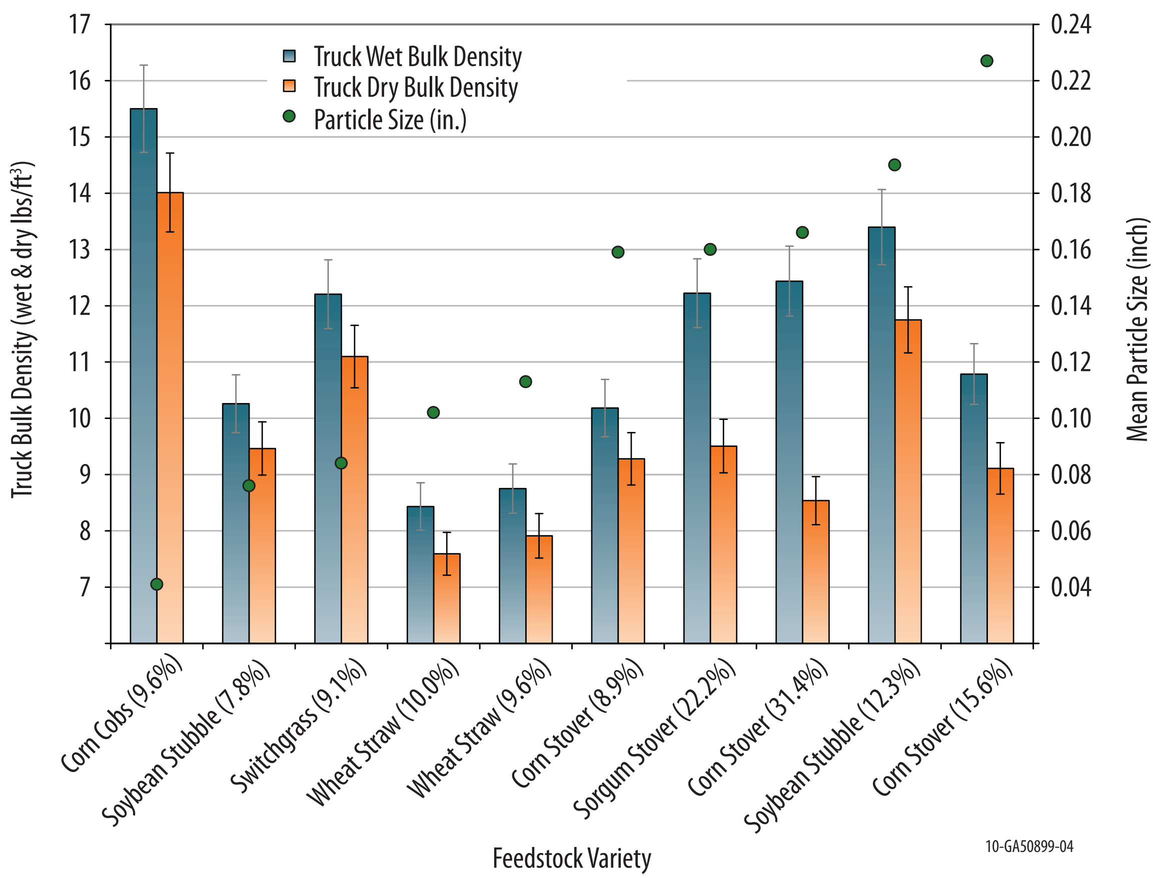
The corn cob feedstock arrives in enclosed trailers from field-side storage locations at the production sites. Similar to the baled feedstock, the corn cobs are weighed and unloaded into either a very short-term queuing yard (~200 ton) or directly into the preprocessing system. The cobs are then preprocessed into a smaller size and queued in evenflow metering bins for the bulk transport system.

3.3.1.1 Biomass Deconstruction, Fractionation, and Physical Property Changes

Many feedstock physical property specifications will remain the same as those required in the Conventional Bale design because they will largely be imposed by the biorefinery. However, additional requirements will be imposed by the handling and transportation operation, which will not only include previously discussed size reduction but will also include more stringent bulk density and flowability requirements. These requirements will directly impact the capacity and efficiency of the handling and transportation system and will be the source of savings that will justify moving preprocessing from the biorefinery to the biomass depot. Specific considerations for particle size and distribution, beyond those needed to maintain pretreatment and conversion efficiencies, is the effect these parameters have on bulk density. Figure 3-22 shows a graph relating bulk density to geometric mean particle size of corn stover, Sorghum stover, soybean straw, switchgrass, and wheat straw. The data show distinct differences between feedstock varieties, regardless of moisture content, indicating a need to fully understand the variety of feedstock being considered in the supply system. Certainly, further investigations into grinding parameters, such as fractionation mechanism, screen shape, and screen thickness, will be needed to determine more precise relationship between mean particle size, bulk density, and the influence of moisture for specific feedstock varieties, including corn cobs.

Particle size and size distribution have an influence on almost all bulk handling properties. These parameters, however, encompass a range of shape factors such as aspect ratio, volume, and roughness, whose influence on bulk density and flowability are not completely understood. Nevertheless, it is generally true that larger particles with more uniform shapes and sizes would be more desirable than smaller particles with varying shapes and sizes because particle uniformity better facilitates prediction of feedstock behavior and optimization of processes dependant on flowability

Figure 3-22. Relationship between truck bulk density and geometric mean particle size of corn stover, Sorghum stover, soybean straw, switchgrass, wheat straw, and corn cobs.



parameters or size-based reactions. However, controlling the size distribution of feedstock materials can be more difficult than improving grinding efficiency or capacity.

3.3.1.2 Format and Bulk Density Impact on Supply System Processes

The impact baled feedstock format has on transportation and handling from the field to the biomass depot and on distributed preprocessing systems is generally the same as discussed in Sections 2.3.1.2 and 2.4.1.2 because these processes use the same equipment as the Conventional Bale design. However, the Pioneer Uniform design, with its forward-deployed preprocessing, will have to handle, transport, and preprocess large round bales and loose materials (i.e., corn cobs) in addition to large square bales as discussed in Sections 2.3 and 2.4. In terms of the baled formats, the reduced scale of the biomass depot operations, compared to centralized biorefinery operations, will limit options to use larger and more complex automated bale unloading and queuing systems (i.e., rail-mounted cranes). Therefore, bale handling out of the fields and at the biomass depot will be performed with self-propelled loaders and flatbed trailers, or in the case of corn cobs, with self-propelled loaders and enclosed trailers.

Even though handling and transportation costs for baled feedstocks are directly impacted by the relatively low bulk density of the baled feedstock (Section 2.3), the shorter transportation distance modeled in the Pioneer Uniform design helps to minimize this cost impact. In order to maximize the handling and transport of baled feedstock, the bale bulk density will need to be high enough to allow a truck to reach its maximum gross vehicle weight (GVW) limit. To achieve this on National Network highways, square and round bale bulk densities will

Table 3-22. *Bale bulk density required to maximize various load capacity configurations to accommodate a range of load limits.*

Truck Configurations	Load Limits		Payload			Maximum Load Bulk Density (DM lb/ft^3)
	Length (ft)	GVW (lb)	Max (lb)	Square Bale Count	Round Bale Count	
48-ft Flatbed Trailer	48[a]	80,000[a]	51,100	24 – 4×4×8-ft		
36 – 3×4×8-ft	30 – 4×5.5-ft	16.6 – 4×4×8-ft				
14.8 – 3×4×8-ft						
18.3 – 4×5.5-ft						
53-ft Flatbed Trailer	53[b]	80,000[a]	50,800	26 – 4×4×8-ft		
39 – 3×4×8-ft	34 – 4×5.5-ft	15.3 – 4×4×8-ft				
13.6 – 3×4×8-ft						
16.1 – 4×5.5-ft						
24-ft Flatbed Tractor with two 30-ft Flatbed Trailers	95[c]	105,500[d]	59,500	44 – 4×4×8-ft		
66 – 3×4×8-ft	50 – 4×5.5-ft	10.6 – 4×4×8-ft				
9.4 – 3×4×8-ft						
12.8 – 4×5.5-ft						

a. Federal minimum trailer length or gross vehicle weight (GVW) that states must allow on National Network (NN) highways.
b. Common state maximum trailer length allowable on National Network (NN) highways.
c. Common allowable trailer length in AK, AZ, CO, FL, ID, IN, IA, KS, MA, MO, MT (93-ft), NE, NV, NY, ND, OH, OK, SD, and UT for two trailing units on non-NN highways.
d. Common allowable GVW limit in AZ, CO, ID, IN, IA, KS, MA, MI, MO, NE, NV, NY, ND, OH, OR, SD, UT, WA, and WY for two trailing units on non-NN highways.

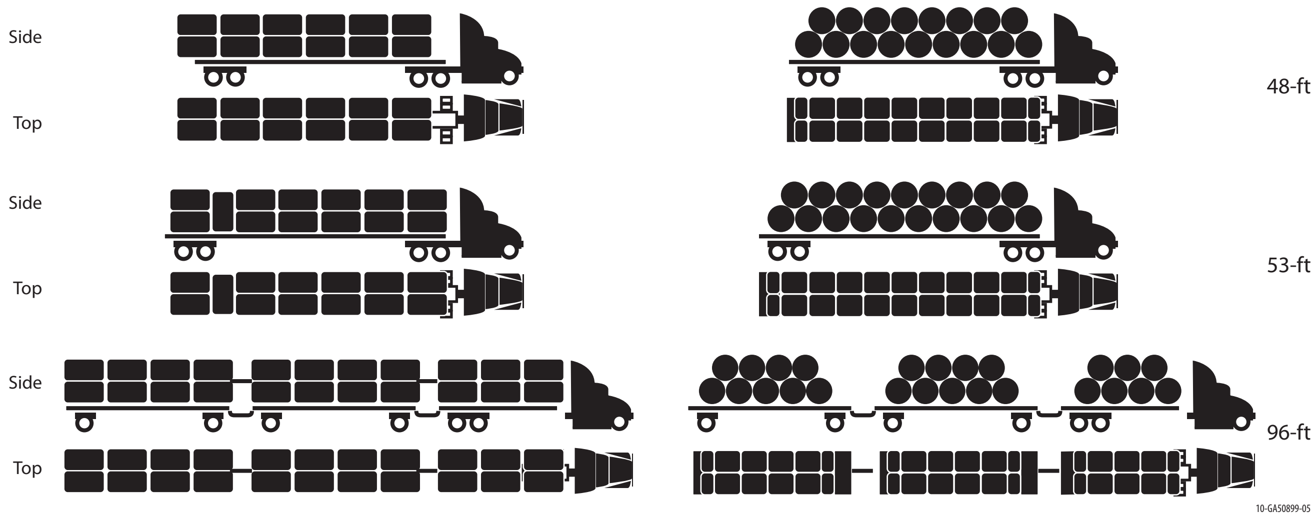


Figure 3-23. Truck configurations for a 48-ft trailer, a 53-ft trailer, and a 24-ft flatbed tractor with two 30 ft trailers carrying both square and round bales.

need to be approximately 15–18 DM lb/ft^3 (Table 3-22 and Figure 3-23). Many states allow a 53-ft semi trailer on National Network roads, which leads to a target bulk density of 16 DM lb/ft^3 for both large square and round bales.

Transportation of corn cobs from the field to the biomass depot will also be most efficient when cob bulk density is high enough to maximize the GVW of the enclosed tractor-trailer unit. For this to occur, cob bulk density would need to be approximately 14 DM lb/ft^3. The National Network-compliant truck configuration and an allowable non National Network configuration with corresponding maximum truck load bulk density are shown in Table 3-23 and Figure 3-22.

The preprocessing of round baled feedstocks will require slight changes to the square bale system described in Section 2.4. These changes will account for the larger round bale cross section (approximately 4 × 6 ft) that will have to fit into the infeed mechanism of the preprocessing system. By removing the bale wrap or twine and implementing an aggressive infeed roller on the grinding system, the same grinder as discussed in Section 2.4 is used to model the Pioneer Uniform preprocessing system.

Once the baled material is preprocessed in the biomass depot, the ground feedstock is queued for transport to the biorefinery. At this stage of the process, bulk density becomes a critical parameter directly impacting the capacity and efficiency of the transportation system. Similar to the bale transport system, the most efficient bulk transport from the biomass depot to the biorefinery will be a system that reaches the GVW limit. Using truck configurations that are legal on National Network roads, the bulk density of the ground feedstock will need to reach

Table 3-21. *Cob bulk density required to maximize various load capacity configurations to accommodate a range of load limits.*

Truck Configurations	Load Limits		Payload		Maximum Load Bulk Density (DM lb/ft^3)
	Length (ft)	GVW (lb)	Max Weight (lb)	Trailer Volume (ft^3)	
48-ft Live-bottom Trailer	48[a]	80,000[a]	48,110	3,940	10.7
53-ft Live-bottom Trailer	53[b]	80,000[a]	46,880	4,371	9.5

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

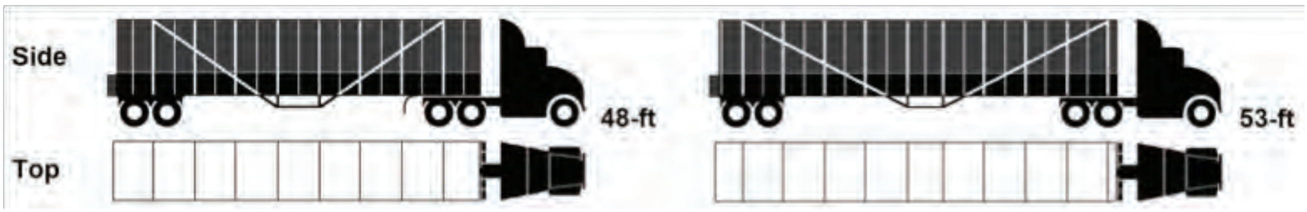


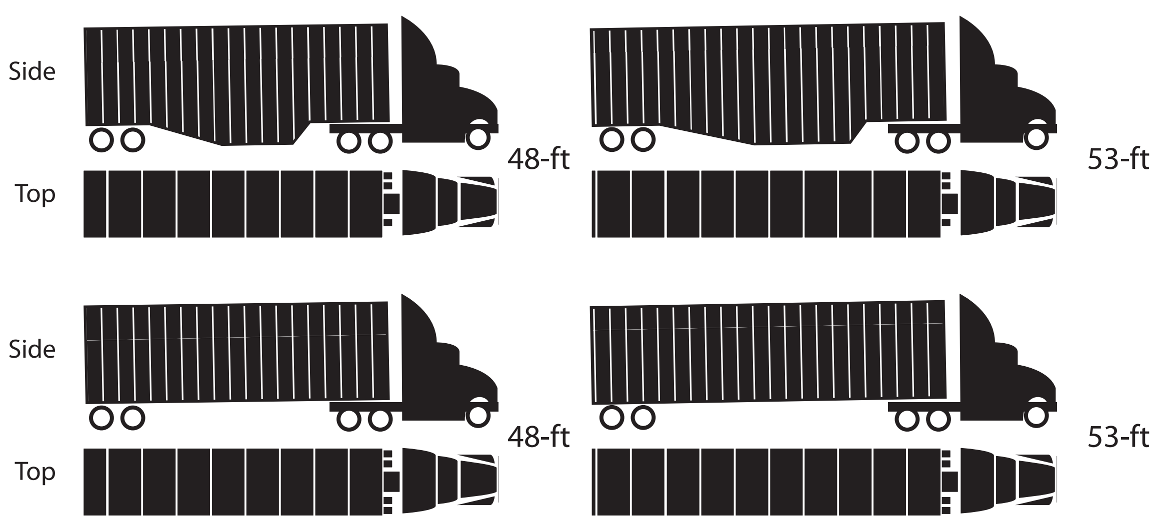
Figure 3-24. Truck configurations for a 48-ft and 53-ft chip van trailer carrying ground bulk feedstock.

Table 3-24. *Bulk density required to maximize various load capacity configurations to accommodate a range of load limits.*

Truck Configurations	Load Limits		Payload		Maximum Load Bulk Density (DM lb/ft^3)
	Length (ft)	GVW (lb)	Max Weight (lb)	Trailer Volume (ft^3)	
48-ft Possum-belly Chip Trailer	48[a]	80,000[a]	48,110	3,940	10.7
53-ft Possum-belly Chip Trailer	53[b]	80,000[a]	46,880	4,371	9.5
48-ft Flat-bottom Chip Trailer	48[a]	80,000[a]	48,110	3,940	10.7
53-ft Flat-bottom Chip Trailer	53[b]	80,000[a]	46,880	4,371	9.5

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

Figure 3-25. Truck configurations for a 48-ft and 53-ft chip van trailer carrying ground bulk feedstock. The possum-belly trailer is used to transport bulk corn stover and switchgrass, while the flat-bottom trailer is used to transport corn cobs.



approximately 9.5–10.7 DM lb/ft3 (Table 3-24 and Figure 3-25). Many states allow a 53-ft semi trailer on National Network roads, which leads to a target bulk density of 9.5 DM lb/ft^3.

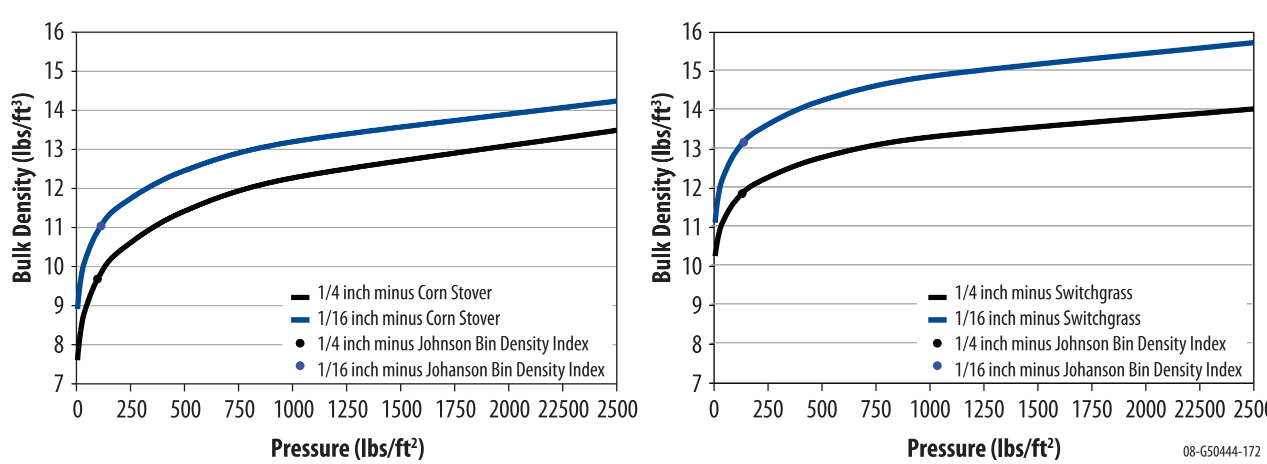
Smaller, more uniform bulk materials tend to be denser and more compressible compared to less uniform materials. As a result, the bulk density becomes a function of applied pressure as well as particle size. Figure 3-26 presents the change in bulk density as a function of applied pressure and moisture for a standard 1/4-in.-minus grind and a smaller 1/16-in.-minus grind fraction of corn stover, switchgrass, and wheat straw. In reviewing the data, it is noted that the smaller particle grind exhibits larger densities at lower compaction pressures. Applied pressures in the range of 2,000–3,500 lb/ft2 are required to produce feedstock densities needed to fully load a semi-trailer with dry (<15% moisture) bulk materials.

The bulk density of the feedstock loaded into a 10-ft deep semi-trailer, or similar transportation container, can be estimated by testing the same material shown in Figure 3-22 in a Johansen bin density index measurement instrument. The bin density measurement accounts for the hydrostatic pressure applied to the bulk feedstock from its own weight. Comparing bin density values with the applied force data shown in Figure 3-26, the hydrostatic pressure is approximately equivalent to 1,000 lb/ft2 of mechanically applied force. Therefore, the particle size and distribution and the hydrostatic force from the weight of the feedstock can either reduce or eliminate altogether the required mechanical force needed to fully load a semi-trailer.

If mechanical compacting is required, there are several tools for compressing feedstock materials as they are loaded into trucks from the grinding operation. For example, hydraulically operated tamper platens used in cotton module builders operate at pressures in the range of 2,100–2,880 lb/ft2 with a typical tamping cycle of 5–10 seconds for a 1–2-ft stroke. This speed could allow the material compaction to occur at processing rates that are competitive with truck loading rates from grinding operations. Compacting auger systems could also be used as feeders to densify bulk materials prior to loading onto conveying systems. These systems can also be designed for high throughput capacities.

While grinding to smaller particle sizes and applying large compression forces can aid with increasing the bulk density of the feedstock, there are other handling complications that may result from these actions. Smaller particles tend to be more frictional and, consequently, may generate more flow problems than coarser materials. The permeability also decreases with decreasing particle size, limiting fluidization and flow of materials through hoppers and storage silos. Because the cohesive strength of materials is

Figure 3-26. Bulk density changes as a function of applied pressure for corn stover and switchgrass at two different grind sizes (Pryfogle, INL test



dependent upon the applied pressure, the compacted materials may have a higher probability of arching or rat-holing within transfer equipment and storage facilities.

In summary, the handling and conveying of loose, bulk feedstock materials is clearly dependent upon the particle size and size distribution of the material. The small size spread in these materials observed in the 1/16- and ¼-in.-minus grinds results in significant changes in the bulk density and flowability properties of the materials. Materials as large as 1/4 in. can be compressed to target limits and handled within the feedstock assembly operation; however, specialized tools and equipment will be required. The trade-off between grinding to smaller particle sizes, increasing feedstock density, and meeting biorefinery quality specifications for conversion while incorporating new technologies is the concept behindan Advanced Uniform supply system.

3.3.1.3 Biomass Moisture Impact on Supply System Processes and Material Stability

Since the bale receiving, handling, and preprocessing systems used in the biomass depots are the same as those used at the biorefinery in the Conventional Bale design, the impact of feedstock moisture content on these systems is essentially the same as those discussed in Section 2.4.1.3. Corn cobs, on the other hand, will be handled, transported, and ground

Table 3-25. *Handling and transportation equipment specifications for the Pioneer Uniform design.*

	Bale Transport	***Bulk Cob Transport***	***Bulk Biomass Transport***						
	Load/ Unload Bale Transport	Transport to Depot	Bale Receiving and Queue for Preprocessing	Load Bulk Transport	Transport to Depot	Bulk Receiving and Queue for Preprocessing	Bulk Queue for Transport	Bulk Cob Transport to Biorefinery	Bulk Stover/ Switchgrass Transport to Biorefinery
Equipment	Telehandler	3-axle Day Cab with 53-ft Flatbed Trailer	Semi-truck Scale and Asphalt Pad	Telehandler	3-axle Day Cab with Trailer	Semi-truck Scale and Unloading pit	Surge Bin, Foreign Material Eliminators and other Conveying Equipment	3-axle Day Cab with Flat-bottom Trailer	3-axle Day Cab with Possum-bottom Trailer
Rated Capacity	47 (ton/hr)	N/A	100 (ton)	24.9 (ton/hr)	2,511 (ft^3)	100 (tons)	N/A	3,456 (ft^3)	4,371 (ft^3)
Field Capacity[a]	40 (bales/hr)	34 (bales/ truck)	100 (ton)	24.9 (ton/hr)	2,511 (ft^3)	100 (tons)	14.0 (tons/hr)	3,456 (ft^3)	4,371 (ft^3)
Operational Efficiency (%)b	40	100%	N/A	100%	100%	N/A	46%	100%	100%
Dry Matter Loss (%)	0	0	0	0	0	0	0	0	0
Operational Window									
hr/day	14	14	14	14	14	14	24	24	24
day/yr	300	300	300	300	300	300	300	300	300

a. Estimate of the operating time that is actually spent working and the amount of capacity used.
b. Ratio of field capacity to rated capacity.

at a moisture content of ~40%. The transportation bulk density requirements discussed above already take this moisture content into account. Likewise, the grinding capacity, which can be significantly impacted by feedstock moisture content, is assumed to be the same for corn cobs as it is for corn stover and switchgrass, at 12% moisture. This assumption is conservatively based on the experience of a preprocessing equipment manufacturer (Kenney 2008).

However, once the feedstock is ground and loaded into the bulk transport system, moisture absorbed from the environment or weather events can influence a number of other properties, such as the tendency of the material to agglomerate and swell, possibly reducing bulk density. Moisture may also impact flow properties, including the compressibility, cohesiveness, and frictional characteristics that affect the flow of material from hoppers and storage facilities. The intent of the biomass depot is to minimize these variables through engineering control of the bulk feed and queuing systems.

3.3.2 Pioneer Uniform Preprocessing and Transportation Equipment

The Pioneer Uniform design uses the same set of bale handling, transportation, and preprocessing equipment for all processes from the field to the biomass depot as was used in the Conventional Bale design (Sections 2.3.2 and 2.4.2); thus, equipment describing the square bale system will not be described in this section. A different set of handling and transportation equipment for corn cobs from the field to the biomass depot is used due to its bulk format. Equipment used for round baled material and corn cobs, as well as bulk material resulting from the preprocessing operation at the biomass depot, will be discussed in the following section.

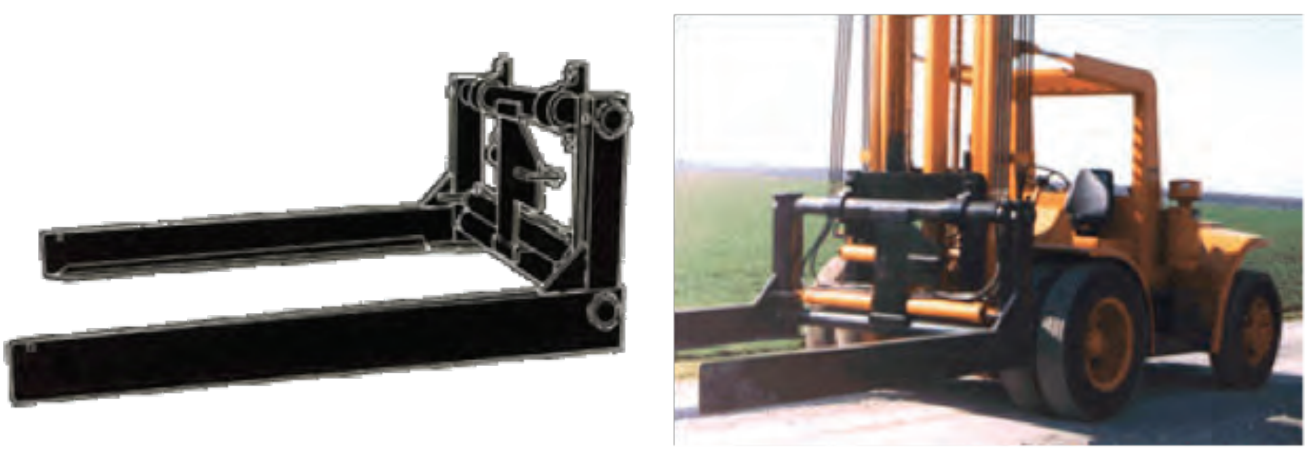
Handling and Transportation

The handling and transportation processes in the Pioneer Uniform design include the movement of baled material and corn cobs from the field to the biomass depot and the movement of bulk material from the biomass depot to the biorefinery. In addition to the square bale format, both a round bale and loose bulk (corn cob) formats are modeled in the Pioneer Uniform design. Handling and transportation equipment specifications used in the model are shown in Table 3-25.

The loading, transport, and unloading of the round baled material is accomplished with a Roadrunner hay clamp attachment on a telehandler loader and a Kenworth T800 semi-tractor with a Fontaine Phantom 53-ft flatbed trailer. This same loader and flatbed semi tractor-trailer were described in Sections 2.2.2 and 2.3.2 and shown in Figures 2-21 and 2-29, respectively. The Roadrunner attachment for round bales is shown in Figure 3-27.

(Photograph from Roadrunner Manufacturing Co., Inc. website < www.roadrunnermfg.com> Permission for use is being requested.)

Figure 3-27. Roadrunner Hay Clamp bale handling attachment.



The corn cobs are loaded in the field with a telehandler into a Trinity Eagle Bridge Live-bottom trailer pulled by a Kenworth T800 semi-tractor. The cob loader is a Caterpillar TH220B telehandler with 100 gross hp and a bucket capacity of 14.7 DM ton/hr (Figure 3-28). The loader and semi tractor-trailer work in tandem to minimize loading time. The Kenworth T800 semi-tractor was described in Section 2.3.3.

The truck scale implemented in this design is the same one described in the Conventional Bale design. The asphalt pad at the biomass depot, though similar to the one used in the Pioneer Uniform design, is only used to queue baled material prior to insertion into the grinder. The timing of the unloading process and the loading of the grinder requires that the asphalt pad be much smaller (only 500 ft2) than the one modeled at the biorefinery in the Conventional Bale design. The queued bales are loaded from this asphalt pad onto the bale-merging conveyor and into the grinding process.

Once the feedstock is preprocessed, the ground material is queued in a surge bin system where it is metered into the bulk transport system. This evenflow metering system is described in Section 2.4.2 and shown in Figure 2-33.

A semi-tractor and a 53-ft chip van are used to transport the bulk material to the biorefinery. The semi-tractor is described in Section 2.3.2.

Figure 3-28. Telehandler loader used to load corn cobs for transport to the biomass depot.

Preprocessing

Preprocessing at the biorefinery as modeled in the Conventional Bale design (Section 2.4) uses a total of nine grinding systems to handle the necessary

Table 3-26. *Preprocessing and queuing equipment specifications for the Pioneer Uniform design.*

	Preprocessing					
	Grinder Loader from Bale Queue	Grinder Infeed System	Grinder	Dust Collection	Surge Metering Bin	Bale and Twine Disposal
Equipment	Telehandler	conveyor	Horizontal Grinder	Cyclone, Baghouse, Conveying Equipment	hopper bottom surge bin	Dump Truck
Rated Capacity	14.0 (ton/hr)	14.0 (ton/hr)	17.1 (ton/hr)	14.0 (ton/hr)	100 (ton/hr)	14.0 (ton/hr)
Field Capacity	14.0 (ton/hr)	14.0 (ton/hr)	14.0 (ton/hr)	14.0 (ton/hr)	14.0 (ton/hr)	14.0 (ton/hr)
Operational Efficiency (%)a	100%	100%	82%	100%	14%	100%
Dry Matter Loss (%)	0	0	0	0	0	0
Operational Window						
hrs/day	24.0	24.0	24.0	24.0	24.0	24.0
days/year	300	300	300	300	300	300

a. Grinder field capacity is conservatively assumed to be the same for corn cobs as it is for corn stover and switchgrass.
b. Estimated efficiency based on the actual operating time and the amount of capacity used.
c. Published efficiency input into the analysis model (Appendix B-2).

capacity. Within the Pioneer Uniform design, these nine complete grinding systems are divided among the nine biomass depots. Thus, all preprocessing equipment located at each biomass depot is the same as the preprocessing equipment used in the Conventional Bale design. This system in its entirety is described in Section 2.4.2 . The equipment specifications for the preprocessing system used in the Pioneer Uniform model are shown in Table 3-26.

3.3.2.1 Equipment Capacity and Operational Efficiency

Table 2-31 shows that the grinder capacity and power requirement will vary for different types of feedstock materials. The capacity value reported in Table 2-31 is provided for both dry ton/hour, a metric widely used in the grinding industry, and dry ton/kilowatt hour, a metric used to capture the power required to produce a given dry-tons-per-hour value. Because of the variance in grinding capacity and efficiency as a function of feedstock variety, the selection of specific grinding configurations or conditions will be important to consider in the preprocessing operation. However, feedstock moisture is still the most influential parameter on grinding capacity and efficiency (Figure 2-39).

The tightly coupled relationship between bulk density and transportation makes truck configurations and road limits critically important in the overall supply system. The location of the biomass depot and the bulk density required to maximize truck capacity is directly dependant on local road laws. For the purpose of identifying a broadly applicable supply system, U.S. National Network truck road limits are used in the Pioneer Uniform design (Tables 3-20 to 3-22, Figures 3-32 to 3-34). These limits specify the truck volume, based on trailer configuration, resulting in a bulk density target to maximize the GVW.

3.3.2.2 Dry Matter Losses

Even though dry matter losses at the biomass depot cost less than the same losses experienced at the biorefinery, because the feedstock has a lower value earlier in the supply chain, losses still constitute too high of an economic and regulatory risk not to be mitigated. Therefore, a cyclone separator and baghouse dust collection system is implemented within each preprocessing system at the biomass depots. This system collects nearly all dust and other small particulates emitted by the grinding and handling processes and provides a way to reintroduce the collected material back into the feed system, thereby minimizing net material losses and their associated costs. The Pioneer Uniform model uses this dust collection system and does not factor operational dry matter losses into the analysis.

3.3.2.3 Operational Window

The bale receiving processes at the biomass depot operate 14 hours per day, six days per week, for 50 weeks a year. This schedule is based on anticipated constraints imposed by typical field operations and field conditions. On the other hand, all preprocessing and bulk transport processes operate 24 hours a day, seven days a week for 350 days a year. The conflicting schedules, along with the lower equipment capacity of bale transport units, decrease the distance between feedstock production sites and a biomass depot and increase the distance between the biomass depot and the biorefinery. The mismatch in schedules will also necessitate a small bale queuing yard at the biomass depot to feed the preprocessing system during times when bale receiving is not operating. Optimizing the distance between individual depots and the production sites will help maximize both bale and bulk transport efficiencies and optimize the size of the bale queuing yard.

3.3.3 Pioneer Uniform Preprocessing and Transportation Cost and Sensitivity Analysis

3.3.3.1 Static Model Cost Summary

A breakdown of the costs associated with each piece of equipment used in the Preprocessing and Transportation unit operation identifies significant cost components that are valuable for making individual comparisons and identifying areas of research potential (Tables 3-27 and 3-28). These costs are reported in terms of DM tons entering each process.

Table 3-27. *Static model costs for major handling and transportation equipment in the Pioneer Uniform corn stover, switchgrass, and corn cob scenarios. Costs are expressed in $/DM ton unless otherwise noted.*

	Equipment	Bale Transport			Bulk Transport	
		Load and Unload	**Transport to Depot**	**Receiving and Queue for Preprocessing**	**Queue for Transport**	**Transport to Biorefinery**
		Telehandlers	**3 axle Day Cab with 53 ft Flatbed Trailer**	**Semi-truck Scale and Asphalt Pad**	**Conveying Equipment**	**53 ft Chip Transport and 3-axle day cab**
Corn Stover	Installed Equipment Quantity	24	35	9	9	8
	Installed Capital[a]	1.98	6.19	0.07	9.61	1.44
	Ownership Costs[b]	0.79	1.18	0.01	1.16	0.39
	Operating Costs[c]	3.67	6.95	0.19	2.28	3.22
	Labor	2.92	5.47	0.19	0.00	1.25
	Non-Labor	0.75	1.48	0.00	2.28	1.97
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	23.6	40.8	N/A	85.7	54.4
Switchgrass	Installed Equipment Quantity	24	34	1	9	8
	Installed Capital[a]	1.98	6.01	0.07	9.61	1.44
	Ownership Costs[b]	0.73	1.14	0.01	1.16	0.39
	Operating Costs[c]	3.51	6.66	0.19	2.28	3.24
	Labor	2.79	5.24	0.19	0.00	1.25
	Non-Labor	0.72	1.41	0.00	2.28	1.98
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	22.6	39.0	N/A	85.7	54.7
	Equipment	**Cob Transport**			**Bulk Transport**	
		Load and Unload	**Transport to Depot**	**Receiving and Queue for Preprocessing**	**Queue for Transport**	**Transport to Biorefinery**
		TH220B Telehandler (1)	**3-axle Day Cab with Trailer 42 ft, 29"/4' side**	**Semi-truck Scale**	**Conveying Equipment**	**3-axle day cab with 48-ft Flat Floor Chip Trailer**
Cobs	Installed Equipment Quantity	13	26	12	12	13
	Installed Capitala	1.07	2.34	0.07	7.45	2.34
	Ownership Costsb	0.43	0.69	0.01	2.28	0.69
	Operating Costsc	2.07	5.75	0.19	6.76	5.75
	Labor	1.65	1.99	0.19	4.46	1.99
	Non-Labor	0.42	3.76	0.00	2.30	3.76
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	13.3	103.8	N/A	117.1	103.8

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).

Table 3-28. *Static model costs for major preprocessing equipment in the Pioneer Uniform corn stover, switchgrass, and corn cob scenarios. Costs are expressed in $/DM ton unless otherwise noted.*

		Grinder Loader from Bale Queue	Grinder Infeed System	Grinder	Dust Collection		Bale and Twine Disposal
		Telehandler	**Conveyor**	**Horizontal Grinder**	**Cyclone, Baghouse, and Other Conveying Equipment**	**Surge Metering Bin**	**Twine Remover, Moisture Meter, etc.**
Corn Stover	Installed Equipment Quantity	9	9	9	9	9	9
	Installed Capital[a]	0.74	4.84	4.66	0.14	3.15	1.47
	Ownership Costs[b]	0.47	0.53	1.87	0.02	0.45	0.17
	Operating Costs[c]	1.65	0.85	5.54	0.02	1.29	0.11
	Labor	1.14	N/A	1.45	N/A	0	0
	Non-Labor	0.51	0.85	4.10	0.02	1.29	0.11
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	15.9	4.1	129.8	N/A	79.6	2.0
Switchgrass	Installed Equipment Quantity	9	9	9	9	9	1
	Installed Capital[a]	0.74	4.84	4.66	0.14	3.15	1.47
	Ownership Costs[b]	0.47	0.53	1.87	0.02	0.45	0.17
	Operating Costs[c]	1.65	0.85	5.54	0.02	1.29	0.11
	Labor	1.14	N/A	1.45	N/A	0	0
	Non-Labor	0.51	0.85	4.10	0.02	1.29	0.11
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	15.9	4.1	129.8	N/A	79.6	2.0
		40 ft Corn Hopper	**12,000 BPH, 180-ft En Masse conveyor**	**Horizontal Grinder**	**Cyclone, Baghouse, and other Conveying Equipment**	**Sukup, hopper bottom surge bin**	**Truck Scale, moisture meter, electro magnet**
Cobs	Installed Equipment Quantity	12	12	12	12	12	1
	Installed Capital[a]	1.09	0.33	6.21	4.50	0.12	1.41
	Ownership Costs[b]	1.43	0.04	2.49	0.64	0.01	0.16
	Operating Costs[c]	2.79	0.23	7.39	1.72	0.02	2.00
	Labor	2.53	0.00	1.93	0.00	0.00	1.93
	Non-Labor	0.26	0.23	5.46	1.72	0.02	0.06
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	N/A	11.0	173.1	106.1	N/A	N/A

3.3.3.2 Cost Sensitivity Analysis

Histograms of the handling and transportation and preprocessing cost were produced for the scenarios shown in Table 3-29, and a sample histogram for the round bale corn stover scenario is shown in Figure 3-31 (histograms for all scenarios are presented in Appendix xxx).

The overall costs associated with the Pioneer Uniform preprocessing and transportation unit operation for corn stover, switchgrass, and corn cobs are provided in Tables 3-30, 3-31, and 3-32 and 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 Pioneer Uniform feedstock supply system.

Table 3-29. *Summary of sensitivity analysis for total handling and transportation. Values are presented in $/DM ton.*

	Mean ± Std Dev	***Mode***	***90% Confidence Range***	***Static Model Value***
Handling and Transportation				
Round Bale Stover	$16.78 ± 1.01	$16.95	$15.17–$18.50	$16.17
Square Bale Stover	$11.88 ± 0.73	$11.87	$10.72–$13.12	$9.20
Round Bale Switchgrass	$ 15.56 ± 0.92	$ 15.56	$14.10–$17.12	$15.68
Square Bale Switchgrass	$ 11.14 ± 0.72	$ 11.38	$10.01–$12.38	$8.53
Corn Cob				
Preprocessing				
Round Bale Stover	$14.75 ± 1.64	$14.23	$12.73–$17.64	$12.97
Square Bale Stover	$14.75 ± 1.64	$12.97	$12.71–$17.62	$14.20
Round Bale Switchgrass	$15.72 ± 2.23	$ 14.21	$12.84–$19.66	$12.97
Square Bale Switchgrass	$15.72 ± 2.24	$ 14.18	$12.83–$19.64	$12.96
Corn Cob	$18.96 ± 3.04	$17.26	$14.00–$24.14	$18.92

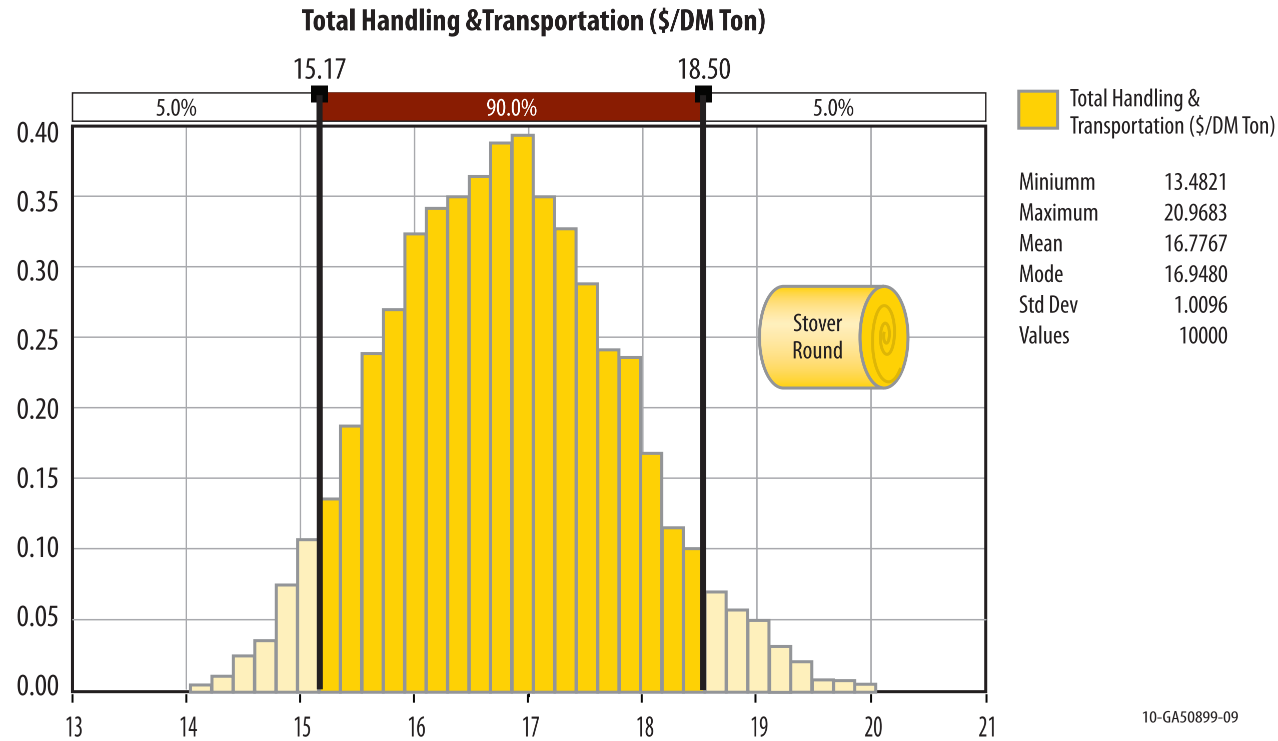


Figure 3-31. Pioneer Uniform—Corn Stover (Round) Handling and Transportation cost distribution histogram from @Risk analysis.

Table 3-30. *Preprocessing cost summary for the Pioneer Uniform corn stover and switchgrass scenarios.*

	Equipment	Grinder Loader from Bale Queue	Grinder Infeed System	Grinder	Dust Collection	Bale and Twine Disposal	Total Preprocessing – Round Bale	Total Preprocessing – Square Bale
		Telehandler	Conveyor	Horizontal Grinder	Cyclone, Baghouse, Conveying Equipment	Dump Truck		
Corn Stover	Modeled Cost Totals[a]	2.17 ± 0.36 ($/DM ton)	1.66 ± 0.23 ($/DM ton)	8.48 ± 1.06 ($/DM ton)	2.10 ± 0.25 ($/DM ton)	0.30 ± 0.05 ($/DM ton)	14.75 ± 1.64 ($/DM ton)	14.75 ± 1.63 ($/DM ton)
		0.92 ± 0.16 ($/bale)	0.70 ± 0.11 ($/bale)	3.58 ± 0.50 ($/bale)	1.20 ± 0.16 ($/unit)	0.09 ± 0.01 ($/unit)	6.52 ± 0.79 ($/unit)	8.58 ± 1.05 ($/unit)
Switchgrass	Modeled Cost Totals[a]	2.42 ± 0.48 ($/DM ton)	1.65 ± 0.21 ($/DM ton)	9.11± 1.44 ($/DM ton)	2.18 ± 0.28 ($/DM ton)	0.33± 0.07 ($/DM ton)	15.72 ± 2.23 ($/DM ton)	15.72 ± 2.24 ($/DM ton)
		1.13 ± 0.24 ($/bale)	0.77 ± 0.11 ($/bale)	4.27 ± 0.72 ($/bale)	1.64 ± 0.22 ($/unit)	0.11 ± 0.02 ($/unit)	7.95 ± 1.17 ($/unit)	10.40 ± 1.54 ($/unit)

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

Table 3-31. *Preprocessing cost summary for Pioneer Uniform corn cob scenario.*

	Grinder Loader from Queue	***Grinder Infeed System***	***Grinder***	***Dust Collection***	***Surge Bin***	***Waste Disposal***
	Corn Hopper	***En Masse conveyor***	***Horizontal Grinder***	***Cyclone, Baghouse, and other Conveying Equipment***	***hopper bottom surge bin***	***Truck Scale, moisture meter, electro magnet***
Modeled Costs ($/DM ton)	4.24 ± 0.87	0.27 ± 0.03	9.89 ± 1.49	2.37 ± 0.33	0.03 ± 0.002	2.16 ± 0.32
Modeled Costs ($/unit)	0.02 ± 0.003	0.001 ± 0.00		2.12 ± 0.31	0.03 ± 0.001	

Table 3-32. *Bale and bulk total transportation cost summary for the Pioneer Uniform corn stover and switchgrass scenarios.*

Crop	***Equipment***	***Load and Unload***	***Transport to Depot***	***Receiving and Queue for Preprocessing***	***Queue for Transport***	***Transport to Biorefinery***	***Total Round Bale Transport***
		Telehandler	***3-axle Day Cab with 53-ft Flatbed Trailer***	***Semi-truck Scale and Asphalt Pad***	***Surge Bin, Foreign Material Eliminators and other Conveying Equipment***	***Chip Transport and 3-axle day cab***	
Corn Stover	Modeled Cost Totals[a]	4.46 ± 0.35 ($/DM ton)	8.43 ± 0.56 ($/DM ton)	0.20 ± 0.00 ($/DM ton)	0.05 ± 0.006 ($/DM ton)	16.78 ± 1.01 ($/DM ton)	3.88 ± 0.46 ($/DM ton)
		1.88 ± 0.09 ($/bale)	3.55 ± 0.10 ($/bale)	0.001 ± 0.00 ($/bale)	0.03 ± 0.004 ($/bale)	5.44 ± 0.19 ($/bale)	0.02 ± 0.002 ($/bale)
		15.16 ± 0.51 $/mi	9.13 ± 0.26 $/mi			27.05 ± 0.77 $/mi	2.75 ± 0.07 $/mi
Switchgrass	Modeled Cost Totals[a]	4.02 ± 0.30 ($/DM ton)	7.60 ± 0.47 ($/DM ton)	0.20 ± 0.00 $/DM ton)	0.04± 0.005 ($/DM ton)	15.56 ± 0.92 ($/DM ton)	3.93 ± 0.53 ($/DM ton)
		1.88 ± 0.09 ($/bale)	3.55 ± 0.10 ($/bale)	0.001 ± 0.00 ($/bale)	0.03 ± 0.004 ($/bale)	5.45 ± 0.19 ($/bale)	0.02 ± 0.003 ($/bale)
		15.17 ± 0.51 $/mi	9.13 ± 0.26 $/mi			27.00 ± 0.77 $/mi	2.70 ± 0.07 $/mi

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

Equipment		***Cob Transport***		***Bulk Transport***	
Load and Unload	***Transport to Depot***	***Receiving and Queue for Preprocessing***	***Queue for Transport***	***Transport to Biorefinery***	
Telehandler	3-axle Day Cab with Trailer 42-ft 29-in./4-ft side	Semi-truck Scale	Surge Bin, Foreign Material Eliminators and other Conveying Equipment	3-axle day cab with 48-ft Flat Floor Chip Trailer	
Modeled Costs	2.73± 0.31 ($/DM ton)	8.99 ± 0.82 ($/DM ton)	± ($/DM ton)	0.03 ± 0.00 ($/DM ton)	6.53 ± 0.75 ($/DM ton)
	0.01 ± 0.00 ($/pile)	0.03 ± 0.00 ($/pile)	± ($/pile)	0.03 ± 0.00 ($/pile)	0.05 ± 0.01

3.4 PIONEER UNIFORM RECEIVING AND HANDLING

Because preprocessing operations have already occurred, the biorefinery receives a feedstock that has been processed to a known uniform-format specification that includes particle size and distribution, moisture, and bulk density. Because biorefinery receiving and handling systems are designed according to this specification, these systems are broadly replicable regardless of feedstock variety and harvesting methods specific to geographical regions. The receiving and handling systems at a biorefinery consist of weighing and unloading incoming bulk transport trucks, storing bulk feedstock in short-term queuing, and feeding bulk feedstock into the conversion process (Figure 3-32). Thus, this section presents a receiving and handling design that can be widely replicated in association with conversion facilities within the varied climatic and regulatory constraints that may be encountered across diverse geographic areas. As such, this design may not necessarily represent lowest cost methods or common practices.

Figure 3-32. Receiving and handling supply logistic processes and biomass format intermediates.

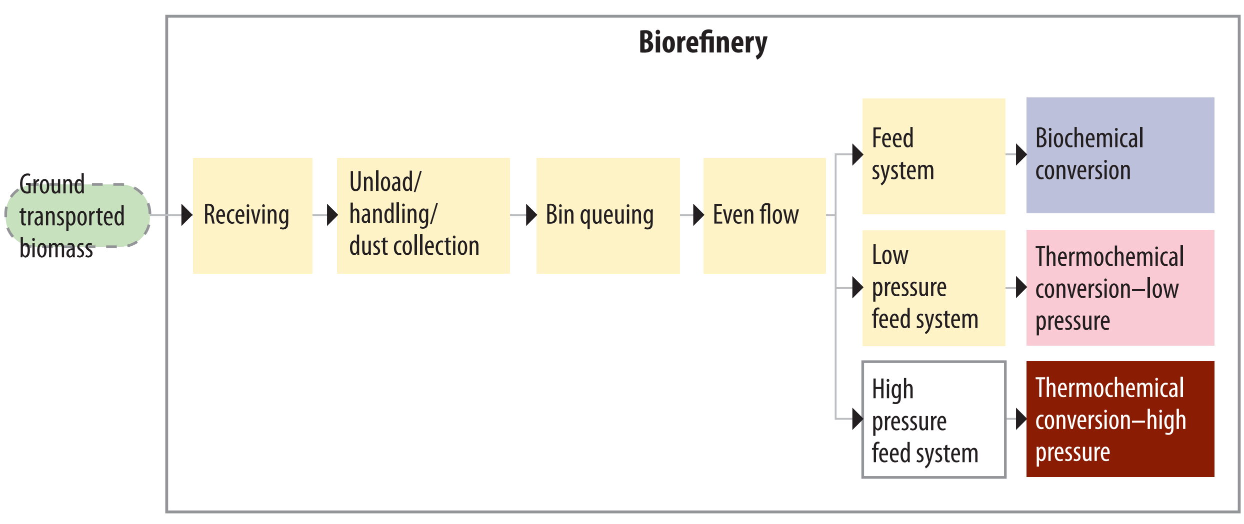
(Note: Green ovals represent biomass format intermediates, tan ovals represent potential waste streams, yellow rectangles represent processes modeled in this report, and white rectangles represent processes not modeled in this report. The blue, pink, and red rectangles represent different conversion processes.)

3.4.1 Pioneer Uniform Receiving Format Intermediates

The feedstock format does not change at this point in the Pioneer Uniform design. Instead, the variables that impact the selection of receiving and handling equipment are based on the bulk format that is produced in the biomass depots (Table 3-33). The receiving and handling processes are largely impacted by the size of the feedstock inventory that is maintained to supply the conversion process in the

***Table 3-33**. Attributes of receiving and handling format intermediates for corn stover, switchgrass, and corn cobs.*

	Receiving, Handling, and Queuing	***Receiving, Handling, and Queuing***	***Receiving, Handling, and Queuing***
Biomass Output	Corn Stover	Switchgrass	Corn Cobs
Yield (DM tons/day)	2,600	2,600	2,600
Format Output	Bulk (1-in. minus)	Bulk (1-in. minus)	Bulk (1-in. minus)
Bulk DM Density Output	7.4 lb/ft3	10.3 lb/ft3	14 lb/ft3
Output Moisture (% w.b.)	12	12	12



event costly disruptions in the supply chain occur, such as weather delays.

3.4.1.1 Biomass Deconstruction, Fractionation, and Physical Property Changes

In the Pioneer Uniform design, the received feedstock has been preprocessed according to the specifications and particle size distribution discussed in Section 3.3.1.2. These feedstock characteristics may ultimately need to be improved based on conversion process requirements and material handling and flowability constraints. As for the Conventional Bale design, a general mean particle size target for the Pioneer Uniform system of 1/4-in. minus, with no range constraint or lower size limit, is being used as a baseline. However, it is generally true that smaller particle size requirements will mean lower grinder capacities and higher preprocessing costs. Figure 3-1 and Section 2.4.1 show the mean particle size and particle size distribution for corn stover and switchgrass at various moisture contents.

3.4.1.2 Format and Bulk Density Impact on Supply System Processes

The handling and queuing of bulk feedstock formats are functions of the physical properties of the material and the design of the equipment used in the various processes. Conducting these processes is complicated because most existing handling and conveying technologies are designed for operation with granular materials, such as food grains or minerals. These materials typically have small, uniform particle sizes, high densities, and are not compressible. In contrast, the herbaceous feedstocks proposed for use in biofuel production may have large particle size variations, low densities, and can be highly compressible.

In order to achieve cost targets, the ground Pioneer Uniform feedstock must be able to flow through conventional feeder, conveyor, transportation, and storage systems. In particular, due to limited harvest windows and the large amount of feedstocks needed to continuously operate biorefineries, storage systems are especially sensitive to cost increases caused by feedstock handling issues. The low bulk density of loose feedstocks dictates the use of large storage volumes and possibly customized structures. Storage in large piles can require labor-intensive means of retrieving the feedstocks, and they may also incur significant losses due to weathering. On the other hand, high-capacity storage structures require large capital expenditures to site and build and, due to the cohesive nature of loose feedstocks, may require large active bridge-breaking devices to assist material conveyance and flow, resulting in additional costs to build and operate the facilities.

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

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

In order to identify a feedstock format that will readily flow through low-cost, conventional feedstock conveying and storage systems, feedstock flowability properties are tested and selected based on criteria developed by Jenike (1964). In these criteria, the yield strength of the material, measured as a function of consolidating stresses, is used to develop a flow function and determine the frictional properties of the material. Jenike then proposes using the ratio of the maximum consolidating stress at steady state flow to the unconfined yield strength, which is also the inverse slope of the flowability graph (Figure 3-25), to produce a value known as the flow function, ffc. Table 3-34 provides the relationship between the flow function and the flowability classification of the material. Five flowability categories are identified ranging from hardened and non flowing to free-flowing material. Figure 3-33 shows this same relationship graphically and highlights the region where material can be considered gravimetrically flowable. It was determined from these flowability categories that the target flow function is a value greater than four (green highlight in Figure 3-33). The material properties of the feedstock will need be tailored to have a flow function, ffc, of greater than four (easy flowing), at the maximum consolidation stress produced within standard silo structures under the most extreme environmental conditions expected during handling and storage. This criterion should result in a material that would be unlikely to form stable bridges or create other flow problems. If flow problems did occur, they could be addressed through common remediation techniques, such as the use of low-friction coatings or liners, drag chains, or aeration or vibration systems.

Table 3-34. *Flow function value ranges and the corresponding flowability classification*

Flow Function (ffc)	Flowability Classification
ffc ≤ 1	Hardened and non-flowing
1 < ffc ≤ 2	Very cohesive
2 < ffc ≤ 4	Cohesive
4 < ffc ≤ 10	Easy flowing
ffc > 10	Free flowing

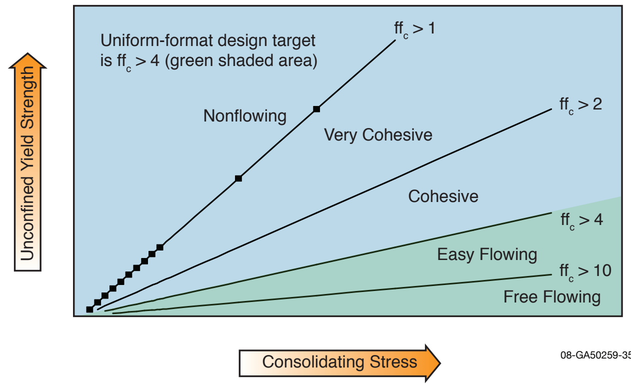


Figure 3-33. Flowability classification ranges. Uniform-Format design target is ffc > 4.

3.4.1.3 Biomass Moisture Impact on Supply System Processes and Material Stability

Material arriving at the biorefinery has passed through the biomass depot and is therefore a relatively consistent and stable material (<20% moisture). Nevertheless, moisture and other quality parameters will be tested at the biorefinery to verify established standards. In addition, the received material is unloaded directly into the queuing structure (in this case, a Eurosilo bulk storage structure), where it is subsequently fed into the conversion process with little opportunity for significant changes in moisture content.

3.4.2 Pioneer Uniform Receiving and Handling Equipment

Material received in the Pioneer Uniform design was preprocessed into a uniform format at a biomass depot such that different feedstocks handle similarly and different equipment is not necessary for receiving corn stover, switchgrass, and corn cobs. As with the Conventional Bale design, the Pioneer Uniform receiving component includes equipment and systems for accepting truckloads of bulk biomass at the biorefinery and conducting a transaction between the buyer (the biorefinery) and the producer based solely on moisture and weight. However, quality assessment laboratories may be added as part of the receiving system as biomass trading quality factors become better understood. After the material arrives

***Table 3-35.** Receiving equipment specifications for the Pioneer Uniform Design.*

	Receiving	Unloading and Handling	Dust Collection	Bin Queuing and Even Flow
Equipment	**Semi-truck Scale**	**drive-through full-truck tipper and hopper**	**Cyclone Separator and Baghouse**	**Eurosilo**
Capacity	137.7 ton/hr	137.7 ton/hr	137.7 ton/hr	1,507,064 ft^3
Operational Efficiency (%)[a]	41 b	76b	100	95 b
Dry Matter Loss (%)	0	0	0	0
Operational Window				
hrs/day	24	24	24	24
days/year	300	300	300	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 A).

and is assessed, it is unloaded into Eurosilos, where it is queued for the conversion process. The equipment specifications for the receiving and handling operation are outlined in Table 3-33.

Weighing

One drive-on truck scale will be used to weigh the trucks as they enter the plant and again as they leave to determine the amount of feedstock delivered to the plant. The truck scale implemented in this design scenario is from Scales Unlimited, Inc.

Unloading

After the trucks arrive in the receiving area and are weighed, the bulk material is unloaded into a below-ground hopper using a Phelps drive-through full-truck tipper. This truck tipper and hopper system have a combined 138 ton/hour field capacity (Figure 3-35).

Dust Collection

A high-efficiency dust collection system, similar to the one used in the Conventional Bale design (Section 2.4.2, Figure 2-44), will be integrated with the conveying system leading from the truck tipper hopper to the Eurosilo queuing bins. Dust collection will be sized to handle only airborne particles released during the unloading and conveying processes.

Conveying Systems

The conveying system between the truck tipper hopper and the Eurosilo consists of several En Masse

Figure 3-34. Receiving processes within the Pioneer Uniform design: Phelps drive-through truck tipper.

conveyors and a 120-ft bucket elevator. Since one Euro Silo will be feeding the conversion process while the other is receiving from the truck tippers, the conveying system is capable of switching between silos for both the fill and discharge process (shown in Figure 3-35).

Queuing and Even Flow

Bulk flowability is a key characteristic of the Pioneer Uniform design. The general risk imposed by biomass feedstocks is their lack of flowability characteristics. While the goal is to engineer material that is flowable in gravimetric systems, the Pioneer Uniform design uses an active flow system to queue feedstock for the conversion process. This system is a 530,000-

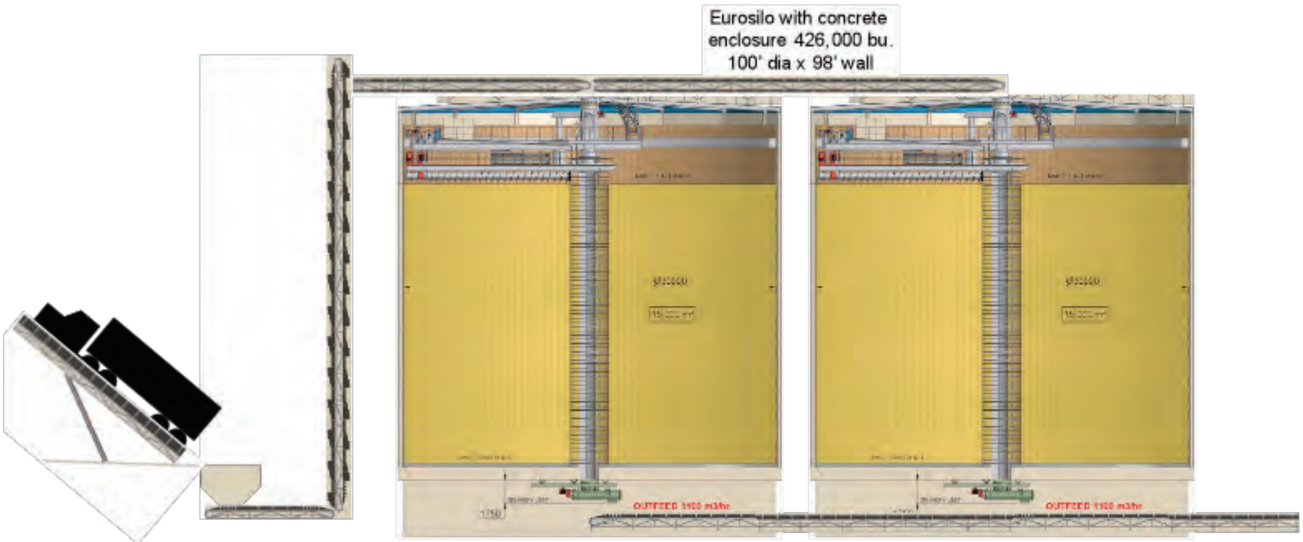


Figure 3-35. Receiving and cueing processes within the Pioneer Uniform design: bulk material being unloaded by tipper truck and being conveyed into the Eurosilo.

ft^3 (3,000 wet ton/day) Eurosilo that is capable of actively filling and discharging the silo volume through a reversible screw-type sweep auger that rotates in a helical pattern up and down the interior of the silo (Figure 3-35). This system eliminates the risks associated with arching and rat holing, which occur in standard bins and hoppers with the proposed feedstock. To meet the needed capacity and provide a reasonable queue time for the biorefinery, two Eurosilos are implemented in the Pioneer Uniform design (Figure 3-35).

3.4.2.1 Equipment Capacity and Operational Efficiency

The Pioneer Uniform receiving and handling system must have a capacity of just under 2,300 DM ton/day. Key to the efficiency of this system is the cycle time of the transportation system and the capacity of the conveying system feeding two 530,000-ft3 Eurosilos.

Receiving and weighing the feedstock as it arrives from the biomass depots is the first process within the plant gate. Both electronic and mechanical drive-over scales can be used to weigh incoming bulk feedstock. Mechanical scales are less expensive to purchase and maintain compared to electronic scales, but electronic scales can weigh trucks in 3–4 minutes compared to 10 minutes for mechanical scales (Badger 2002). Given the need for low cycle times in large-scale processing plants, electronic scales are preferred despite their higher costs. Further, bar codes or radio frequency identification (RFID) tags can be used to automatically record truck weights and to automate payments for deliveries to improve the efficiency of the process.

Once the trucks are weighed, they move to the unloading area. The design of the truck unloading process is largely based on the required truck unloading time, which becomes increasingly more important as the size of the biorefinery increases. Self-unloading trucks, such as those with live-bottom trailers that have a belt or chain conveyor in the bottom of the trailer, require no additional equipment for unloading and are generally capable of unloading in 5–10 minutes. Walking-floor trailers are slower than live-bottom trailers and are capable of unloading in about 15–20 minutes, depending on the load (data from INL unpublished data). Standard semi-trailer vans require hydraulic truck dumpers. Trailer-only dumpers require detaching the trailer from the tractor to tilt the trailer on end for unloading, while whole truck dumpers can tilt the entire tractor trailer unit. Trailer-only dumpers unload in 15–20 minutes, while whole-truck dumpers can unload in half the time (7–10 minutes) (Badger 2002). The Pioneer Uniform design uses a drive-through, whole-truck tipper to take advantage of the use of standard high-volume trailers and a 7–10-minute unload time.

The proper selection of conveying systems to provide adequate and reliable material transport is critical to the performance of receiving and handling operations. In fact, the conveying system should be one of the most important considerations, because, unlike the rest of the supply system where many pieces of equipment provide ample redundancy if a single piece of equipment goes down, a failure in the plant conveying system could cause costly production delays. There are many methods used to convey bulk materials, generally combining mechanical, inertial, pneumatic, and gravity forces (Srivastava et al. 2006). Mechanical conveyors use belts, drag chains, or screws to move material while vibratory or oscillatory conveyors rely on inertial and frictional forces. Pneumatic conveyors use aerodynamic drag forces on an air-entrained solid to move material. The proper conveyor selection depends on the following considerations:

- Material properties—Material property considerations include particle size, homogeneity, shape, moisture, and bulk flow properties.
- Capacity requirement—Capacity is important not only for conveyor sizing, but some conveyors can inherently handle higher capacities than others.
- Process configuration—Changes in elevation and conveyance distance are of primary importance.
- Processing efficiency—Some conveying methods are chosen for the ability to process the material while conveying. For example, screw conveyors are good if mixing is desired, while vibratory conveyors are good for sizing/sieving while conveying.

Table 3-36 describes the advantages and disadvantages of different conveying equipment with regard to conveying woody bulk materials (Badger 2002), but it is broadly applicable to bulk biomass materials in general.

The selection of conveying equipment for the Pioneer Uniform design is based on the physical characteristics of the received bulk feedstock. Using the characteristics of the feedstock format described previously, the following considerations are presented in support of the conveying system design:

- The dry matter bulk density of the Pioneer Uniform system will likely be in the range of 20–30 lb/ft3. To achieve this density the biomass must be compacted or densified in some fashion. While the durability of this compacted mass must be sufficient to withstand the forces associated with material handling, consideration should be made to reduce these forces where possible. Pneumatic and screw conveyors are both known to damage

Table 3-36. *Advantages and disadvantage of wood fuel conveying systems (Badger 2002).*

Type	Cost	Advantage	Disadvantage
Belt conveyors	Highest capital cost/ energy efficient	Any type of material	Limited to 20-degree incline, light dry particles, easily blown off
Screw conveyors	High capital cost/ energy efficient	When site space is a premium, easily used on inclines	Not applicable for large pieces or stringy wood
Chain/drag conveyors	Medium capital cost/ energy efficient	Rugged and adaptable to plant conditions	High maintenance, possible fire hazard, limited to 18-degree inclines
Bucket conveyors	Medium capital cost	Applicable for inclines and vertical transport	Not suitable for long horizontal runs
Oscillating conveyors	Low capital cost/ energy efficient	Dense, bulky and stringy wood fuels, horizontal transport	Not applicable for small light fuels such as sawdust limited incline
Pneumatic conveyors	High operating (energy) cost	Small, lighter fuels (i.e., finely hogged dry waste, sawdust and sander dust, long distances)	Not applicable for larger particles, fugitive dust problems

grain (Srivastava 2006), and for this reason are not considered for primary conveying from the unloading pit hopper to short-term storage.

- Oscillating conveyors are considerably slower than other options, and because sizing is not required, they are not considered in the Pioneer Uniform design.
- As discussed in the following section, storage systems will likely consist of bins and hoppers. In this case, vertical transport is required. Because screw conveyors and pneumatic conveyors have been omitted due to their tendency to damage the conveyed biomass, a bucket elevator remains a viable option.
- Belt and drag-chain conveyors remain the best options for horizontal conveying. Because the receiving and plant handling operations described in this design resemble the grain industry, this design is following the grain model with the use of drag chain conveyors.

Options for short-term storage (queuing) of bulk biomass feedstocks consist of open, uncovered piles; covered piles; and storage structures such as bins, hoppers, or silos. Open, uncovered piles are the lowest cost, but they are prone to wind and moisture losses. Covered storage such as a shed, a covered bunker, or a fully enclosed building, will help mitigate these losses, but can add significant cost. While a partially covered pile may be adequate to protect the feedstock from precipitation and wind and meet regulatory requirements for wind-blown debris, the extra protection afforded by complete enclosure is warranted to protect against extreme weather conditions.

Because the Pioneer Uniform design does not assume the feedstock is fully flowable but that it is still prone to arching and rat-holing, which are difficult to control in large capacity bins because of the high static pressures and the cohesive nature of the feedstock, a fully active storage system that uses augers rather than gravity to load and unload the bins must be used. Thus, the Pioneer Uniform design uses two Eurosilos to queue feedstock for the conversion process. These silos are capable of actively moving materials that are prone to flowability problems. These two silos function so that one silo is being filled while the other is being emptied into the conversion process. Each silo contains enough material for 25 hours of operation. The silos also act as metering bins and control the flow into the conversion process.

3.4.2.2 Dry Matter Losses

Dry matter losses include material that is not recovered from dust emissions and spillage and causes economic, environmental, and air quality issues. Dust emissions and equipment leaks within the Pioneer Uniform design are controlled with a cyclone separator and baghouse that reintroduces captured material into the queuing system, as were used in the Conventional Bale design. Thus, no dry matter losses are modeled in the Pioneer Uniform design.

3.4.2.3 Operational Window

The receiving operation at the biorefinery will not operate on the same schedule as the conversion process. Instead, it will match the bulk transportation schedule (24 hr/day, 6 day/wk) of the biomass depots. This schedule will allow receiving to provide bulk biomass to the queuing system at a rate that will maintain a minimum of 25-hr inventory for the conversion process. The queuing system, on the other hand, is an integral part of the conversion process and will match the biorefinery schedule. The Eurosilo queuing bins will provide a steady flow of feedstock to the conversion process 24 hr/day, 7 day/wk, for 350 day/yr.

3.4.3 Pioneer Uniform Receiving and Handling Cost and Sensitivity Analysis

3.4.3.1 Static Model Cost Summary

A breakdown of the costs associated with each piece of equipment used in the receiving and handling unit operation identifies significant cost components that are valuable for making individual comparisons and identifying areas of research potential (Table 3-35). These costs are reported in terms of DM tons entering each process.

Table 3-37. *Static model costs for major receiving and handling equipment in the Pioneer Uniform corn stover, switchgrass, and corn cob scenarios.*

	Equipment	Receiving		Dust Collection	Biochem Feed System	
		Truck Scales	Full Truck Tipper/Hopper	Baghouse and Cyclone	Conveyors	Eurosilos
Corn Stover	Quantity of Equipment	1	1	1	1	3
	Installed Capital	0.07	1.24	0.36	0.80	17.44
	Ownership Costs	0.01	0.14	0.05	0.09	6.64
	Operating Costs	0.19	0.38	0.13	0.23	1.88
	Labor	0.19	0.19	0.00	0.00	1.11
	Non-Labor	0.00	0.18	0.13	0.23	0.78
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	N/A	N/A	8.1	7.7	N/A
Switchgrass	Quantity of Equipment	1	1	1	1	1
	Installed Capital	0.07	1.24	0.36	0.80	5.81
	Ownership Costs	0.01	0.14	0.05	0.09	2.21
	Operating Costs	0.19	0.38	0.13	0.23	1.37
	Labor	0.19	0.19	0.00	0.00	1.11
	Non-Labor	0.00	0.18	0.13	0.23	0.26
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	N/A	N/A	8.1	7.7	N/A
Corn Cobs	Quantity of Equipment	1	2	1	1	2
	Installed Capital	0.07	2.49	0.36	0.80	11.63
	Ownership Costs	0.01	0.27	0.05	0.09	4.43
	Operating Costs	0.19	0.39	0.13	0.23	1.63
	Labor	0.19	0.19	0.00	0.00	1.11
	Non-Labor	0.00	0.19	0.13	0.23	0.52
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton	N/A	N/A	8.1	7.7	N/A

The overall costs associated with the Pioneer Uniform receiving and handling unit operation for both corn stover and switchgrass are provided in Table 3-37 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.

3.4.3.2 Cost Sensitivity Analysis

Histograms of the receiving and handling cost were produced for the scenarios shown in Table 3-38, and a sample histogram for the round bale corn stover scenario is shown in Figure 3-37.

3.5 SUMMARY OF COSTS FOR THE PIONEER UNIFORM FEEDSTOCK SUPPLY SYSTEM

The objectives of the sensitivity analysis are to:

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

3.5.1 Selection and Definition of Input Parameters

A single-point sensitivity analysis (a straightforward analysis to represent variations of a single variable) was conducted on the Pioneer Uniform design to identify and rank all input factors that affect the delivered feedstock cost (Table 3-39). 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 provide a ranking of input parameters according to the magnitude of their influence on the delivered feedstock cost.

Based on the ranking of input variables resulting from the single-point sensitivity analysis, we then defined each parameter's uncertainty using a probability distribution. 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 a range of operating parameters suggested by skilled equipment operators. The most likely value included in each distribution is the benchmark value input to the feedstock model.

Table 3-38. *Summary of sensitivity analysis for receiving and handling. Values are presented in $/DM ton.*

	Mean ± Std Dev	Mode	90% Confidence Range	Static Model Value
Round Bale Stover	$3.04 ± 0.01	$3.04	$3.03–$3.05	$3.04
Square Bale Stovera	N/A	$2.93	$2.81–$2.94	$2.94
Round Bale Switchgrass	$1.98 ± 0.01	$1.98	$1.97–$1.99	$1.98
Square Bale Switchgrassa	N/A	$2.81	$2.81–$2.94	$2.81
Corn Coba	N/A	$2.65	$2.51–$2.67	$2.66

a. As the results are bi-modal, reflecting the step function of costs when moving to a second expensive piece of equipment, the distribution is not normal, and it is not meaningful to report a mean or standard deviation.

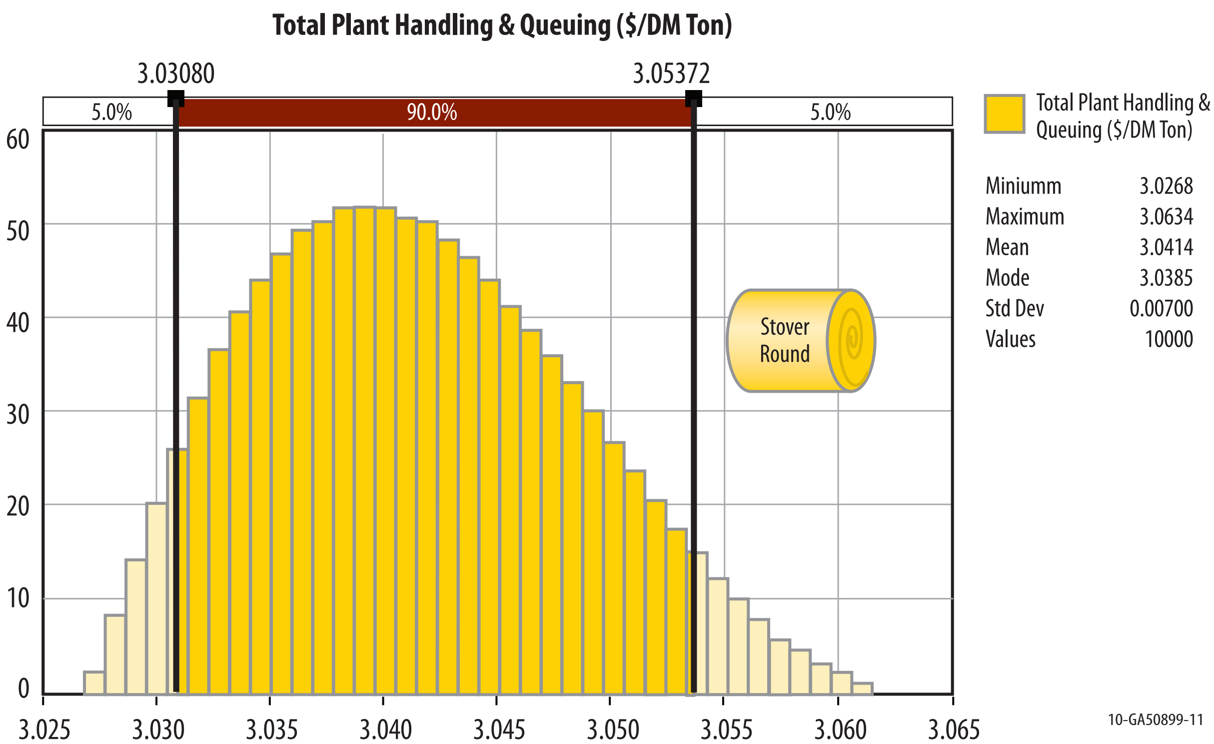


Figure 3-37. Pioneer Uniform—Corn Stover (Round) receiving and handling cost distribution histogram from @Risk analysis.

Table 3-39. *Receiving and handling cost summary for the Pioneer Uniform corn stover, switchgrass, and corn cob scenarios.*

	Equipment	Receiving			Dust Collection	Biochem Feed System	Total Receiving, Queuing, and Feed
		Truck Scales	Truck Tipper and unloading hoppers	Eurosilos		Surge Bin and Conveying Equipment	
Corn Stover	Modeled Cost Totals[a]	0.20 ± 0.00 ($/DM ton)	0.51 ± 0.00 ($/DM ton)	1.83 ± 0.00 ($/DM ton)	0.18 ± 0.004 ($/DM ton)	0.32 ± 0.003 ($/DM ton)	3.04 ± 0.01 ($/DM ton)
		0.001 ± 0.00 ($/bale)	0.002 ± 0.00 ($/bale)		0.18 ± 0.004 ($/bale)	0.001 ± 0.00 ($/bale)	0.19 ± 0.004 ($/bale)
Switchgrass	Modeled Cost Totals[a]	0.20 ± 0.00 ($/DM ton)	0.51± 0.00 ($/DM ton)	0.77± 0.00 ($/DM ton)	0.18 ± 0.004 ($/DM ton)	0.32 ± 0.003 ($/DM ton)	1.98 ± 0.01 ($/DM ton)
		0.001 ± 0.00 ($/bale)	0.003 ± 0.00 ($/bale)		0.18 ± 0.004 ($/bale)	0.002 ± 0.00 ($/bale)	0.19 ± 0.004 ($/bale)
Corn Cobs	Modeled Cost Totals[a]	0.20 ± 0.00 ($/DM ton)	0.64 ± 0.05 ($/DM ton)	1.30 ± 0.00 ($/DM ton)	0.18 ± 0.003 ($/DM ton)	0.32 ± 0.003 ($/DM ton)	2.64 ± 0.05 ($/DM ton)
		0.001 ± 0.00 ($/pile)	0.004 ± 0.00 ($/pile)		0.18 ± 0.003 ($/pile)	0.002 ± 0.00 ($/pile)	0.19 ± 0.004 ($/pile)

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

Table 3-40. *Input parameter distributions for sensitivity analysis.*

Yield	Grain Yield (bu/acre)b	Pert	140	220	180
	Feedstock Yieldd	Pert	3	8	5
Harvest Input	Harvest Window (wk/yr)	Static			=6*Harvest_ Window
	Shredder Speed (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	0.75	0.9	0.77
	Harvest Collection Efficiency (%)e	Pert	0.15	0.20	0.18
	Mower/Conditionerd	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 (wk/yr)	Static			=6*Harvest_ Window
	Baling Collection Efficiency (%)c	Pert	0.33	0.65	0.54
	Baling Collection Efficiency (%)d	Pert	0.8	0.95	0.86
	Baling Moisture (%)	Pert	0.1	0.2	0.12
	Round Baler (bale/hr)c	Pert	18	57	26
	Round Baler Field Efficiency (%)	Pert	0.55	0.75	0.65
	Bale Bulk Density (lb/ft3)[c]	Pert	8	11	9
	Bale Bulk Density (lb/ft3)d	Pert	9	12	10
Roadsiding Input	Roadsiding Window (wk/yr)	Static			=6*Harvest_ Window
	Roadsiding Distance (mile)	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 (bale/hr)	Pert	60	120	80
Transport Input	Winding Factor	Pert	1.2	1.5	1.2
	Transporter Semi (mph)	Pert	40	55	50
	Transport Loader (round bale/hr)	Pert	22	42	40
	Transport Unloader (round bale/hr)	Pert	22	42	40
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
	Bin Density (DM lb/ft3)d	Static			=11.9*FDI_CDI_Multiplier
	Feeder Density (DM lb/ft3)e	Static			=12*FDI_CDI_Multiplier
	Bin Density (DM lb/ft3)e	Static			=17*FDI_CDI_Multiplier

a. Harvest Window, Baling Window, and Roadsiding Window are tied into the same distribution function.
b. ASABE, ASAE D497.5 2006.
c. Corn stover only parameter.
d. Switchgrass only parameter.
e. Corn cob only parameter.

3.6 COMPARISON OF SUPPLY SYSTEMS

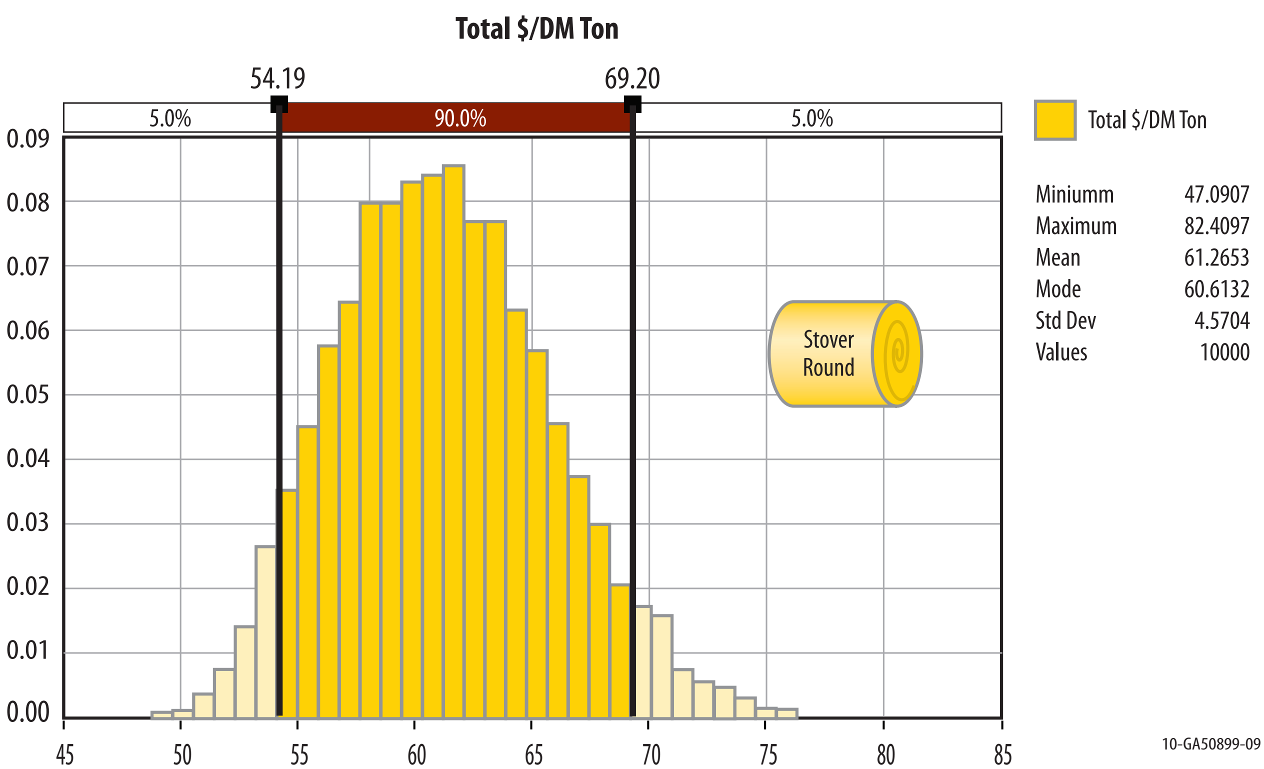
3.6.1 Monte Carlo Analysis

A 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 3-40), and the resulting total delivered feedstock cost as well as the incremental feedstock costs throughout each stage (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-4, "Sensitivity Analysis."

Figure 3-38. Total Pioneer Uniform—Corn Stover (Round) supply system design cost distribution histogram from @Risk analysis.

A histogram of the final cost for the round bale corn stover scenario, delivered to the throat of the conversion reactor at a biorefinery (Figure 3-38) for the Pioneer Uniform shows with 90% confidence that the cost ranges between $54.19 and $69.20 per DM ton. Further, the mean and standard deviation of this range is $61.27 ± 4.57 per DM ton. The mode value of the final cost is $60.61 per DM ton. This value closely represents the result of the static model, which is $57.01 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

Similarly, a histogram of the final delivered cost for the square bale corn stover scenario to the throat of the conversion reactor at a biorefinery (Figure 3-39) for the Pioneer Uniform shows with 90% confidence that the cost ranges between $52.18 and $64.19 per DM ton. Further, the mean and standard deviation of this range is $57.78 ± 3.72 per DM ton. The mode value of the final cost is $55.83 per DM ton. This value closely represents the result of the static model, which is $53.35 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.



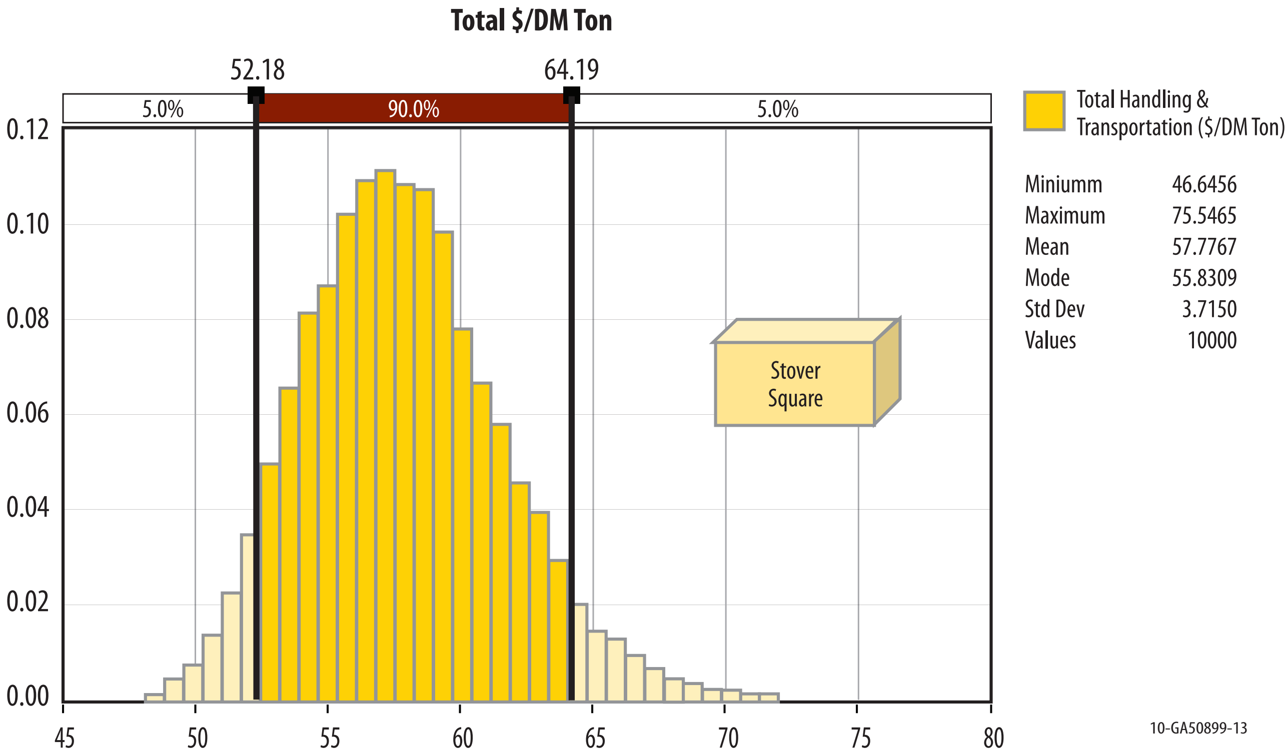


Figure 3-39. Total Pioneer Uniform—Corn Stover (Square) supply system design cost distribution histogram from @Risk analysis.

A histogram of the final cost for the round bale switchgrass scenario, delivered to the throat of the conversion reactor at a biorefinery (Figure 3-40) for the Pioneer Uniform shows with 90% confidence that the cost ranges between $49.74 and $65.88 per DM ton. Further, the mean and standard deviation of this range is $57.12 ± 4.92 per DM ton. The mode value of the final cost is $54.84 per DM ton. This value closely represents the result of the static model, which is $53.64 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

For the square bale switchgrass scenario, a histogram of the total cost of biomass delivered to the throat of the conversion reactor at a biorefinery (Figure 3-41) for the Pioneer Uniform shows with 90% confidence that the cost ranges between $46.05 and $58.51 per DM ton. Further, the mean and standard deviation of this range is $51.58 ± 3.79 per DM ton. The mode value of the final cost is $51.16 per DM ton. This value closely represents the result of the static model, which is $46.45 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

Finally, for the corn cob scenario, a histogram of the total cost of biomass delivered to the throat of the conversion reactor at a biorefinery (Figure 3-42) for the Pioneer Uniform shows with 90% confidence that the cost ranges between $62.40 and $75.83 per DM ton. Further, the mean and standard deviation of this range is $68.91 ± 4.11 per DM ton. The mode value of the final cost is $68.50 per DM ton. This value closely represents the result of the static model, which is $66.93 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

The total costs (including all unit processes) are presented in Table 3-41. The square bale switchgrass scenario had the lowest cost per dry matter ton, and the corn cob scenario had the highest cost per dry matter ton.

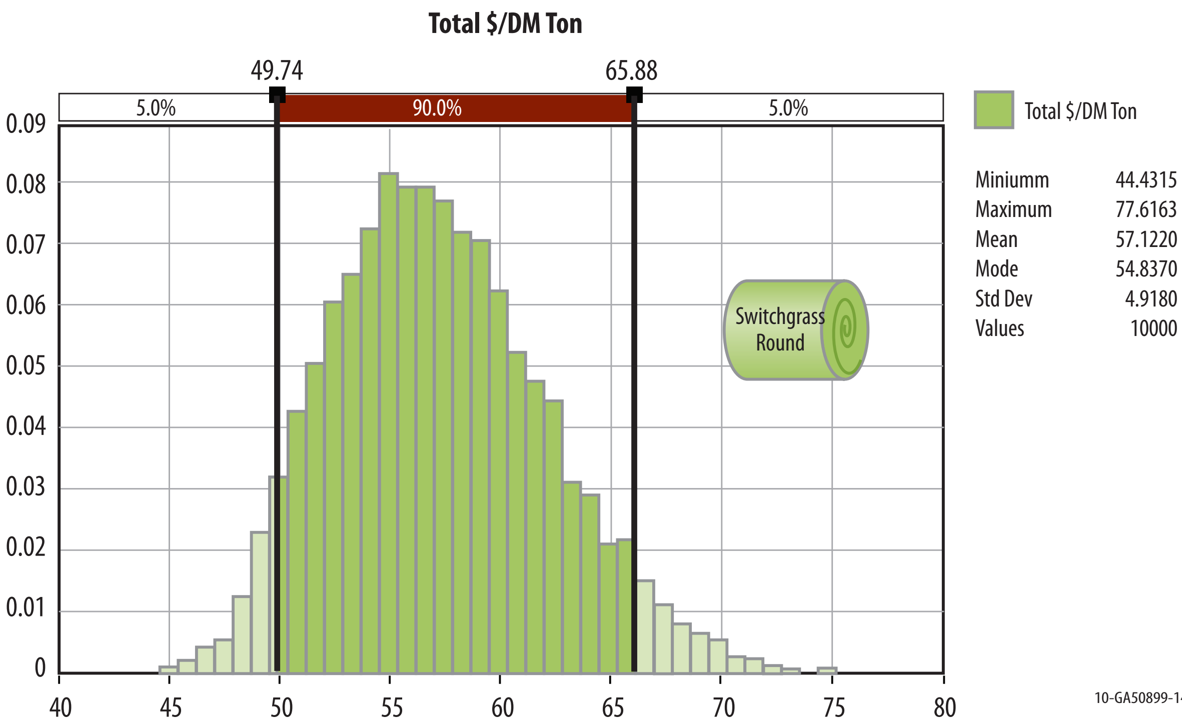
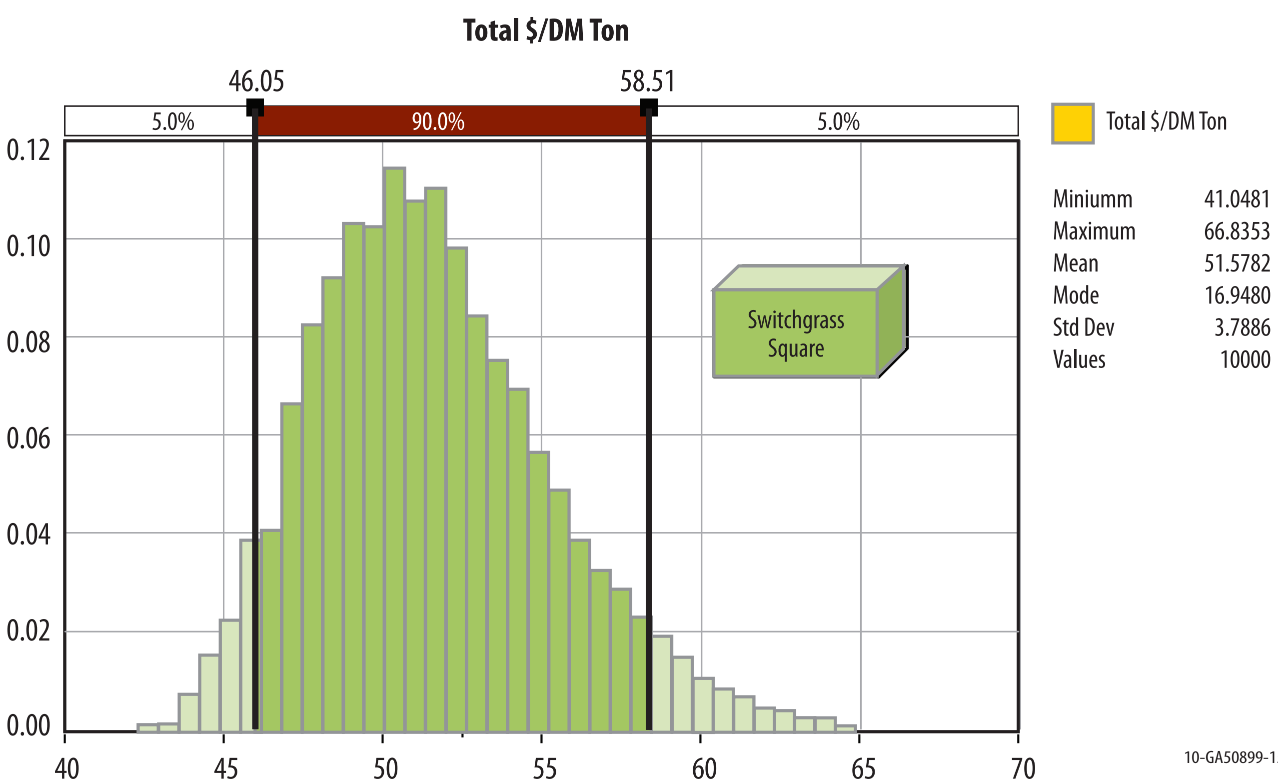


Figure 3-40. Total Pioneer Uniform—Switchgrass (Round) supply system design cost distribution histogram from @Risk analysis.

Figure 3-41. Total Pioneer Uniform—Switchgrass (Square) supply system design cost distribution histogram from @Risk analysis.



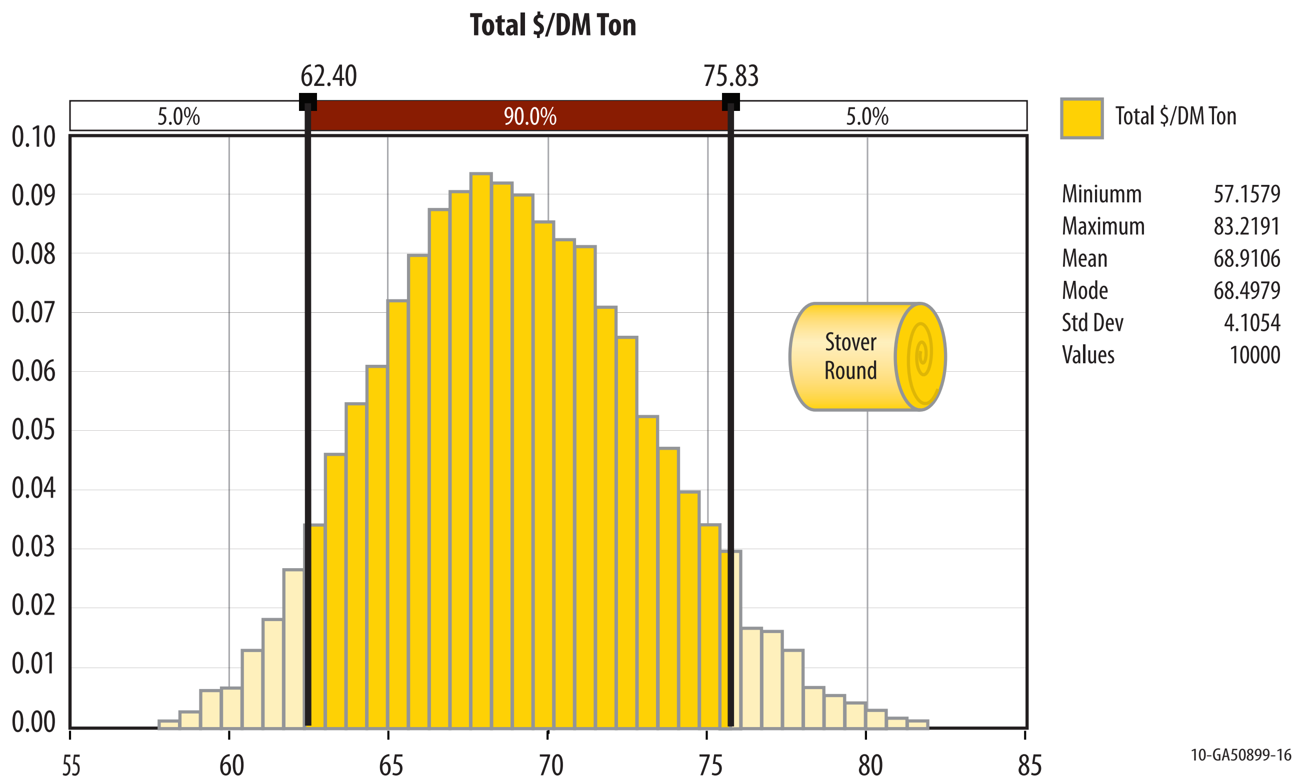


Figure 3-42. Total Pioneer Uniform—Corn Cob supply system design cost distribution histogram from @Risk analysis.

Table 3-41. *Summary of costs for the Pioneer Uniform feedstock supply systems (presented in $/DM ton).*

	Corn Stover	Switchgrass
Round Bale	61.27 ± 4.57 ($/DM ton)	57.12 ± 4.92 ($/DM ton)
Square Bale	57.78 ± 3.72 ($/DM ton)	51.58 ± 3.79 ($/DM ton)
Cob	68.91 ± 4.11 ($/DM ton)	N/A

3.6.2 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 14 parameters from this ranking were further analyzed to produce the correlations shown in Figure 3-43, which represents the response of feedstock cost changes to these top 14 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 3-43). 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.

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

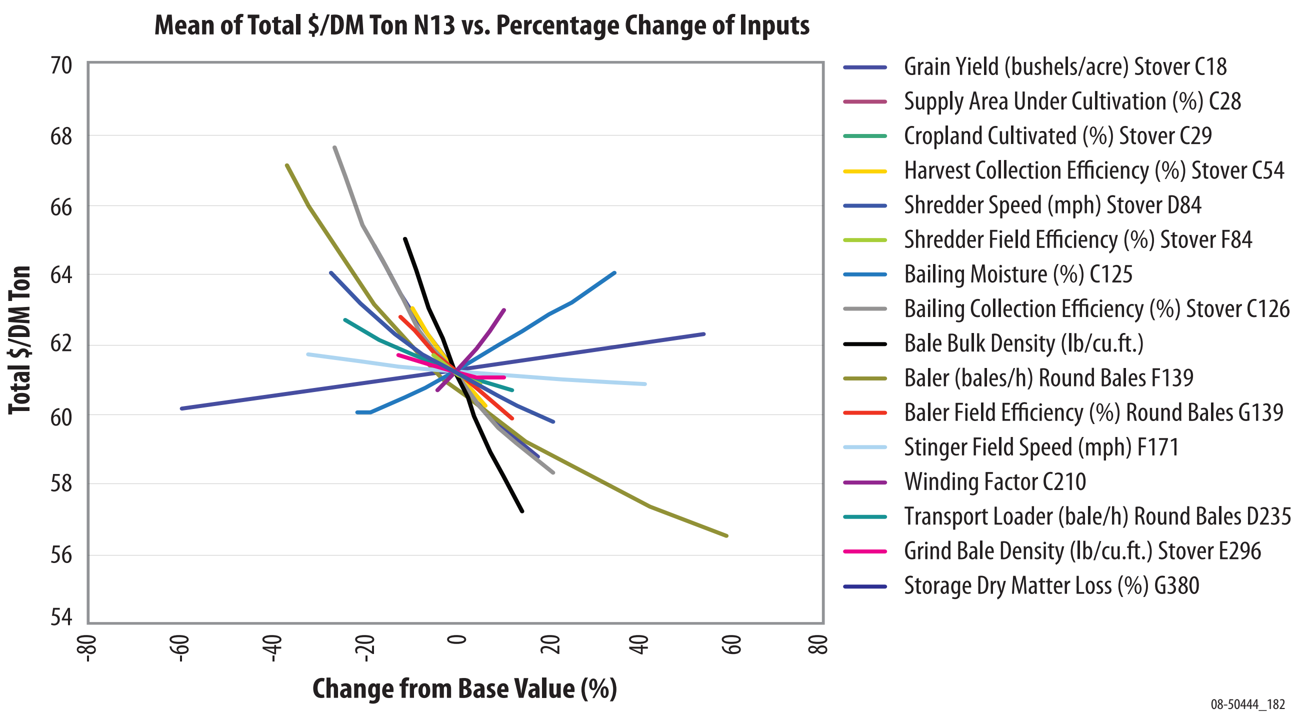
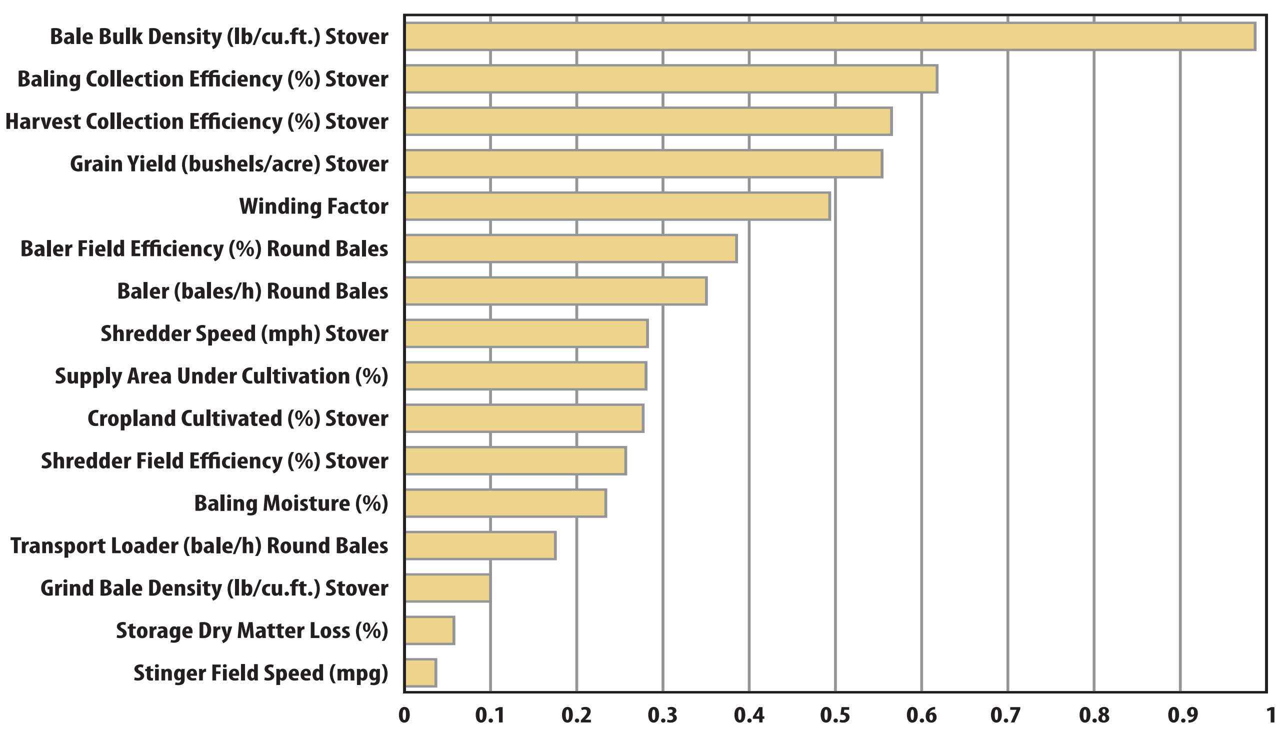


Figure 3-43. Percent change of variable to output.

Figure 3-44. Relative sensitivity of individual supply system parameters.



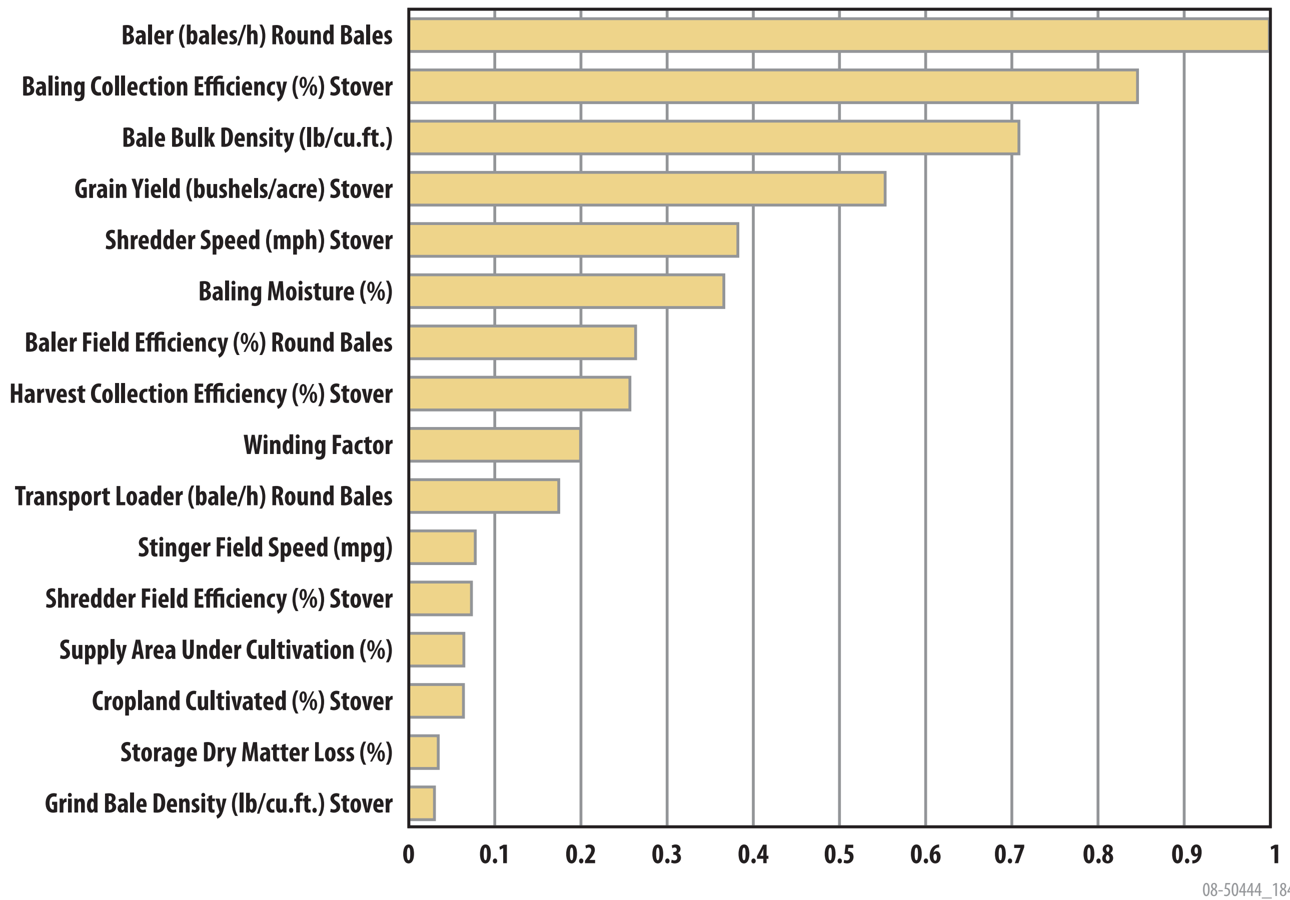


Figure 3-45. Relative cost impact of individual supply system parameters.

sensitivity comparison (Figure 3-44). 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 3-45).

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 3-44), but it ranks much lower (eighth in Figure 3-45) 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 Pioneer Uniform design, the rankings in Figure 3-44 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 section of this report. The objective of the sensitivity analysis of the Pioneer Uniform design is to quantify the uncertainty in the design; thus, the rankings shown in Figure 3-45 are most relevant. As such, the final ranking of input parameters for the Pioneer Uniform, expressed in a tornado chart that represents the uncertainty or variability in delivered feedstock cost, is shown in Figure 3-46. The tornado chart shows that baler field losses, bale bulk density, and bale moisture are the top three parameters in order of decreasing uncertainty.

Finally, additional analyses were conducted to examine the cause-and-effect relationship of the parameters shown in the tornado chart since

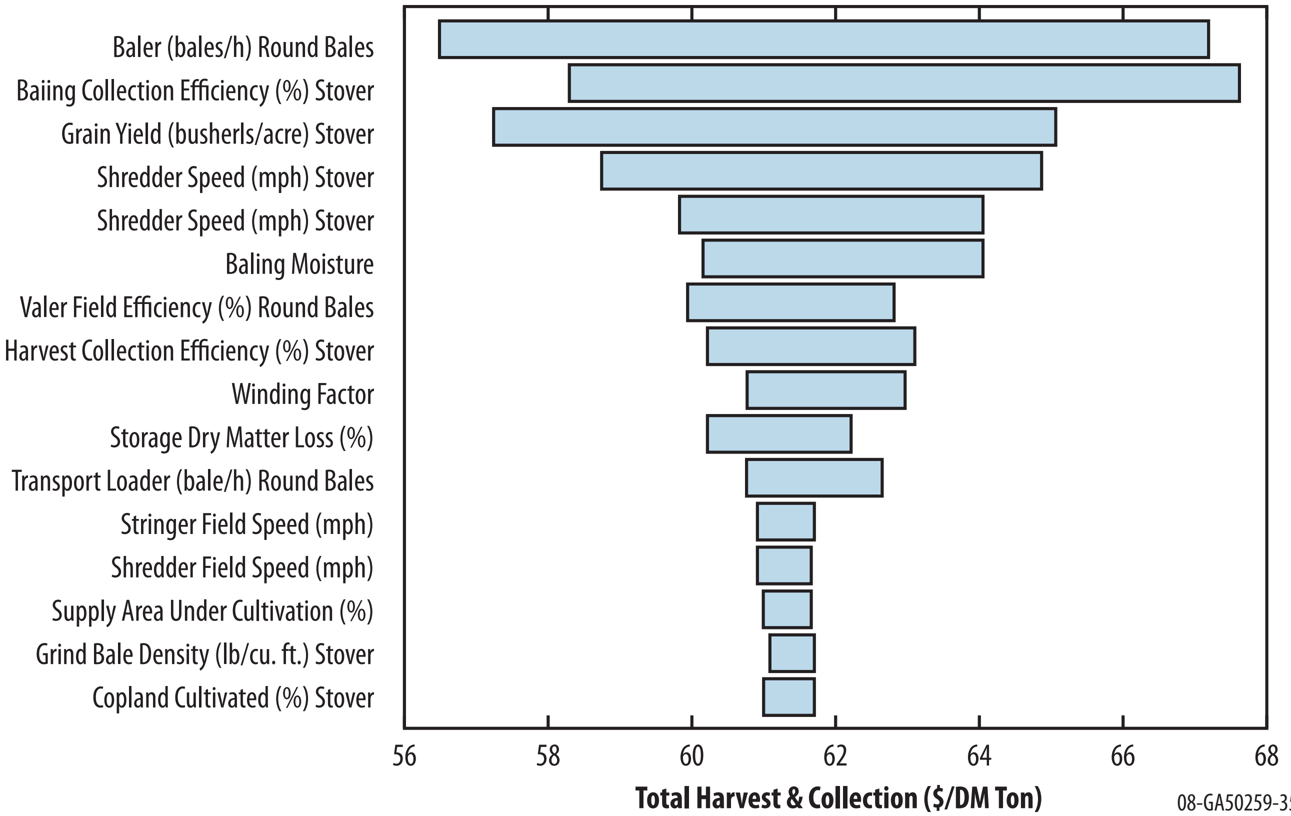


Figure 3-46. Tornado chart reflecting the final cost in dollars according to the distribution ranges defined.

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 (Figure 3-45).

3.6.3 Discussion

The Monte Carlo analysis confirms that the Pioneer Uniform supply system design is not able to achieve DOE cost targets (Table 3-41). However, the intention of the Pioneer Uniform system is to incorporate design improvements as they become available, and to move towards a system that meets both equipment performance and cost targets, while supplying the quantity and quality of biomass needed to meet supply goals. Further analysis defined and ranked the supply system equipment and biomass material parameters that must be addressed to achieve cost targets. The simulation also produced a ranking of input parameters based on the statistical relationship between each parameter and the total supply chain logistics costs to determine the impact of each parameter individually, and capture the interdependence of each respective input parameter.

The @Risk simulation produced a ranking of input parameters based on the statistical relationship between each parameter and the delivered feedstock cost. The top parameters were further analyzed to produce the correlations shown in Figure 3-43, which represents the response of feedstock cost changes to these parameters. The slope of the response curve in Figure 3-43 represents the statistical correlation between the delivered feedstock cost and the input parameter. Therefore, as baler collection efficiency has a highly sloped line, that parameter is highly correlated to the delivered feedstock cost. As the slope is negative, increasing the baler efficiency will result in a proportionally large decrease in the total delivered cost. The baling rate (i.e. bales/hr) and bale bulk density also have a large negative slope, and increases in these parameters will result in large decreases in delivered biomass cost. Focusing research efforts on improving the performance of the baler is key to moving from the Pioneer Uniform system to the Advanced Uniform system that meets all cost targets. Alternatively, the Stinger stacker field speed has a very flat curvature, and therefore a large change in that parameter will have little impact on the total delivered biomass cost. Baling moisture has a large positive slope; therefore large increases in the moisture content of the biomass at the time of baling will have a proportionally large impact on the total delivered biomass cost.

The length of the response curve in Figure 3-43 represents the magnitude of the variability or uncertainty. For example, the baling rate has a long response curve compared to the grinder baling density. Therefore the magnitude of variability in baling rate is much higher than for grinder bale density. Grain yield has a long curve but has a fairly mild slope. Therefore grain yield has a large magnitude of variability (i.e. from approximately -60% to +60% over the base value); however, the impact of the change in this variable over that range on the total delivered cost of biomass is fairly limited. The supply area under cultivation, however, has a small magnitude of variability (i.e. short line length), but the slope is highly positive. Although there is a small range of reasonable values for this parameter, a small increase in cultivated area has a large increase in costs due to higher transportation 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. For example, the baling rate has a more curved line than the bale bulk density, and therefore the baling rate has a broader interdependence than bale bulk density. Approximating the slope using a linear regression of each response curve, followed by normalization with respect to the highest slope (i.e. bale bulk density), provides a good relative sensitivity comparison (Figure 3-44).

As was the case in the Conventional Bale system, the highest sensitivity results from the bale bulk density, which was used as the basis for comparison, followed by the baler collection efficiency and harvest collection efficiency. Therefore, small increases in the bale bulk density, baler collection efficiency, and harvest collection efficiency will result in large decreases in total delivered cost of biomass. However, unlike the Conventional system, the sensitivity of the system to changes in bale bulk density is not as large compared to the other variables. This is because the material is reformatted at a preprocessing depot prior to long distance transport. Other parameters have different levels of impact over the Conventional system. For example, grain yield and road winding factor in the Pioneer Uniform system have a higher significance than in the Conventional Bale. As improvements are made, different parameters will cause a relatively higher or lower impact on delivered feedstock cost.

Normalizing the delta-Y in Figure 3-43 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 3-45). Therefore, although the bale bulk density has the highest relative sensitivity (Figure 3-44, and reflected in Figure 3-43 as the line with the highest slope), the baling rate has a higher overall impact on the total delivered cost of biomass, reflected in the largest range of possible total delivered costs (the y-axis in Figure 2-43). Looking at the impact of variables on supply system cost (Figure 3-45), the highest impact in total delivered biomass cost is from the rate of bales collected (i.e., bales per hour), followed by baling collection efficiency, and bale bulk density. Again, the parameter of highest impact has less of an influence relative to other parameters than in the Conventional Bale scenario, and the relative ranking has changed.

3.7 CONCLUSION

The Pioneer Uniform feedstock supply system is the pioneer implementation of the "Uniform-Format" Vision. This design addresses some of the material and equipment barriers identified through analyses of the Conventional Bale system, including increasing mass bulk density, grinder capacity, and harvest and collection efficiency. The Pioneer Uniform design incorporates new equipment such as the cob harvester, keeping in mind that grain quality and quantity cannot be compromised while getting more residues.

A key feature of the Pioneer Uniform system is the introduction of a biomass preprocessing depot. The depot provides a regionally centralized facility where local producers can bring their biomass to be dried (if necessary) and densified. The depot has equipment specialized to format biomass specific to a region into a uniform-format, bulk solid, flowable material, therein decreasing handling costs at the biorefinery that result from having to handle many different formats.

A sensitivity analysis of the Pioneer Uniform feedstock supply system identifies major opportunities to improve equipment performance, improve equipment use efficiency, reduce material loss, and decrease system costs exist in the Pioneer-Uniform system. However, the expansion of the resource base available to biorefineries once an advanced system is in place is critical to an expanding biofuels industry. Section 4 expands on the transition from the Pioneer-Uniform system to an advanced system that meets all cost and equipment performance targets, as well as quantity goals set out by the U.S. DOE.

3.8 REFERENCES

Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, Wallace B, Montague L, Slayton A, Lukas J (2002) Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover. NREL/TP-510-32438. http://www.nrel.gov/docs/fy02osti/32438.pdf. Accessed 17 January 2008.

ASABE (American Society of Agricultural and Biological Engineers) (2006) Agricultural Machinery Management Data. ASAE D497.5.

ASABE (American Society of Agricultural and Biological Engineers) (2006a) Agricultural Machinery Management. ASAE EP496.3.

Badger PC (2002) Processing Cost Analysis for Biomass Feedstocks. Oak Ridge National Laboratory. ORNL/TM-2002/199.

Bern C, Brumm T (2009) Grain Test Weight Deception. Iowa State University, University Extension, PMR, 1005, October 2009. http://www.extension.iastate.edu/Publications/PMR1005.pdf. Accessed 11 June 2010..

Bruynis C, Hudson B (1998) Land Rental Rates: Survey Results and Summary. Survey. Ohio State University. http://aede.osu.edu/resources/docs/pdf/D8QOMB09-77MY-IDPZ-DST14X1DMQ007PS6.pdf.

Buggeln R, Rynk R (2002) Self-Heating in Yard Trimmings: Conditions Leading to Spontaneous Combustion. Compost Sci Util 10(2):162–182.

Cromwell (2002)

Cundiff JS, Marsh LS (1995) Effects of Ambient Environment on the Storage of Switchgrass for Biomass to Ethanol and Thermochemical Fuels. Department of Biological Systems Engineering, Virginia Tech, Blacksburg, Virginia. NREL subcontract No XAC-3-13277-04.

Dhuyvetter KC, Harner JP III, Boomer G, Smith JF, Rodriquez R (2005) Bunkers, piles, or bags: which is the most economical? http://www.oznet.ksu.edu/pr_silage/publications/SilageStorage$_(Nov2005).pdf. Accessed 16 March 2010.

DuBose R (2008) Carroll County Fighting Andersons Blaze. WLFI TV 18. 27 Dec 2008. http://www.wlfi.com/dpp/news/Local_WLFI_Delphi_Andersonsfire_20081227. Accessed 16 March 2010.

Dunning JW, Winter P, Dallas D (1948) The Storage of Corncobs and Other Agricultural Residues for Industrial Use. Agricultural Engineering 29(1):11–13, 17.

Edwards W, Hofstrand D (2005) Estimating Cash Rental Rates for Farmland. Iowa State University. http://www.extension.iastate.edu/feci/Leasing/FM-1801.pdf. Accessed 16 March 2010.

Festenstein (1971)

Foley, KM (1978) Chemical Properties, Physical Properties and the Uses of the Andersons' Corncob Products. The Andersons, Maumee, OH.

Grant D (2003) Custom Baling and Transportation Rates and Straw Price Marketing Data for Jerome, Idaho Dairy Straw Market. Personal communication. Grant 4-D Farms, Rupert, Idaho.

Groover (2003)

Heslop LC, Bilanski WK (1986) Economic Benefits of Weather Protection for Large Round Bales. Cm Agric Eng 28:131–135.

Hess JR, Kenney KL, Ovard LP, Searcy EM, Wright CT (2009-Draft) “Uniform-Format” Feedstock Supply System Design Report Series, Report 1: Commodity-Scale Production of an Infrastructure-Compatible Bulk Solid from Herbaceous Lignocellulosic Biomass, Volume A: “Uniform-Format” Vision and Conventional-Bale Supply System Design.

Holmes BJ (2004) Round bale hay storage costs. University of Wisconsin Extension. Presentation: http://www.uwex.edu/ces/crops/uwforage/HayStorCosts5-12-04.ppt. Accessed 16 March 2010.

Hoskinson RL, Karlen DL, Birrell SJ, Radtke CW, Wilhelm WW (2007) Engineering, Nutrient Removal, and Feedstock Conversion Evaluations of Four Corn Stover Harvest Scenarios. Biomass and Bioenergy 31:126–136.

Idaho National Laboratory (2007, 2008) Grinder field tests in Kansas and Iowa.

Jenike AW (1964) Storage and Flow of Solids. Bulletin of the University of Utah, Number 123, Utah Engineering Experiment Station, University of Utah, Salt Lake City, UT. November 1964.

Johnson et al. (1991)

Li et al. (2006)

Nelson et al. (2007)

OMAFRA (1993)

Palisade (2010) @Risk, http://www.palisade.com/RISK/. Accessed March 16, 2010.

Phillips S, Aden A, Jechura J, Dayton D, Eggeman T (2007) Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass. NREL Technical Report, TP 510-41168, National Renewable Energy Laboratory, Golden, Colorado.

Pordesimo LO, Sokhansanj S, Edens WC (2004) Moisture and Yield of Corn Stover Fractions Before and After Grain Maturity. 2002 ASAE Annual Meeting, Chicago, Illinois, July 28–31, 2002. Trans ASAE 47(5).

Pryfogle, INL test data, March 2009.

Remaining data from INL grinder field tests in Kansas, November 2007, and Iowa, July 2008.

Richey CB, Liljedahl JB, Lechtenberg VL (1982) Corn Stover Harvest for Energy Production. Trans ASAE 1982 25(4):834–44.

Rider AR, Batchelor D, McMurphy W (1979) Effects of Long-Term Outside Storage on Round Bales. ASAE Paper No. 79-1538. Am Soc Agric Eng, St. Joseph, MI.

Shinners KJ et al. (2006)

Shinners KJ, Binversie BN, Muck RE, Weimer PJ (2006a) Comparison of Wet and Dry Corn Stover Harvest and Storage. Biomass and Bioenergy 31:211–221.

Shinners KJ, Binversie BN (2007) Fractional Yield and Moisture of Corn Stover Biomass Produced in the Northern U.S. Corn Belt. Biomass and Bioenergy 31:576–584. doi:10.1016/j.biombioe.2007.02.002.

Smith RD, Liljedahl JB, Peart RM (1983) Storage and Drying of Corn Cobs. ASAE Technical Papers, 83-3007. Conference: American Society of Agricultural Engineers, Bozeman, Montana. 26 June 1983.

Smith RD, Peart RM, Liljedahl JB, Barrett JR, Doering OC (1985) Corncob property changes during outside storage. Trans ASAE 28(3):937–942, 948.

Srivastava AK, Goering CE, Rohrbach RP, Buckmaster DR (2006) Engineering Principles of Agricultural Machines. 2nd Ed. ASAE Publication 801M0206.

4. ADVANCED UNIFORM FEEDSTOCK SUPPLY SYSTEM DESIGN

Lignocellulosic biomass feedstocks are not considered a commodity resource because of the great diversity in material composition and form (Wiselogel 2008). Additionally, low bulk densities and the perishable nature of many biomass resources constrain both the supply and demand of these resources to local independent markets and/or contracting regions. Conversely, the national renewable fuel goals to displace as much as 30% of the 2004 gasoline use with biofuels (EIA 2007) will require development of a national biomass market that draws from multiple geographically dispersed resources and includes biomass trading across the country (i.e., a commodity biomass market). To accomplish these national goals, the “non-commodity” characteristics of biomass be overcome. As such, the fundamental objective of the Advanced Uniform feedstock supply system design (Advanced Uniform) is to preprocess the diversity of lignocellulosic biomass resources into a definable set of “uniform-format” resources that are consistent across a national and potentially international biorefining market (Figure 4-1). In other words, the goal of the Advanced Uniform design is to transform lignocellulosic biomass into a commodity resource.

The Conventional Bale and Pioneer Uniform supply system designs presented in Sections 2 and 3 are incapable of producing a commodity biomass resource, because they cannot achieve the required material quality standards within cost targets. An Advanced Uniform design vision that sustainably meets commodity-scale handling requirements, feedstock spec requirements, and DOE cost targets is presented in this section, along with discussion of principal barriers that must be overcome and potential pathways to overcome those barriers.

The primary material standard of this Advanced Uniform design is a high-density, aerobically stable, bulk solid material that is compatible with the highly efficient, large-capacity, and dependable commodity-scale grain handling and storage infrastructure. An alternate commodity-scale preprocessed biomass resource would be a stable high-density liquid, or bio-crude format, which will not be discussed here, but will be presented in a future design report. An annual supply of over 400 million dry tons is required to support a national biorefining industry. Currently, there are no alternate supply system designs for solid lignocellulosic biomass that are capable of handling such large quantities of biomass more efficiently or reliably than the existing grain handling infrastructure. However, this can be accomplished through the development of harvesting and preprocessing systems that reformat lignocellulosic biomass resources into a uniform-format bulk feedstock.

Achieving the Advanced Uniform design will allow lignocellulosic biomass to be traded and supplied to biorefineries as a commodity similar to grain. In addition, the Advanced Uniform system will stimulate rural economies as a vast network of biomass preprocessing depots are deployed across the nation to convert a diverse, low-density, perishable feedstock resource into a densified, aerobically stable and uniform-format bulk solid resource that can enter the existing agricultural bulk solid commodity infrastructure. This approach will allow bioenergy industry development to progress in a logical, cost-effective manner.

4.1 ADVANCED UNIFORM DESIGN PERFORMANCE TARGETS

The key feature of the Advanced Uniform design is the positioning of the biomass preprocessing operation early in the supply system. Preprocessing depots are central to this design, which produce a final uniform material that is compatible with the grain storage and handling infrastructure. Figure 4-2 shows an overview of the Advanced Uniform design concept.

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

- Material deconstruction – overcoming resistance to deconstruction and drying, and therein improving the ability to change physical form, improving flowability characteristics, and developing progressive/final material formats

- Density – increasing biomass bulk density and energy density for more efficient handling and transportation
- Moisture – management and removal of moisture to produce an aerobically stable material.
- The remaining challenges are related to the supply system equipment:
- Capacity and operational efficiency – includes overcoming capital and energy costs associated with doing a prescribed amount of work
- Dry matter losses – includes dust collection/control, field losses, and biological losses
- Operational window – as operations move forward in the supply system, they become constrained to harvest windows and other logistic constrains.

The full implementation of the Advanced Uniform design vision overcomes all of these barriers for all biomass resources, regardless of moisture content, and a modeled analysis will be detailed in a later report.

4.2 THE ADVANCED UNIFORM SUPPLY SYSTEM VISION

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

High-Efficiency Bulk Solids Handling

Existing grain commodity markets effectively move billions of tons of bulk-solid biomass (corn and cereal grains) around the globe. Commodity-scale supply system handling infrastructures have been designed around the natural attributes of these materials:

Particle size is small and fairly uniform

Particle density is high

- Flowability characteristics are favorable for cost-effective handling and transportation
- Moisture management is relatively easy (i.e., they are aerobically stable) and consistent throughout each lot.

Similarly, the key to managing biomass resources efficiently at the commodity scale is to preprocess them into a format that shares the same qualities: high dry matter bulk density, good flowability, and aerobic stability. The Advanced Uniform design vision introduces comprehensive preprocessing that produces lignocellulosic bulk-solids with material properties comparable to those of existing grain commodities. Storage and handling systems for grain are highly replicable, scalable, and optimized for cost-effective performance. These systems are typically sold and constructed as “turnkey” products that are assembled with common interchangeable components to meet each customer’s performance specification. This dynamic provides an opportunity for highly efficient and economical implementation.

The equipment used for handling and transporting grain from storage to downstream processes is similarly replicable and interchangeable. Consistent, uniform material properties of grain allow trucks and trains to seamlessly move biomass large distances to terminals or destination markets. Another important consequence of grains’ material characteristics is the ability to blend, grade, and efficiently track material throughout trading within the supply system. In the case of corn, distributors employ fast screening

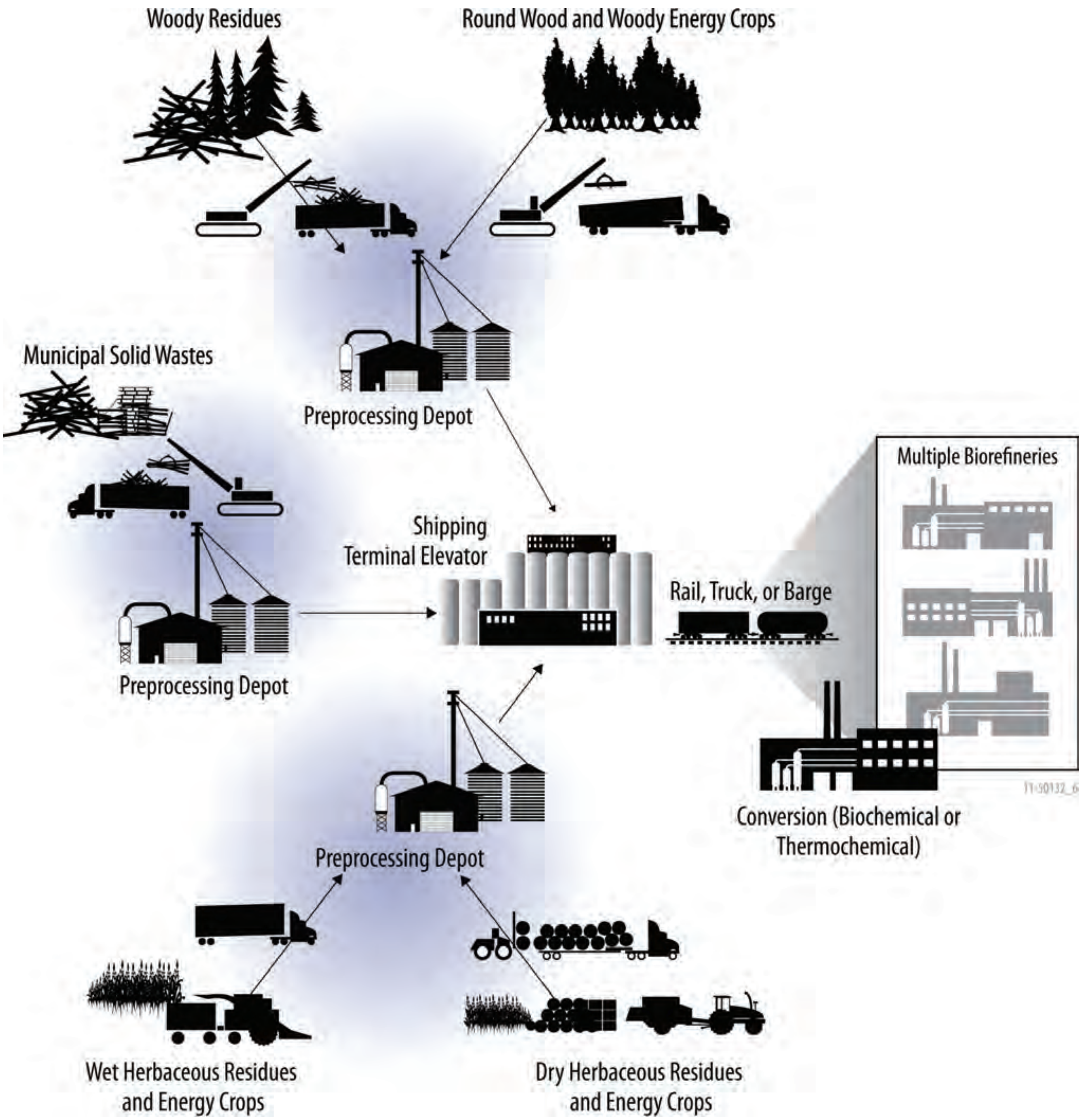


Figure 4-1. The Advanced Uniform-Format feedstock supply system (Advanced Uniform) design emulates the current grain commodity supply system, which manages crop diversity at the point of harvest and at a biomass depot/elevator, allowing subsequent supply system infrastructure to be similar for all biomass resources. The commodity produced could be either a liquid or a solid format.

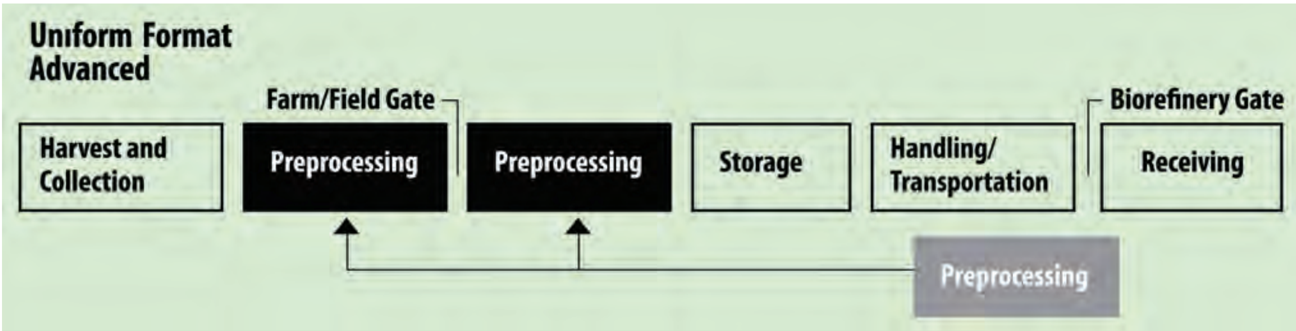


Figure 4-2. The Advanced Uniform design concept. Advanced preprocessing technologies are incorporated into the harvest/collection and depot operations. The preprocessed biomass is then compatible with existing bulk solid storage, transportation, and handling infrastructures and technologies.

methods to test and blend feedstock to stringent specifications of individual biorefineries, while maintaining the integrity of non-genetically modified organism (GMO) food supplies. This is possible by using a uniform-format material with adequate bulk density and flowability performance that allows a common, replicable set of high-capacity bulk-solids handling equipment to be employed throughout the supply system. In the case of lignocellulosic feedstocks, the testing and blending of materials will correspond to biorefinery needs based on characteristics such as sugar, lignin, ash, and energy content. This ability leverages the existing grain commodity markets to provide the basis for the Advanced Uniform system design in terms of material specification, and equipment/process design.

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

4.3 MEETING TARGETS WITH THE ADVANCED UNIFORM DESIGN

Progression to the Uniform-Format system focuses on decreasing the delivered cost of biomass sufficiently to achieve cost targets while increasing supply volume of material with appropriate characteristics for the targeted conversion method. This will be accomplished by addressing key material property and machine/engineering challenges to increase biomass supply logistics efficiency. Table 4-1 compares design attributes of the three systems and shows how progression from the non-uniform Conventional systems commonly used today to Advanced Uniform systems that rely on existing and new technologies can overcome material property and engineering challenges, address long-term sustainability issues, and achieve national cost and supply goals.

Table 4-1. Comparison of the attributes of the non-uniform and uniform herbaceous feedstock supply systems. The Advanced Uniform design achieves all national goals while overcoming material property and engineering goals, and addresses long-term sustainability issues.

Meeting long-term U.S. DOE biofuels production goals requires the integration of many resources. The diversity of biomass feedstocks, including crop residues, herbaceous energy crops, woody energy crops, and forest resources will be addressed through transition from conventional agriculture and forestry biomass supply systems to advanced systems. Whereas conventional supply systems address critical logistics challenges such as efficiency/capacity of equipment, dry matter losses, and operational window for gathering material, the advanced system builds off of these improvements to the conventional system and incorporates new considerations such as quality, quantity, stability, and densification. The Advanced Uniform design is a commodity-based, spec-driven system achieved by engineering format intermediates throughout the supply chain.

4.3.1 National Goals

DOE biofuel production goals, both intermediate and long-term, will require herbaceous biomass supply systems that economically scale beyond the capability of existing systems. Effective scale-up will require feedstocks that use consistent and replicable infrastructure and equipment. Furthermore, the material characteristics of the feedstocks need to maximize the capacity and efficiency of the equipment and infrastructure. The Conventional Bale supply system does not meet these criteria, and can be effectively implemented only at the scale of custom, feedstock-specific supply systems. The Pioneer Uniform supply system begins to address the issue of feedstock uniformity, allowing for more consistent equipment and infrastructure downstream of the preprocessing unit operation. However, the Pioneer Uniform design does not yet achieve the material property characteristics necessary to facilitate capacities and efficiencies that allow the system to economically scale to meet national production goals. Only the Advanced Uniform design provides the means to overcome material and engineering barriers to economic supply system scale-up. The Advanced Uniform system creates a consistent, uniform material that performs similarly to commodity bulk-solids such as corn grain, and subsequently can use existing replicable equipment and infrastructure that has been proven to scale economically. These Advanced Uniform design characteristics also provide the opportunity to meet cost targets for delivered feedstock price.

4.3.2 Material Properties Barriers

The fundamental material properties that drive supply system performance are moisture content and dry matter bulk density. Moisture content must be low enough for aerobic stability (typically <15–20%) to limit costly material losses within the system (Figure 3-16), and reduced moisture content often increases grinding efficiency of residues (Yancey et al. 2009). In recent INL field testing, Yancey et al. (2009) found that grinding efficiency of switchgrass was reduced by 40 to 50% as a result of increasing the moisture content in the biomass from 10 to 25%, and similar trends were observed while grinding corn stover. Dry matter bulk densities must be greater than 30 lb/ft^3 to facilitate efficient transport and storage. As described in Section 3.3.1.2, maximizing load weight and volume simultaneously not only decreases transportation costs, but also reduces the frequency of trucks or trains that arrive at the conversion facility. Increasing the dry matter density decreases the amount of water being hauled, and again reduces the transportation costs and frequency.

The Conventional Bale and Pioneer Uniform designs fail to sufficiently address these barriers. Drying is not built into either system, and dry matter bulk densities are below 30 lb/ft^3. Within the biomass depots in the Advanced Uniform supply system, the feedstock is dried to aerobically stable levels, and dry matter bulk density reaches 45 lb/ft^3.

Another important material property consideration is biomass deconstruction characteristics. Significant improvements in capacity and efficiency can be achieved by engineering systems that leverage deconstruction characteristics, as well as material composition. For example, ongoing INL research studies the impacts of biomass anatomy on its deconstruction tendencies of lignocellulosic biomass. Figure 4-3 shows radiograph projections of barley straw (left) and corn stover (right). Understanding that the biomass tends to split into strips when struck along the stem, but breaks more readily when struck at the nodes, is key to optimizing deconstruction.

Understanding these material properties is critical to improving equipment performance, and may also be applied in fragmentation studies to separate out

Table 4-1. *Comparison of the attributes of the non-uniform and uniform herbaceous feedstock supply systems. The Advanced Uniform design achieves all national goals while overcoming material property and engineering goals, and addresses long-term sustainability issues.*

	Non-Uniform	Uniform-Format	
Design Attributes	**Conventional**	**Pioneer**	**Advanced**
National Goals			
Can be economically scaled up to help meet DOE-projected biofuel production goal to displace 30% of 2004 gasoline use by 2030	○	○	●
Can meet 2012 ($35/DM ton) and 2017 (25% of ethanol production cost) DOE cost targets[b] for delivered biomass[c] to the conversion process	○	◒	●
Barriers: Material Properties			
Produces aerobically stable material for all feedstock types (moisture content of 15–20% or less for all resources)	○	○	●
Achieves target dry matter bulk density of >30 lb/ft³ after preprocessing	○	○	●
Leverages biomass material deconstruction properties to improve capacity and efficiency of all engineered systems and matches systems to material composition	○	◒	●
Barriers: Machine/Engineering			
Optimizes all machinery operation and capital for operational window	○	◒	●
Achieves all equipment efficiency/capacity goals within cost and energy consumption targets (i.e., target harvesting efficiency of 35 DMT[d]/hr)	○	◒	●
Can meet total supply chain material loss of <5%	○	●	●
Commodity System Attributes			
Ensures reliable feedstock supply (biomass can be acquired from many sources beyond 200 miles, reducing supply risk)	○	○	●
Produces aerobically stable and flowable product	○	◒	●
Formats material to fit all common high-capacity solids handling equipment	○	◒	●
Broadens feedstock accessibility (biomass can be purchased and sold through regional and national markets)	○	◒	●
Sustainability			
Expands regional cropping options (handles various biomass formats, moisture content, and composition)	○	○	●
Enables access to remote biomass resources (able to reach DOE goal of 25 M dry ton biomass by 2012, 110 M dry ton by 2017, and 530 M dry ton by 2030)	○	◒	●
Allows efficient transport of feedstock beyond a 200-mile supply radius	○	◒	●
Addresses feedstock supply risks associated with weather, competition, pests, and other local issues	○	◒	●

[a] ○ = does not meet requirement; ◒ = partially meets requirement; ● = meets requirement
[b] DOE-EERE Office of the Biomass Program (OBP), 2007. Biomass Multi-Year Program Plan, October 2007.
[c] Includes harvesting and collection, storage and queuing, preprocessing, and transportation and handling costs, in 2007 $U.S.
[d] Dry matter ton.

various components to be used according to their greatest value. For example, in straw, the leaves and sheaths have higher nutrient levels than the rest of the plant, and therefore are better suited as organic matter for soil conservation (Hoskinson et al. 2001). In corn stover, the cobs, leaves, and husks produce over 300% more glucose than the stalks (Montross and Crofcheck 2003), which gives those fragments greater value for biochemical conversion.

The Conventional Bale design does not take full advantage of these characteristics. The preprocessing systems introduced in the Pioneer Uniform system begin to take advantage of these properties, and the Advanced Uniform design effectively leverages these properties. In an effort to better understand material properties and machine performance (Section 4.3.3), INL has assembled a deployable Process Demonstration Unit (PDU) that provides a demonstration-scale model of a biomass depot, like that included in the Uniform-Format supply system designs. The goal of the deployable PDU system is to process as large of a variety of input materials as possible while providing a flexible interface that allows the introduction of emerging and novel processing technologies. The input material will ultimately consist of materials such as wheat straw, barley straw, rice straw, corn stover, switchgrass, miscanthus, wood products, and biowaste.

The PDU is highly instrumented to facilitate data collection and has numerous sampling ports to simplify sample collection. The material samples produced can be characterized to improve understanding of the behavior and properties of material as it flows through various equipment. The PDU allows observation of a continuous flow of different kinds of biomass through various preprocessing operations. This deployable system greatly improves understanding of preprocessing lignocellulosic materials, and helps to provide information on material properties to modify or design new equipment to meet material targets. (See Appendix 4 for further description of the PDU system.)

4.3.3 Machine/Engineering Barriers

The key barriers with machines and equipment in the feedstock supply system are associated with limited operational windows, efficiency and capacity, cost and energy use, and dry matter losses. The constraints from limited operational windows are primarily an issue for the harvest and collection operation. The specific challenge is associating high equipment costs with lower feedstock throughput due to short periods of time in which an operation can be performed. This is particularly true for the Conventional Bale and Pioneer Uniform designs, where field drying is an important component of the supply system.

In many locations for many feedstocks, weather and other constraints leave a short time frame. available for collecting a majority of the feedstock needed for an entire year's supply. This causes a large, expensive fleet to be deployed in a limited amount of time. Once the operation is complete, this capital investment is idle. The single-pass harvest concepts introduced in the Advanced Uniform design help address this barrier by allowing equipment to process more feedstock through greater efficiencies. Thus, the capital cost of the machines is distributed across larger tonnages.

A combination of improvements in supply system efficiencies and capacities show steady progress from the Conventional Bale to Pioneer Uniform, and ultimately Advanced Uniform designs. The Conventional Bale design requires several customized application-specific components, which inherently causes inefficiencies. Also, the feedstock formats in the Conventional Bale design are not conducive to maximizing system capacity, or throughput. The introduction of biomass depots into the Pioneer

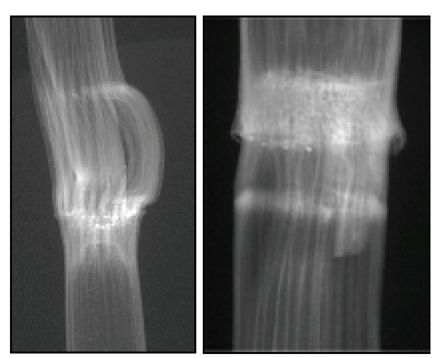


Figure 4-3. Radiograph projections of barley straw (left) and corn stover (right).

Uniform system moves the feedstock supply system to higher efficiencies and capacities downstream of the preprocessing operation. Higher dry matter bulk density, greater flowability, and a uniform material specification are the contributing factors for these increases.

Similarly, the Advanced Uniform design further increases efficiencies and capacities by advancing these attributes to even more favorable levels. The cost of dry matter loss within the system is directly correlated to the value of the material at the point at which it is lost. Any aggregate loss within the system results in less volume delivered to the biorefinery, but as material moves through the supply system, each operation incurs more cost and energy use. One of the key attributes of the Advanced Uniform design is its ability to move the feedstock through proven, standardized bulk-solid handling equipment and processes. These systems incorporate dust collection systems to minimize dry matter loss. As such, both the Pioneer and Advanced Uniform-Format systems are capable of total supply chain losses less than 5%.

Another component of the supply chain that offers opportunity for improvement in cost and efficiency is preprocessing. Increasing grinder efficiency, for example, will increase machine throughput and therefore decrease the machine use cost. Finer grinds would reduce the particle size distribution as well. Ongoing research at INL on material deconstruction of residues has increased understanding of how these materials behave in common wood grinding equipment that has not been optimized for these "stringy" materials. Figure 4-4 shows an example of some of these research efforts, where a camera placed inside the grinder enables direct observation of the behavior of the residues throughout the grinding process.

Tests, such as the one shown in Figure 4-4, reveal how residues—in this case stover—break down in an inefficient manner; the pith explodes and becomes suspended around the outer grinder casing, and much of the stem strings become entrained and pulled along with the rotating grinder instead of breaking down. By developing equipment specialized for residues, system performance and costs will be improved.

As mentioned in Section 4.3.2, INL has designed and assembled a deployable PDU to better understand material properties and machine performance. The PDU will allow observation of machine performance in various configurations and using various types of preprocessing operations. Examples of possible preprocessing equipment used are a pellet mill, hammer mill, briquetter, torrefaction unit, and various grinders. This deployable system will greatly improve understanding of the performance of preprocessing equipment using lignocellulosic materials, and will help to provide information to modify or design new equipment to meet equipment performance targets.

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

4.3.4 Commodity System Attributes

Building a commodity market and trading system for lignocellulosic biomass is essential for creating a large-scale industry. As demonstrated through the current bulk-solid grain commodity system, with an aerobically stable and flowable product, replicable high-capacity equipment can be used to economically connect supplies with markets across large distances without spoiling. The ability to economically connect feedstock with markets 200 or more miles away ensures reliable supply by reducing production risks, and broadens accessibility by creating regional and national markets. Also, large commodity networks with organized and predictable commodity transfer between buyers and sellers and among markets limits spatial price differences, and therefore facilitating remote resources to enter the market (Schnepf 2006).

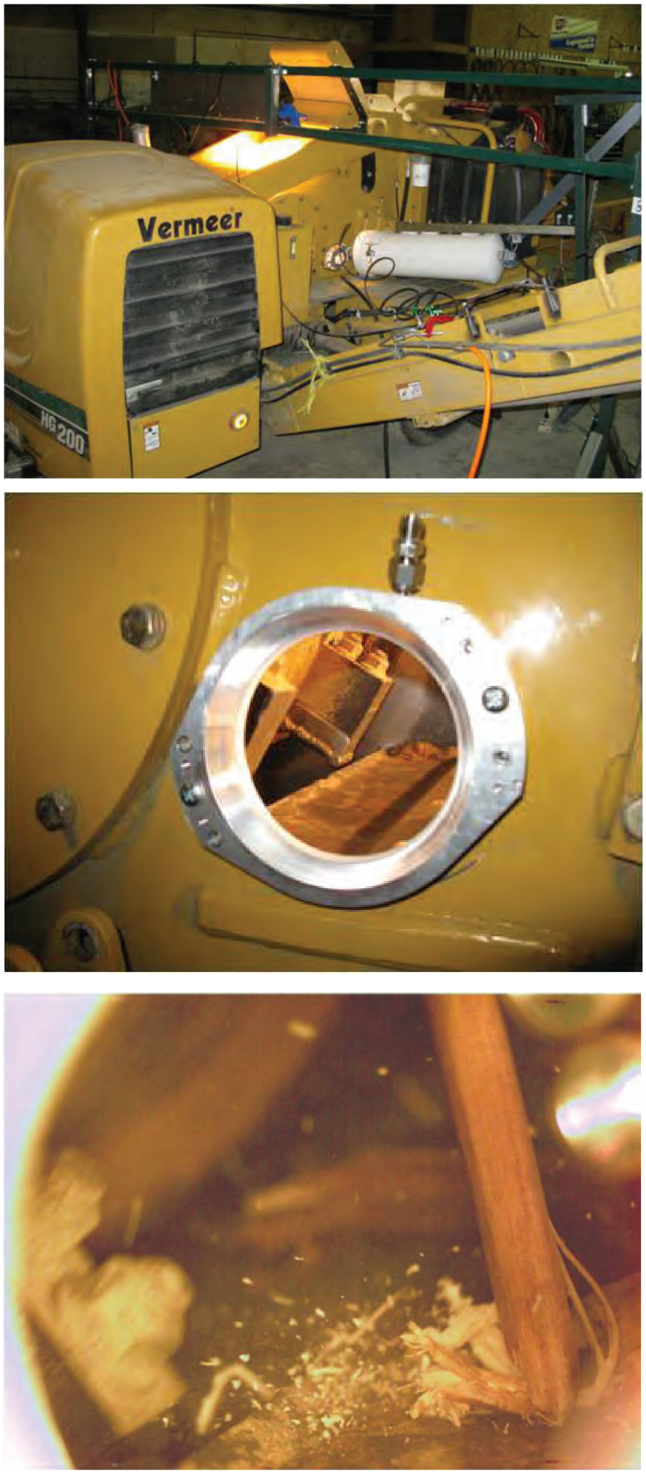


Figure 4-4. A Vermeer grinder (a) modified with a viewing window (b) and equipped with a camera allows direct observation of the residue decomposition process. The inefficient decomposition is apparent (c), as the stem strings apart instead of being cut into uniform sizes, and the pith explodes out into fines.

Aerobic stability also allows for longer-term storage, if required. The Conventional Bale system design does not produce aerobically stable and flowable materials capable of working with common high-capacity solids handling equipment compatible with regional and national markets. The Pioneer Uniform design produces a more uniform, flowable material through the initial implementation of biomass depots, but does not yet achieve dry matter bulk densities that ensure each system implementation can economically move the feedstock hundreds of miles. The Pioneer Uniform system broadens feedstock accessibility by producing a formatted material that begins to move in common high-capacity solids handling systems, which creates new local markets for the feedstock. The Advanced Uniform design meets the requisite material specifications creating the ability to trade and move material several hundred miles to available markets. Note that, although this report focuses on producing a bulk-solid commodity; the Advanced Uniform system commodity format may be either solid or liquid (or example, a biocrude).

One inherent characteristic of a commodity system (including the grain commodity system) is that the material meets a definitive specification (a spec). With new lignocellulosic feedstocks, the quality characteristics of biomass are less consistent than for grain, which has known quantity and highly consistent attributes developed over decades of seed development. Grain-fed biorefineries rely on their consistent feedstock to achieve design production rates; however, a new cellulosic crop has much higher variation (depending on age, storage time, growing conditions, etc). Meeting the spec requirements ensures that biorefineries receive a consistent feedstock for their conversion process, and that the material has the appropriate properties that balance feedstock cost and conversion optimization. For example, thermochemical conversion processes are often sensitive to ash content, whereas biochemical conversion processes desire high sugar content. The feedstock properties can be achieved by mixing various biomass feedstocks at the terminal. A more controlled spec would come at a higher cost. An important consideration for the spec system is that biomass has certain inherent characteristics that would be cost prohibitive or impossible to change, such as the presence of oxygen. An example of the role of spec in the biomass commodity system is shown in Table 4-2.

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

4.3.5 Resource Coupling

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

Facilitating diversity in regional cropping options

Expanding regional cropping options requires the supply system to handle diverse material formats, moisture contents, composition, etc. This is attainable only through the Advanced Uniform design, which includes biomass depots that have processes in place to handle the diversity. The benefits of increased cropping options are widely studied, and include:

- Increases soil organic carbon (USDA 2003).
- Increases land productivity (NDSU 1998) by increasing yields (Classen and Kissel 1984).
- Decreases wind and water erosion when combined with recommended tillage practices (Peterson and Rohweder 1983) and leaving sufficient residue.
- Decreases transmission of disease and decreases insect proliferation (Maxon 1948, Miller 1982, McCalla 1964).
- Helps with weed control (populations of weeds can be suppressed with competition).
- Increases available soil nitrogen through addition of legumes or alfalfa to the rotation (Bauer and

Table 4-2. *Feedstock specifications are a key component of a commodity-based biomass system. These specs impact feedstock cost, as well as conversion properties and other in-plant operations.*

	Impacts		
Spec	***Feedstock***	***Interface***	***Conversion***
Moisture Content	Cost increases with reduction in moisture target	Effects storage, grinding, and handing	Impact on pyrolysis chemistry and product quality
Particle size	Cost increases with particle size reduction, bulk handling	Handling issues (explosion) and injection challenges	Impact on pyrolysis rate and conversion efficiency
Ash content and composition	Cost increases with ash reduction target	Minor impact	Impact on pyrolysis chemistry
C:H ratio, C:O ratio	Costs increase with severity of torrefaction	Improved feedstock storage, grinding, and injection	Potential improvement of pyrolysis rates and product quality
Trace species concentration	High costs for removing chlorides, sulfur, ash elements	Potential impact on handling and injection equipment	Impacts gas cleanup and product upgrading

Zimmerman 1975, Uulsema and Christie 1987, Bailey 1982, Balruddin and Meyer 1986).

- Improves tilth or friability of soil (Schumaker et al. 1967); increased aggregate stability associated with increased crop rotations reduce the tendency of the soil surface to crust, which increases rate of water infiltration under certain conditions and may also reduce wind erosion.
- Can increase soil water and nitrogen use efficiency (Brun and Worcester 1975). For example, deep-rooted crops such as sunflower following small grains can take advantage of an extra reserve of deep moisture and also any nitrogen that was too deep for a shallow-rooted crop to reach.
- Can reduce unwanted water accumulation. Deep-rooted crops such as alfalfa and sweetclover have been used to dry up saline seeps (Black et al. 1981), preventing surface salt accumulation and allowing salt to leach deep in the soil, therein allowing recropping of a cash crop such as wheat, and other wet areas (NDSU 1998).

Enabling access to remote resources

Biomass distribution in the United States is more concentrated in some regions than in others. The majority of high-density regions are in the Midwest, where huge quantities of grains, and therefore agricultural residues, are produced. Designing biorefineries to be dependent on local resources strands large amounts of dispersed biomass and pockets of higher density production that could greatly increase biomass availability and would contribute significantly to national biofuels production goals. In fact, relying solely on local resources limits the national biofuels production capability to far below these goals (Perlack et al. 2005). Relying on local resources also promotes construction of smaller-scale facilities that are not optimized for capital economics (Searcy and Flynn 2008), and leaves the biorefinery feedstock supply vulnerable to local weather conditions, disease, and pests.

Figure 4-5 simulates the impact of distributed preprocessing depots on the delivered feedstock cost and resource availability. This scenario is centered in the high corn stover yielding area of Boone County, Iowa, and shows how the Advanced Uniform system can make more resources available for biofuels production by expanding the distance over which biomass may be transported economically.

The Conventional Bale scenario (as described in Section 2) is shown on the left. In this scenario, collecting bailed corn stover from Boone County for biofuels production in that same county results in a delivered feedstock cost of $41.96/DM ton. Accessing the biomass presently produced in Boone County from elsewhere within a 200-mile radius of the biorefinery increases the delivered cost of biomass to $66.74/DM ton. Similarly, accessing the biomass that is presently produced in Boone county from a distance of 500 miles away from the biorefinery increases the cost to $112.18/DM ton for stover bales. The more distant resources become very expensive and difficult to incorporate into the biomass supply chain. Under the conventional system, the 114,000 DM ton/year of material is effectively stranded.

Looking at the same county but using the Advanced Uniform system, material is delivered to the biorefinery via a combination of rail and truck in a consistent, dense, uniform format that meets the specification for biochemical conversion. In the Advanced Uniform system, accessing material from within Boone County costs more than in the Conventional system: $63.44/DM ton compared to $41.60/DM ton. This is due to a higher processing cost required to create a stable, flowable material densified to 30 lb/ft^3. However, this system also makes other biomass resources within a 200 mile radius of the Boone County and the refinery available for the same cost. For production locations as far as 500 miles from Boone County and the biorefinery, the delivered cost of biomass increases by less than $10/DM ton.

This is considerably less than the over $70/DM ton incremental amount required to move Conventional Bale formatted biomass resources 500 miles. The reduced cost at the farther transport distance is a result of moving a more dense material, using more efficient transport modes, and achieving higher effective biomass yields. Regarding the latter advantage, the Advanced Uniform system more than

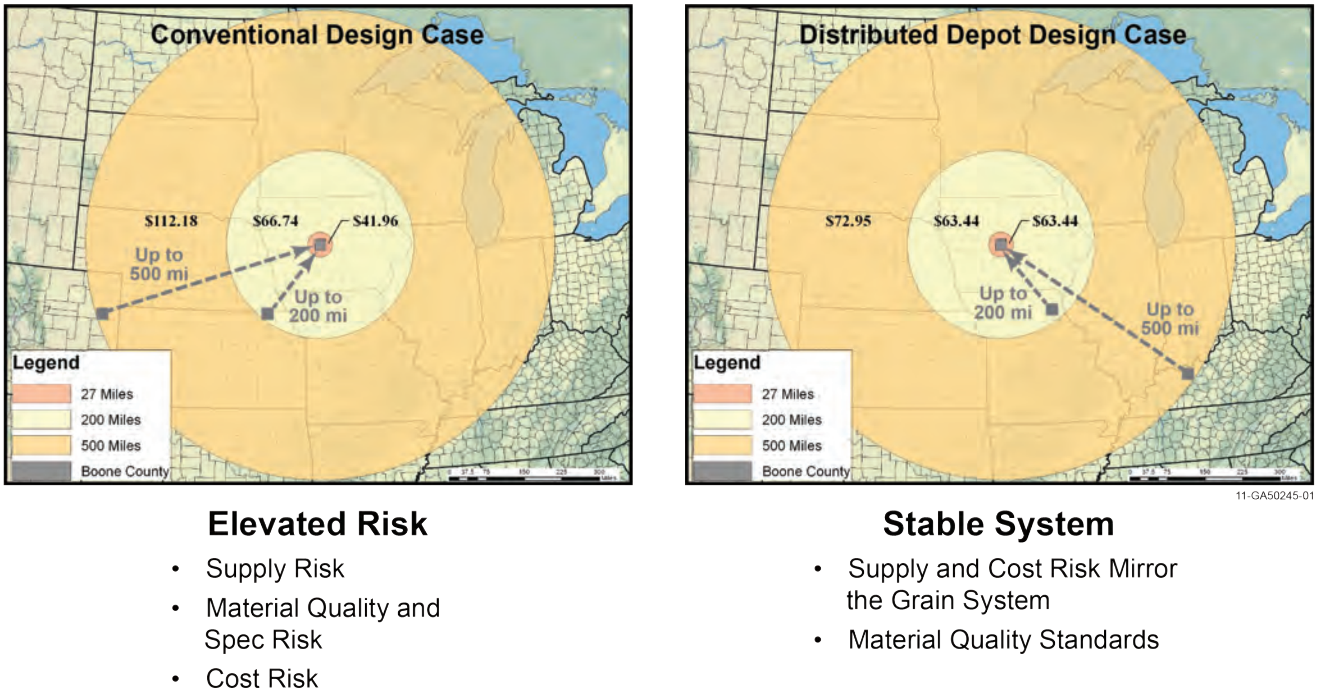


Figure 4-5. The Advanced Uniform design brings in more resources at a lower cost than Conventional Bale systems, demonstrated here for Boone County, Iowa. Moving to Advanced biomass supply system also increases the distance that the biomass could be moved for conversion, and delivers an on-spec material to the biorefinery, whereas the conventional does not.

doubles the accessible resource available for the Boone County refinery. Reasons for this include an increased operational window as a result of single-pass harvesting equipment and higher flexibility in material accepted into the system (Conventional systems are under much higher material constraints, such as <15% moisture, and are unable to deal with varying material specifications). This feature of increased material availability, combined with the consistent quality of the delivered biomass, greatly decreases supply risk to biorefineries.

Allowing efficient transport of biomass beyond 200 miles

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

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

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

4.4 ENGINEERING APPROACH TO UNIFORM-FORMAT FEEDSTOCK SUPPLY SYSTEM

The current Conventional Bale feedstock supply system is not capable of supplying the U.S. DOE target of 530 million tons of biomass annually for less than 30% of the ethanol production cost. The proposed Uniform-Format supply system meets the biomass cost, quantity, and quality supply goals. Transitioning from the Conventional Bale to the Uniform-Format system, however, presents many challenges, including limitations in existing harvesting and collection equipment and incorporation of biomass depots and blending terminals early in the feedstock supply chain. The transition also imposes many constraints, including total delivered cost targets; optimizing energy input, machine capacity, and machine efficiency; minimizing material losses; and optimizing machine utilization through the operational window. These constraints are the primary drivers of the Conventional system, and they carry through in the Advanced Uniform design. Additional considerations in the Advanced Uniform system that are not in the Conventional include material stability (i.e. shelf life, chemical and biological activity), material specs/quality, and density (bulk, energy). Figure 4-6 shows the current least-cost feedstock supply system path and barriers that need to be overcome for the incremental progression toward meeting performance targets.

The three dashed lines in the left half of Figure 4-7 represent improvements needed in bulk density, grinder capacity, and harvest and collection efficiency to transition from the Conventional Bale to the Pioneer Uniform system. The five dashed lines in the right half of Figure 4-7 represent the incremental improvements required to transition from the Pioneer Uniform to the Advanced Uniform system, the final implementation of the Uniform-Format design.

For maximum supply system efficiency, handling and transportation costs must be minimized by reducing the variety of equipment necessary to move biomass from the field to the biorefinery. For example, a Conventional Bale feedstock supply system described in Section 2 changes the biomass format at least three times from the field to the biorefinery (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, there are multiple bale formats (round and square in a variety of sizes) with their respective lines of harvesting and handling equipment. Thus, managing feedstock format diversity by increasing feedstock bulk density and flowability (as near to the feedstock production location as is practical) can greatly improve supply logistics efficiency. However, the cost and energy inputs required to reformat biomass and achieve optimum densities and product quality must also be improved.

Supply logistics costs vary substantially between regions and are impacted by weather, crop species, moisture content, and feedstock types, as well as transportation highway load limits and other regulations. Cropping systems and storage methods also can change supply logistics costs substantially. It is necessary to manage these inherent complexities and diverse feedstock types to optimize supply logistics and minimize costs in the biofuel production system. However, Section 2 discusses an industry-wide set of feedstock supply chains; therefore, site-specific logistical solutions are not always preeminent. When considering the development of an entire industry that can be rapidly deployed, a uniform-format feedstock supply system becomes key for both conversion facilities and equipment manufacturers, who require capital assets to be broadly applicable across the industry for optimization on a national scale. Modularized feedstock supply systems, such as the Uniform-Format system, are better suited to handle feedstock diversity than capital-intensive systems located at biorefineries.

Implementation of the Advanced Uniform vision is needed to achieve national biofuels production goals. An Advanced Uniform supply system engineering design—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—will be detailed in a forthcoming report.

4.5 REFERENCES

Associated Press (2008) National Guard Troops Work to Contain Iowa Flood Damage, http://www.foxnews.com/story/0,2933,367142,00.html, verified 03/11/2010.

Bailey LD (1982) Nitrogen fixation and legumes in crop rotation. Agdex 537/121. Ag. Canada, Brandon, Manitoba.

Balaruddin M, DW Meyer (1986) Influence of including several legumes in wheat cropping systems in eastern North Dakota. North Dakota Ag. Assn. Crop Production Guide. 57:205-215.

Bauer A, L Zimmerman (1975) Alfalfa harvested for hay as a source of available nitrogen for wheat. North Dakota Research Report 57. North Dakota State University, Fargo, North Dakota.

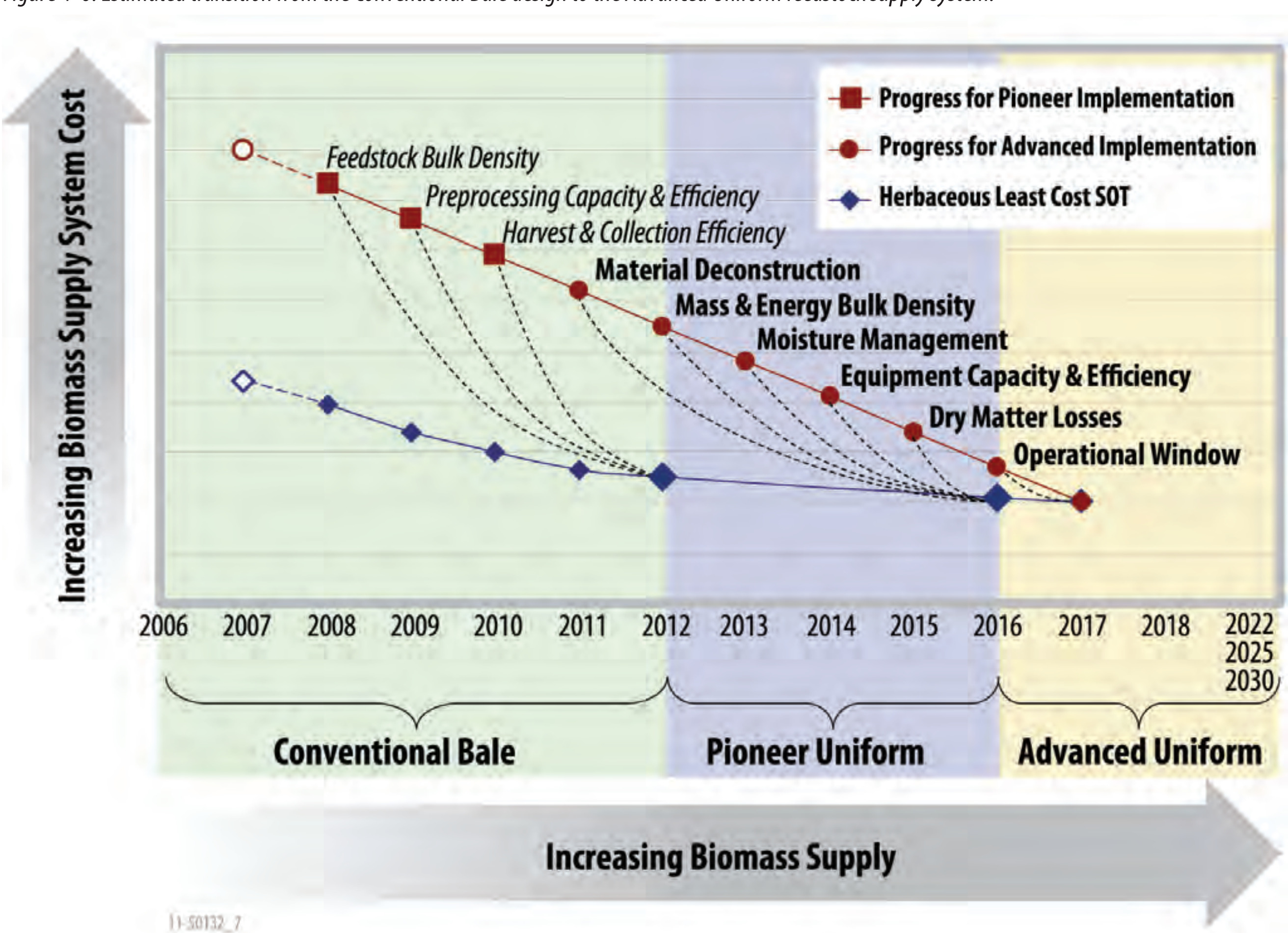
Black AL, PL Brown, AD Halvorson, FH Siddoway (1981) Dryland cropping strategies for efficient water use to control saline seeps in the Northern Great Plains. Agriculture Water Management. 4:295-311. Elesevier Publ. Co., Amsterdam, Netherlands.

Brun LJ, BK Worcester (1975) Soil water extraction by alfalfa. Agron. J. 67:586-588.

Classen MM, DE. Kissel (1984) Rotation with soybeans increases corn and grain sorghums yields. Kansas State University, Manhattan, Kansas.

Energy Information Administration (EIA) (2007) Energy Independence and Security Act, http://www.eia.doe.gov/oiaf/aeo/otheranalysis/aeo_2008analysispapers/eisa.html, verified 03/11/2010.

Figure 4-6. Estimated transition from the Conventional Bale design to the Advanced Uniform feedstock supply system.



Hess JR, KL Kenney, LP Ovard, EM Searcy, CT Wright (2009-Draft) "Uniform-Format" Feedstock Supply System Design Report Series, Report 1: Commodity-Scale Production of an Infrastructure-Compatible Bulk Solid from Herbaceous Lignocellulosic Biomass, Volume A: "Uniform-Format" Vision and Conventional-Bale Supply System Design

Hoskinson RL, JR Hess, TD Foust, WT McKean, MS Lewis (2001) Fractionation of Higher Value Crop Residue Components for Conversion into Bioenergy and Industrial Products, http://asae.frymulti.com/abstract.asp?aid=7316, verified 03/11/2010.

Mattoon R (2008) Assessing the Midwest Floods of 2008 (and 1993), Feral Reserve Bank of Chicago, http://midwest.chicagofedblogs.org/archives/2008/07/mattoon_flood_b.html, verified 03/11/2010.

Maxon AC (1948) Insects and diseases of the sugarbeet. Beet Sugar Development Foundation. Ft. Collins, Colorado, 425.

McCalla IM, FA Haskins (1964) Phytotoxic substances from soil microorganisms and crop residues. Bact. Rev. 28:181-207.

Miller D (1982) Alfalfa poisons new seedlings. Wisconsin Agriculturist. March edition.

Montross MD, CL Crofcheck (2003) Effect of Stover Fraction and Storage Method on Glucose Production During Enzymatic Hydrolysis, http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V24-4B0SVB6-5&_user=3213484&_coverDate=05%2F31%2F2004&_alid=1245124255&_rdoc=2&_fmt=high&_orig=search&_cdi=5692&_sort=r&_docanchor=&view=c&_ct=4&_acct=C000059095&_version=1&_urlVersion=0&_userid=3213484&md5=90df89cf3ccb1a749171d88a1cfada4a, verified 03/11/2010, Bioresource Technology, Vol. 92 Issue 3, 269-274.

National Renewable Energy Laboratory (NREL) (2005) Biomass Resources Available in the United States, http://www.nrel.gov/gis/images/map_biomass_sqkm.jpg, verified 03/11/2010.

NDSU (1998) Crop Rotations for Increased Productivity, http://www.ag.ndsu.edu/pubs/plantsci/crops/eb48-3.htm#bibliography, verified 03/11/2010.

Peterson AE, DA Rohweder (1983) Value of cropping sequences in crop production for improving yields and controlling erosion. Depts. of Soil Science and Agronomy. University of Wisconsin, Madison, Wisconsin.

Schnepf R, Congressional Research Service (CRS) (2006) CRS Report for Congress, Price Determination in Agricultural Commodity Markets: A Primer, http://www.nationalaglawcenter.org/assets/crs/RL33204.pdf, verified 03/11/2010.

Schumaker GA, CW Robinson, WD Kemper, HM Golds, M Amemiya (1967) Improved soil productivity in western Colorado with fertilizers and alfalfa. Technical Bulletin 91, pp.36-37. Colorado State University, Ft. Collins, Colorado.

Searcy E, P Flynn (2008) The impact of biomass availability and processing cost on optimum size and processing technology selection. Applied Biochemistry and Biotechnology DOI 10.1007/s12010-008-8407-9.

Searcy E, P Flynn, E Ghafoori, A Kumar (2007) The relative cost of biomass energy transport. Applied Biochemistry and Biotechnology 136-140: 639-652.

U.S. Department of Agriculture (USDA) (2004)

U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (2003) Managing Soil Organic Matter, The Key to Air and Water Quality, http://soils.usda.gov/sqi/concepts/soil_organic_matter/files/sq_tn_5.pdf, verified 03/11/2010.

University of Wisconsin and University of Minnesota (2000).

uulsema TW, BR Christie (1987) Nitrogen contribution to succeeding corn from alfalfa and red clover. Agron. J. 79:96-100.

Wiselogel, A. (2008) Facing the Challenge of Development. Cittes Corner, Biomass, 8.

Yancey NA, CT Wright, CC Connor, JR Hess (2009) Preprocessing Moist Lignocellulosic Biomass for Biorefinery Feedstocks, 2009 ASABE Annual International Meeting, http://www.inl.gov/technicalpublications/Documents/4247204.pdf, verified 03/11/2010.

08-50444