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

Conversion Pathway: Biological Conversion of Sugars to Hydrocarbons

"The 2017 Design Case"

September 2013

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EXECUTIVE SUMMARY

The U.S. Department of Energy promotes the production of a range of liquid fuels and fuel blendstocks from lignocellulosic biomass feedstocks by funding fundamental and applied research that advances the state of technology in biomass collection, conversion, and sustainability. As part of its involvement in this program, the Idaho National Laboratory (INL) investigates the feedstock logistics economics and sustainability of these fuels. Between 2000 and 2012, INL conducted a campaign to quantify the economics and sustainability of moving biomass from standing in the field or stand to the throat of the biomass conversion process. The goal of this program was to establish the current costs based on conventional equipment and processes, design improvements to the current system, and to mark annual improvements based on higher efficiencies or better designs. The 2012 programmatic target was to demonstrate a delivered biomass logistics cost of $35/dry ton. This goal was successfully achieved in 2012 by implementing field and process demonstration unit-scale data from harvest, collection, storage, preprocessing, handling, and transportation operations into INL's biomass logistics model. Looking forward to 2017, the programmatic target is to supply biomass to the conversion facilities at a total cost of $80/dry ton and on specification with in-feed requirements.

The goal of the 2017 Design Case is to enable expansion of biofuels production beyond highly productive resource areas by breaking the reliance of cost-competitive biofuel production on a single, abundant, low-cost feedstock. If this goal is not achieved, biofuel plants are destined to be small and/or clustered in select regions of the country that have a lock on low-cost feedstock. To put the 2017 cost target into perspective of past accomplishments of the cellulosic ethanol pathway, the $80 target encompasses total delivered feedstock cost, including both grower payment and logistics costs, while meeting all conversion in-feed quality targets. The 2012 $35 programmatic target included only logistics costs with a limited focus on biomass quality.

The 2017 Design Case explores two approaches to addressing the logistics challenge of blending feedstocks: one is an agronomic solution based on blending and integrated landscape management and the second is a logistics solution based on biomass depots. The concept behind blended feedstocks and integrated landscape management is to gain access to more regional feedstock at lower access fees (i.e., grower payment) and to reduce preprocessing costs by blending high quality feedstocks with marginal quality feedstocks. Blending has been used in the grain industry for a long time; however, the concept of blended feedstocks in the biofuel industry is a relatively new concept. The blended feedstock strategy, which relies on the availability of multiple feedstock sources that are blended using a least-cost formulation within an economical supply radius, which, in turn, decreases the grower payment by reducing the amount of any single biomass. This report will introduce the concepts of blending and integrated landscape management and justify their importance in meeting the 2017 programmatic goals.

The biomass feedstock supply system is a combination of multiple operations that include harvest and collection, storage, preprocessing, and transportation. Each operation within the supply system incurs a cost while influencing the biomass quality. This report summarizes the improvements that are being targeted, based on the research objectives in the following five research areas: (1) blending, (2) harvest and collection, (3) storage, (4) preprocessing, and (5) transportation. Feedstock logistics research aims to reduce delivered cost, improve or preserve feedstock quality, and expand feedstock access. Strategies to improve logistics operations include (1) organizing logistics in innovative ways, (2) improving existing operations for efficiency and interaction with other operations, and (3) implementing new technologies to overcome quality issues. The result is a new advanced biomass supply system that meets the $80/dry ton logistics supply system cost.

Table ES-1. Biochemical feedstock design cost analysis for 2017.

Cost Element	Single-Pass Corn Stover	Multi-Pass Corn Stover	Switchgrass	Municipal Solid Waste	Blend
Formulation Contribution	*35%*	*25%*	*35%*	*5%*	–
Grower payment/access cost	27.20	27.20	29.80	18.00	**27.70**
Harvest and collection ($/dry T)	10.50	19.20	15.40	–	**13.90**
Transportation ($/dry T)	8.70	8.30	7.20	18.00	**8.60**
Preprocessing ($/dry T)	23.40	23.40	19.70	19.70	**21.90**
Storage ($/dry T)	6.50	6.50	5.50	4.50	**6.10**
Handling ($/dry T)	1.90	1.90	1.90	1.90	**1.90**
Total Delivered Feedstock Cost ($/dry T)	**78.30**	**86.60**	**79.60**	**62.10**	**80.00**
Delivered Feedstock Specifications*					
Ash content (wt. %)	3.5	7	4	10	**4.9**
Moisture content (%, wet basis)	9	9	9	9	**9**
Carbohydrate content (wt. %)	64	57	57	57	**59**

*Corn stover and switchgrass composition data were obtained from the INL Biomass Library. See Appendix A for MSW ash and carbohydrate data.

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CONTENTS

EXECUTIVE SUMMARY ii

AUTHORS AND CONTRIBUTORS iv

REVIEWERS vi

1. INTRODUCTION 12

  1.1 Limitations of Conventional Supply System Designs 13

    1.1.1 Expansion Beyond Highly Productive Regions 13
    1.1.2 Biorefinery Quality Specifications 14
    1.1.3 Expanding the 2012 Conventional Design 17

  1.2 Approach of the 2017 Design Case 18

    1.2.1 Addressing the Grower Payment Challenge 19
    1.2.2 Addressing the Feedstock Specification Challenge 20
    1.2.3 Addressing the Logistics Challenge 20

2. 2017 FEEDSTOCK SUPPLY SYSTEM DESIGN: ADDRESSING GROWER PAYMENT 22

  2.1 2013 State of Technology 22

  2.2 Resource Selection Design Basis 23

  2.3 Resource Selection Cost Estimation 26

3. 2017 FEEDSTOCK SUPPLY SYSTEM DESIGN: ADDRESSING FEEDSTOCK LOGISTICS 27

  3.1 Harvest and Collection 27

    3.1.1 Overview 27
    3.1.2 2013 State of Technology 29
    3.1.3 Harvest and Collection Design Basis 31
    3.1.4 Harvest and Collection Cost Estimation 32

  3.2 Storage 33

    3.2.1 Overview 33
    3.2.2 2013 State of Technology 34
    3.2.3 Biomass Storage Design Basis 36
    3.2.4 Biomass Storage Cost Estimation 39

  3.3 Preprocessing 39

    3.3.1 Size Reduction 40
    3.3.2 Drying and Densification 45

3.3.3 Formulation/Blending 48

3.4 Transportation and Handling 50

3.4.1 Overview 50
3.4.2 Transportation and Handling Design Basis 50
3.4.3 Cost Estimation for Transportation and Handling 51

4. SUPPLY SYSTEM ECONOMICS 52

4.1 Delivered Feedstock Costs 52

5. CONCLUSIONS 54

6. REFERENCES 55

Appendix A, Municipal Solid Waste 58

Appendix B, Chemical Preconversion 63

FIGURES

1. Farm gate price for corn stover at 100-ton/mi2 density 14

2. Flow diagram of the 2012 Relocated (Baseline) Design Case to supply biochemical conversion refineries 17

3. Typical farm gate price function for corn stover 19

4. Typical farm gate price function for three feedstocks: corn stover, switchgrass, and wheatstraw 20

5. The farm gate cost curves would suggest that corn stover would be the preferred feedstock because it is available at a lower cost than switchgrass 22

6. Accounting for logistics costs as quality (dockage)—the real cost to the biorefinery—shows that about 300,000 tons of switchgrass can be supplied at a lower cost than corn stover 23

7. A corn stover/switchgrass blend that will deliver at about $81/dry T 24

8. A minimum of 5% MSW (at $1/dry T) is needed to achieve the $80/dry T cost target with a corn stover, switchgrass, and municipal solid waste blend 25

9. Comparison of individual and blended feedstock costs 25

10. Resource selection for the 2017 Design Case to support biochemical conversion 26

11. Ash content of corn stover bales from Stevens County, Kansas, that are collected using single-pass baling and a variety of multi-pass methods, including two rakes, two balers, a mower, and a flail shredding windrower 31

12. Ash content (bars) and yield (text) of corn stover bales from Stevens County, Kansas, show the impact of collection efficiency and windrowing equipment on yield and soil entrainment 31

13. Dry matter loss of corn stover in laboratory storage conditions at fixed moisture contents 34

14. Change in moisture content of stacked corn stover bales in northern Iowa 35

15. Change in glucan and xylan over time as corn stover is stored in laboratory reactors 36

16. Dry matter loss of corn stover in the simulated storage conditions, with three air flows simulating three different oxygen availabilities 37

17. The impact of dry matter loss on bale ash content and final conversion efficiency (based on a 35% initial moisture and 10% ash) 38

18. Material flow in the 2017 Design Case that incorporates many improvements in preprocessing, including fractional milling, chemical preconversion, high-moisture densification, and formulation/blending 40

19. Particle-size distributions for five grinding scenarios 41

20. Comparison of conventional, two-stage grinding and fractional milling 42

21. Grinding energy and throughput is highly dependent on screen size 43

22. Hammer mill energy consumption is highly dependent on biomass moisture content 43

23. Conventional pelletization process 46

24. High-moisture pelletization process 47

TABLES

ES-1. Biochemical feedstock design cost analysis for 2017 iii

1. Delivered corn stover composition assumptions (NREL 2011 Design Report) 15

2. 2012 relocated (baseline) design cost estimate (all costs are in 2011 U.S. dollar) 18

3. Resource access cost estimate 26

4. Summary of assumptions underpinning progressive design implementations 28

5. Mean total ash values and ranges for selected lignocellulosic biomass 30

6. Technical targets for harvest and collection of herbaceous resources in the 2017 Design Case 32

7. Biomass harvest and collection cost estimates 33

8. Biomass storage design basis 39

9. Field-side storage cost estimation 39

10. Size-reduction design basis 45

11. Fractional milling cost estimates 45

12. Drying and densification design basis 47

13. Drying and densification cost estimates 48

14. Feedstock formulation/blending of ash and moisture contents 48

15. Feedstock formulation design basis 49

16. Formulation cost estimation 50

17. Transportation cost estimates 51

18. Biochemical conversion feedstock design cost analysis 52

A-1. National average municipal solid waste composition 58

A-2. Per capita generation rates for various fractions of municipal solid waste and construction and demolition waste (lb/person/day) 59

A-3. Physical parameters of solid waste 60

B-1. Ash composition of initial, untreated corn stover 64

B-2. Expected unit operations and assumptions for the application of a drain and fill leaching system for the removal of soluble ash from biomass in a feedstock depot 66

2017 Design Case

1. INTRODUCTION

The U.S. Department of Energy (DOE) has established a goal to make cellulosic biofuels competitive with petroleum-based fuels at a modeled cost of mature technology of $3/gallon gasoline equivalent (gge) ($2011) by the year 2022. The DOE Bioenergy Technology Office feedstock platform contribution to this goal is to demonstrate a modeled feedstock cost of $80/dry T (dry U.S. short ton) by the year 2017. The purpose of this report is to document a single, feasible feedstock supply system design capable of achieving the 2017 target. This design is referred to in this report as the 2017 Design Case.

The Idaho National Laboratory (INL) has a long history of supporting the DOE Bioenergy Technology Office with techno-economic assessments and technology improvements in the area of feedstock logistics. The INL was instrumental in the DOE Bioenergy Technology Office accomplishment of demonstrating the cost-competitiveness of cellulosic ethanol through achievement of the 2012 $35/dry T feedstock logistics cost target (Wright et al. 2012). The focus of feedstock logistics in the cellulosic ethanol pathway was demonstration of commercially available equipment and practices currently used in the hay and forage industries to support pioneer biofuel production plants.

The success of the cellulosic ethanol pathway from a feedstock perspective was that it demonstrates that through proper equipment selection and best management practices, conventional systems (referred to in this report as convention designs, or specifically the 2012 Conventional Design) can be successfully implemented to address sustainability, dry matter loss, and quality issues and enable feedstock cost reductions that help to de-risk and commercialize biomass feedstock supply chains. This does not imply that barriers do not still exist. In fact, the caveat of this success is that conventional designs depend on abundant, low-cost feedstock. In this respect, the success of conventional designs is very much tied to specific, highly productive regions such as the Midwest Corn Belt.

The goal of the 2017 Design Case is to enable expansion of biofuels production beyond highly productive resource areas by breaking the reliance of cost-competitive biofuel production on a single, abundant, low-cost feedstock. If this goal is not achieved, biofuel plants are destined to be small and/or clustered in select regions of the country that have a lock on low-cost feedstock. This design document describes a single, feasible feedstock supply and logistics design capable of achieving this goal. This document begins with a discussion of the limitations of the conventional supply systems when located outside of highly productive resource areas. Next, the discussion shows how these limitations can be resolved through integration of multiple types of feedstocks, clear definition of biomass quality specifications, and technology advancement in logistics and preprocessing.

To put the 2017 cost target into perspective of past accomplishments of the cellulosic ethanol pathway, the $80 target encompasses a total delivered feedstock cost, including both grower payment and logistics, and meeting all conversion in-feed quality targets. The $35 target included only logistics costs, with a limited focus on biomass quality. An estimated grower payment associated with the 2012 Conventional Design was $23.50/dry T to access 26 million tons of corn stover. Adding grower payment and logistics, the total delivered feedstock cost in 2007 dollars was $58.50/dry T in 2007 dollars. Translated to 2011 dollars, the total delivered feedstock cost of the 2012 Conventional Design scales to about $65/dry T. With only $15/dry T margin over the Conventional Design target, achieving the goals of the 2017 design case will require innovative solutions and significant technological advancements.

This report is intended to couple with the National Renewable Energy Laboratory's (NREL's) hydrocarbon design report, "Dilute-Acid Prehydrolysis and Enzymatic Hydrolysis Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons," (draft in progress) that describes a single viable route from biomass to hydrocarbon fuels. Because of this coupling, the assumptions of scale and feedstock quality requirements are consistent with the design case assumptions used by NREL in their report and techno-economic assessments. In addition, this design does not consider the different requirements and nuances of other biological conversion processes or other hydrocarbon pathways. Feedstock design reports associated with alternate hydrocarbon pathways of the DOE Bioenergy Technologies Office program will follow this report.

1.1 Limitations of Conventional Supply System Designs

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

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

Feedstock quality. Biomass is highly variable in quality (e.g., ash, moisture, and particle size). Conventional systems can only address feedstock quality indirectly through passive controls such as resource selection or best management practices. When positioned in a highly productive area, biorefineries can be selective in contracting only those feedstocks that meet their specifications. Best management practices also can be used to reduce issues of moisture and ash, but they will not eliminate them.

Two requirements that distinguish the 2017 Design from the 2012 Conventional Design are (1) expansion beyond highly productive resource areas and (2) adherence to biorefinery quality specifications. These requirements are discussed in detail in the following subsections.

1.1.1 Expansion Beyond Highly Productive Regions

Expansion beyond highly productive resource areas has significant implications to the feedstock supply chain. Lower density resources, whether due to reduced yields and/or higher dispersion, typically increase feedstock logistics costs. Higher harvest and collection costs are incurred due to the need to spread machinery ownership costs over fewer tons of biomass or the need to cover more acres for the same quantity of biomass. Additionally, lower resource density increases the supply radius and biomass transportation distances.

Consider, for example, the scenarios depicted in Figure 1. This resource map illustrates a county-level assessment of corn stover farm gate prices (this includes grower payment, harvest, and collection costs) at a density of 100 ton/mi^2, which is the density required to support an 800,000 ton/year biorefinery within a 50-mile supply radius. Farm gate price data were extracted from the *Billion Ton Update* (U.S. DOE 2011) data supplied from Oak Ridge National Laboratory.

The cost competitiveness of conventional designs was demonstrated by Wright et al. (2012) (referred to in this report as the 2012 Conventional Design) in the scenario located in central Iowa. We further suggest, based on the consistency of farm gate prices shown in this map, that the Conventional Design can be deployed cost effectively throughout much of the interior Corn Belt. Commercial readiness of conventional supply systems ultimately will be demonstrated by commercial-scale cellulosic ethanol plants opening in these areas in the near future.

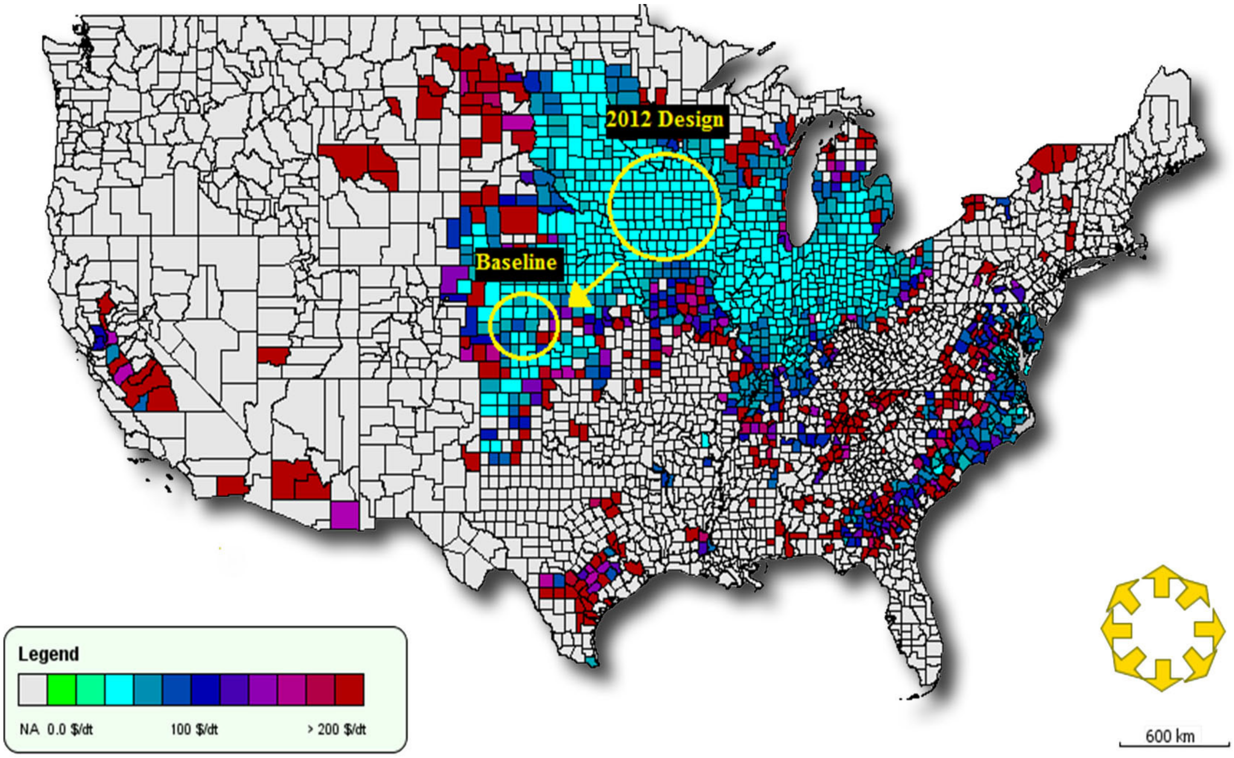

Figure 1. Farm gate price for corn stover at 100-ton/mi2 density. Yellow circles show areas represented in the Conventional Design and the Relocated (Baseline) Design Case.

The map also depicts a fairly steep gradient where farm gate prices increase rapidly toward the fringes of the Corn Belt. Significant county-to-county fluctuations in farm gate price are seen within this fringe zone as well. In these areas, as in the scenario depicted in western Kansas, ample corn stover exists to support large-scale biorefining; however, feedstock access costs alone may be more than double the Corn Belt prices. A more dispersed corn stover resource, due to lower yields in these regions, also results in increased harvest, collection, and transportation costs compared to the lower-cost scenario.

1.1.2 Biorefinery Quality Specifications

When developing their techno-economic model for production of cellulosic ethanol from corn stover, NREL established the corn stover composition assumptions shown in Table 1 (Humbird et al. 2011). These assumptions were based on the composition of a representative sample chosen from an overall sample distribution of 508 commercial corn stover samples collected from 47 sites in eight states over a 3-year period.

A combination of biomass selection (i.e., dry corn stover), utilization of best management storage practices that preserve carbohydrates, and harvest practices that minimize introduced ash (soil) comprised the solutions that were implemented in the 2012 Conventional Design Case for adherence to feedstock quality assumptions. However, quality “specifications” were neither defined nor enforced in the Conventional Design Case.

These same corn stover composition assumptions have been carried through to the current NREL hydrocarbon pathway design report (in progress) to which this 2017 Design Case is associated. However, this 2017 Design Case introduces the expectation that the feedstock supply chain will be held accountable to these feedstock assumptions, hereby elevating these assumptions to feedstock specifications that currently define the feedstock quality requirements associated with the NREL biological conversion pathway.

Table 1. Delivered corn stover composition assumptions (NREL 2011 Design Report).

Component	Composition (dry wt%)
Glucan	35.05
Xylan	19.53
Lignin	15.76
Ash[a]	4.93
Acetate[b]	1.81
Protein	3.10
Extractives	14.65
Arabinan	2.38
Galactan	1.43
Mannan	0.60
Sucrose	0.77
Total structural carbohydrate	*58.99*
Total structural carbohydrate + sucrose	*59.76*
Moisture (bulk wt%)	*20.0*

[a] Future studies will break down ash constituency.

[b] Represents acetyl groups present in the hemicellulose polymer converted to acetic acid in pretreatment.

The passive approaches (i.e., biomass selection and best management practices) implemented in the Conventional Design Case are not sufficient to guarantee feedstock specifications. Further, passive approaches to feedstock quality assurance restrict feedstock availability and producer participation, and ultimately increase risk to biorefineries by making them dependent on limited, highly specific feedstocks.

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

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

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

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

- ***Moisture Specification.*** From a biochemical processing perspective, feedstock moisture content does not have significant, direct cost implications to the conversion process. In most cases, a moisture specification is a surrogate measurement of biomass quality, recognizing that degradation and consumption of structural carbohydrates during long-term storage is largely diminished if moisture content is uniformly reduced below the threshold for aerobic stability—generally recognized as 20% (wet basis). The degradation issue specifically is addressed below with regards to a convertibility dockage; therefore, implementation of moisture dockage to cover other moisture-related issues within the biorefinery is not justified at this time.

  In reality, the feedstock supply system typically is much more sensitive to biomass moisture content than is the biochemical conversion process. In addition to its implications for storage stability, biomass moisture content can significantly increase transportation, preprocessing, and feedstock handling costs (Kenney et al. 2013). These logistics-related costs are discussed in Section 2.

- ***Ash Specification(s).*** Feedstock ash content represents an additional, variable, operational cost to the biorefinery because it reduces pretreatment efficacy (Kenney et al. 2013), increases wear in handling and feeding systems, increases water treatment cost, and accumulates as a waste stream that requires treatment. Bonner et al. (2013) estimated the cost of biomass ash above and beyond a 5% feedstock specification for a sugars/fermentation pathway to ethanol, considering both the additional replacement costs and additional disposal costs. Their analysis showed that these costs ranged from \$4.88 to \$20.23/dry T for corn stover ash levels, ranging from 10 to 25%, respectively. Two-thirds of the cost increase was due to feedstock replacement costs to maintain the required supply of convertible biomass to the biorefinery and one-third of the increase was due to the biorefinery's ash disposal costs. Based on feedstock and ash disposal costs from the 2011 NREL cellulosic ethanol design report (Humbird et al. 2011), the analysis by Bonner et al. equates to about \$1/dry T per percent ash above the 5% specification (Table 2).

  Ash dockage assessed in this report also assumes the disposal cost of \$15.36/ton established by Humbird et al. (2011). However, because our feedstock costs are higher than those assumed by Bonner et al. (2013), the ash dockage is about \$2.25/dry T per percent ash above the 5% specification.

- ***Carbohydrate content.*** Consistent and predictable conversion of cellulosic biomass to fuels by a biochemical conversion facility requires that a feedstock's structural carbohydrates are delivered at a known quantity and quality. The feedstock specifications shown in Table 1 indicate that a minimum 59% total structural carbohydrate content is required for the biorefinery to meet conversion yield targets. However, it is critical to consider the quality of these carbohydrates from the broad perspective of total conversion efficiency. For example, if a feedstock is delivered "at-spec" in terms of carbohydrate mass, but the carbohydrates do not convert at the anticipated efficiency (either during pretreatment or enzyme hydrolysis), the effective quantity of usable carbohydrates purchased is reduced. This reduction in carbohydrate performance, largely due to increased recalcitrance, must be accounted for when conceiving a meaningful specification. This requires the feedstock supply system to provide proper composition and performance. Failure to meet either requirement would require more biomass to be utilized (i.e., more tons procured, handled, and processed) to maintain production goals. Because of the increase in tonnage throughput without the benefit of increased product yield, the biorefinery would incur additional processing costs. As a penalty for delivering lower-yielding feedstock, this cost ultimately would be transferred back to the feedstock supply chain as dockage.

While many factors contribute to the performance of a feedstock in a biochemical conversion process, the primary source of post-harvest quantity and quality loss in the biomass supply chain is degradation during storage. Losses that occur in storage are driven by microbial consumption of structural sugars, potentially jeopardizing the delivered feedstock's carbohydrate quantity and altering its recalcitrance. To this extent, the moisture quality control discussed above will have a large role in minimizing dry matter loss and preserving material quality. In order to better quantify and communicate this relationship, deviation from the carbohydrate spec will be addressed specifically from the perspectives of storage and the relationship between conversion performance and dry matter loss. The potential impacts and sources of this measure are discussed in Section 3.2.

1.1.3 Expanding the 2012 Conventional Design

The cost implication of enforcing conformity to biorefinery quality specifications and expansion beyond the most highly productive regions is illustrated in development of a baseline design case that illustrates the cost challenge of simply applying the Conventional Design to a broader design basis. This approach for establishing the baseline case is illustrated in Figure 2, where the Conventional Design supply system demonstrated in central Iowa in 2012 to achieve the $35/ dry T cost target for logistics is applied to a baseline scenario centered in western Kansas.

With the Conventional Design Case located in a highly productive corn stover production area, the main constraining assumption of the design was that the biorefinery could be selective in contracting only stover that was field-dried to a moisture content that meets the 20% specification (Table 2). In the baseline case, this assumption is removed and, instead, it is assumed that field drying is not always possible; thus, the supply system must be capable of managing biomass moisture contents up to 30% (Smith et al. 2013). An additional assumption in the baseline case is that corn stover will be harvested using best management practices for multi-pass methods that result in a bale ash content of 11% (Bonner 2013).

The feedstock supply chain unit operations modeled in the baseline case are shown in Figure 2. These unit operations are identical to those in the Conventional Design demonstrated in 2012 (Wright et al. 2012), with the exception of a drying operation that was added to the baseline case to accommodate higher moisture biomass (i.e., 30%) entering the system. The details of these unit operations are discussed in the design basis sections of this report.

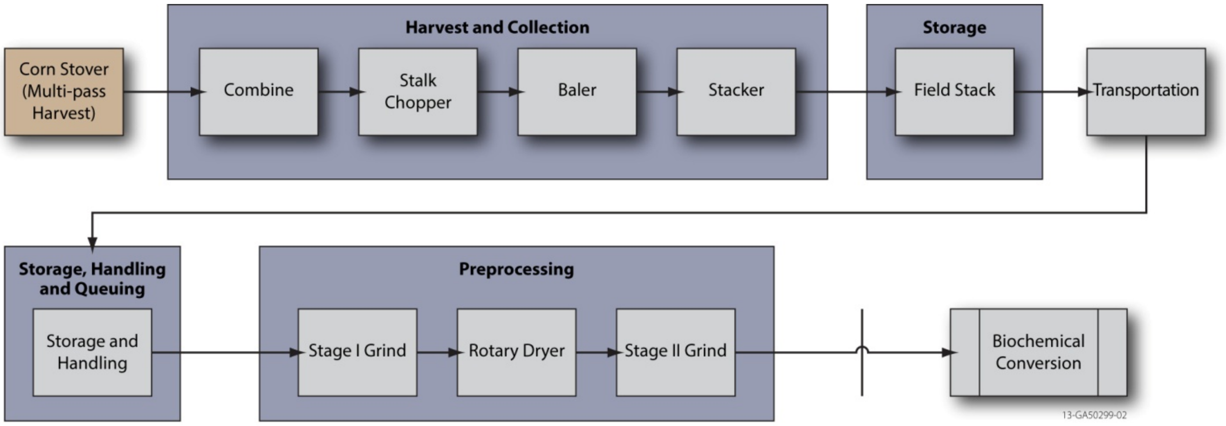

Figure 2. Flow diagram of the 2012 Relocated (Baseline) Design Case to supply biochemical conversion refineries.

The cost estimate of the baseline system (Table 2) shows a logistics costs total of $81.60/dry T, compared to $35/dry T for the central Iowa 2012 Conventional Design case. The increased logistics costs of the baseline system are attributed to the following:

- Lower stover yields (3.6 dry T/acre compared to 5.0 dry T/acre), which increases harvest, collection, and transportation costs
- Higher corn stover moisture content, which increases storage dry matter losses (i.e., 12% wet basis in the baseline case compared to 8% in the Conventional Design Case)
- Higher corn stover moisture, which increases size reduction energy and costs
- Additional rotary drying costs.

Additional costs are incurred in the baseline design case with dockage. The baseline design case does not include an ash reduction operation to achieve the feedstock ash specification; therefore, a dockage of $14/dry T is applied (approximate $2.25/dry T per percent ash above the 5% spec). Similarly, the baseline case assumes that storage dry matter losses also reduce conversion efficiency with the microbial consumption of easy-to-convert carbohydrates, resulting in reduced yields. The current assumption, discussed in detail in Section 2.3, is that for each percentage of dry matter loss (i.e., carbohydrate loss), conversion efficiency also is reduced by 0.25%. Therefore, a convertibility dockage of $6.10/dry T also is applied to feedstock costs. Including grower payment, logistics, and dockage, the total delivered feedstock cost for the baseline design is $133/dry T.

Table 2. Baseline design cost estimate (all costs are in 2011 U.S. dollar).

Cost Element	Cost by Operation ($/dry T)	Cumulative Cost ($/dry T)	Reference
Grower Payment	40.00	40.00	Section 2.1
Harvest and collection	19.20	59.20	Section 3.1
Storage	4.30	63.50	Section 3.2
Preprocessing		63.50	
Size Reduction	28.40	91.90	Section 3.3
Drying	15.20	107.10	Section 3.4
Handling	3.00	110.10	Section 3.4
Transportation	11.50	121.60	Section 3.4
Ash Dockage	14.00	135.60	Section 3.1
Carbohydrate Dockage	6.10	141.70	Section 3.2
Total Delivered Feedstock Cost		**141.70**	
Delivered Feedstock Specifications			
Ash Content	5%		Section 1.2.1
Moisture Content	12%		

1.2 Approach of the 2017 Design Case

The baseline case illustrates three specific challenges for reducing the current estimated feedstock costs to achieve the $80/ton cost target of the 2017 Design Case. First, it is implausible that grower payment can consume 50% of overall feedstock costs. Grower payment (access costs) must be reduced. This does not suggest that the payment producers receive for biomass will decrease; rather it will be shown that the supply curve depends on the supply/demand dynamic. Second, feedstock specifications must be developed to reduce, if not eliminate, the quality penalty incurred through dockage fees. Third, technological improvements in all supply chain unit operations must occur to reduce logistics costs. This section discusses the general approach of the 2017 Design Case for addressing these challenges.

1.2.1 Addressing the Grower Payment Challenge

The Billion Ton Update (U.S. DOE 2011), which is the definitive source of national biomass supply/cost data, represents biomass access costs in terms of "farm gate" price, which includes the cost of production, harvest and storage field side, compensation for soil nutrient removal, and grower profit. Because feedstock logistics designs consider harvest, collection, and storage operations within logistics costs, we subtract harvest, collection, and storage costs from the reported farm gate price and refer to this biomass access cost as grower payment.

Neither grower payment nor farm gate prices are constant; rather they are functions of the marginal cost of procuring the next additional quantity of biomass. *The Billion Ton Update* (U.S. DOE 2011) provides projected farm gate prices for each county in the United States for all available feedstocks. Farm gate prices for most feedstocks, including biomass residues, start around $40/dry T. Figure 3 exemplifies typical farm gate cost functions, demonstrating that very little corn stover (i.e., approximately 300,000 tons) can be accessed at $40/dry T. In fact, a farm gate price of about $70/dry T would be required to access enough corn stover to supply 800,000 ton/year, leaving only $10/dry T to cover transportation and preprocessing costs within the $80 feedstock cost target of the 2017 Design Case.

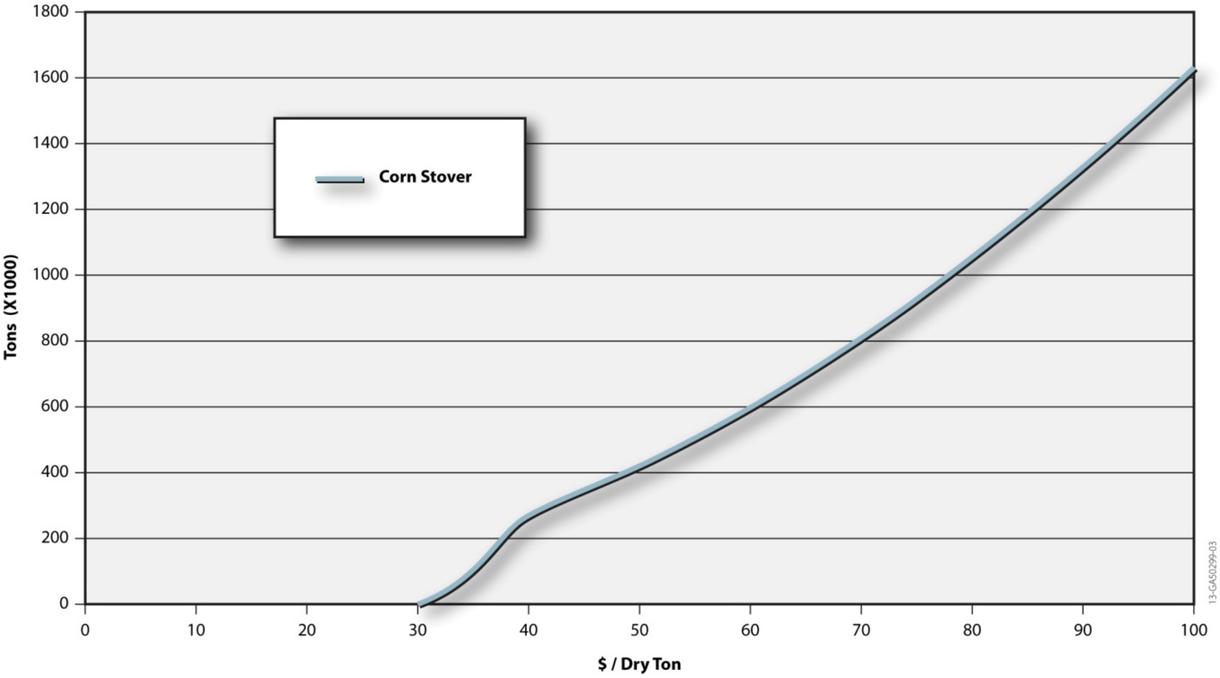

Figure 3. Typical farm gate price function for corn stover.

Supply curves differ geographically and by resource type (Figure 4); however, they all exhibit the same trend of access costs (i.e., grower payment or farm gate cost) that increase as volume and demand increase. Given this trend, the strategy for reducing feedstock access costs in the 2017 Design Case is to source multiple types of biomass feedstocks, each at volumes that allow us to remain low on the supply curve. This approach is demonstrated in Figure 4. In this example, corn stover, wheat straw, and switchgrass are available in sufficient quantities (i.e., 350,000; 310,000; and 140,000 tons, respectively) to supply an 800,000 ton/year biorefinery at a feedstock access cost of $45/ton compared to the $70/ton cost of corn stover alone. This multi-feedstock approach amounts to a biorefinery annual savings of $20 million.

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

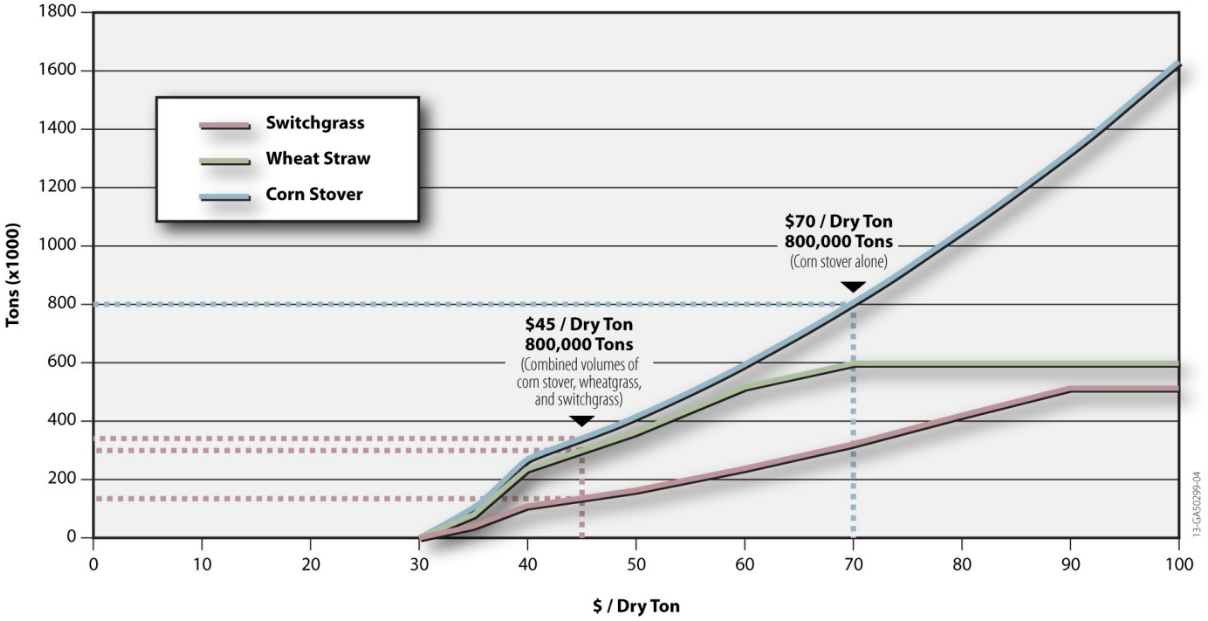

Figure 4. Typical farm gate price function for three feedstocks: corn stover, switchgrass, and wheatstraw. The combined volumes of corn stover, wheatstraw and switchgrass cost around $45/dry T for 800,000 tons, while 800,000 tons of corn stover alone cost around $70/dry T.

1.2.2 Addressing the Feedstock Specification Challenge

Blending biomass materials of different physical or chemical properties provides an opportunity to adjust feedstock quality; given the right blendstocks, it may be possible to blend to spec. Blending for such purposes is a common practice in many industries. For example, blending grain of the same kind to adjust quality is an accepted practice in the U.S. grain industry (Hill 1990); different grades of coal are blended to reduce the sulfur and nitrogen content for power generation (Boavida et al. 2004, Shih and Frey 1995); animal feed is blended to the specific nutrient requirements of the target animal (Reddy and Krishna 2009); and high-ash biomass sources are mixed with low-ash coal to allow their use in biopower (Sami et al. 2001). Using the blended feedstock strategy, it may be possible to blend to a moisture, carbohydrate, and/or ash specifications.

Though it may be possible to blend to the required specification as measured by composition and physical properties, an additional challenge of the blended feedstock approach is to have the blended feedstock actually perform as well as or better than a singular feedstock in the conversion process. Better understanding of the interactions of blendstocks in the conversion process will require an additional research and development focus to better inform blended feedstock development.

1.2.3 Addressing the Logistics Challenge

The high logistics costs of the baseline case, compared to the Conventional Design Case, are mostly attributed to ash and moisture mitigation. The requirement of the 2017 Design Case to handle higher moisture biomass (up to 30%, wet basis) stretches the capabilities of conventional systems. Storage dry matter losses at 30% moisture are estimated to be double those at 20% moisture. Therefore, improvements to biomass storage systems and processes are needed to improve the tolerance of these systems to biomass moisture. Likewise, the grinding energy for biomass size reduction is estimated to triple as biomass moisture increases from 15 to 30%. Therefore, improvements in biomass size reduction systems are needed to reduce the sensitivity of these systems to biomass moisture content. Finally, the definitive solution for biomass moisture mitigation—drying—also is cost prohibitive, requiring innovative solutions and technological advancements to reduce drying energy requirements.

Logistics solutions also are needed to reduce and/or eliminate quality dockage fees (described in Section 1.1.2) that account for about 15% of the delivered feedstock costs in the baseline case. Excessive feedstock ash content associated with the $14/ton ash dockage is attributed to introduced ash, which results from entrainment of soil in the biomass during multi-pass harvest. Further development and market adoption of single-pass harvest systems will help mitigate this issue, but reducing soil entrainment of multi-pass harvest systems also is necessary for the vast majority of farmers who do not use single-pass systems. In addition, convertibility dockage that results from degradation of structural carbohydrates during biomass storage must be reduced with improvements in biomass storage.

The blended feedstock strategy, which relies on the availability of multiple feedstock sources within a reasonable supply radius, adds an additional logistics challenge to the 2017 Design Case. The distributed nature of this approach could drive up transportation distances and associated costs, as well as bring in more business management overhead to simultaneously manage multiple feedstocks. In opposition to the specific technological solutions discussed above, overcoming this logistics challenge of a blended feedstock design will require system-level solutions. The 2017 Design Case explores two approaches: one is an agronomic solution based on integrated landscape management and the second is a logistics solution based on biomass depots.

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

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

2. 2017 FEEDSTOCK SUPPLY SYSTEM DESIGN: ADDRESSING GROWER PAYMENT

The least-cost formulation approach to resource selection was introduced in Section 1.2.1 as a solution to the grower payment challenge (i.e., to reduce feedstock access costs). As a quick note, the objective of "reducing grower payment" does not imply that we are promoting a solution that results in growers getting less. This should be clear as the least-cost formulation strategy is developed and demonstrated in this section. This section builds on the baseline scenario located in western Kansas to illustrate the least-cost formulation approach to resource selection for the 2017 Design Case. This approach challenges the single-feedstock paradigm by allowing available resources to compete based on cost, quantity, and quality considerations. It ultimately is demonstrated that such an approach can contribute significant cost reductions to biomass feedstock supply.

2.1 2013 State of Technology

Most cellulosic biomass feedstock supply systems are designed around a single feedstock, typically corn stover. Figure 5 illustrates the available resources for corn stover and switchgrass at varying farm gate prices for the western Kansas scenario that was chosen for the 2017 Design Case. Note that these supply curves represent the projected cost (i.e., farm gate) and quantity available in 2017 based on data from *The Billion Ton Update* (U.S. DOE 2011).

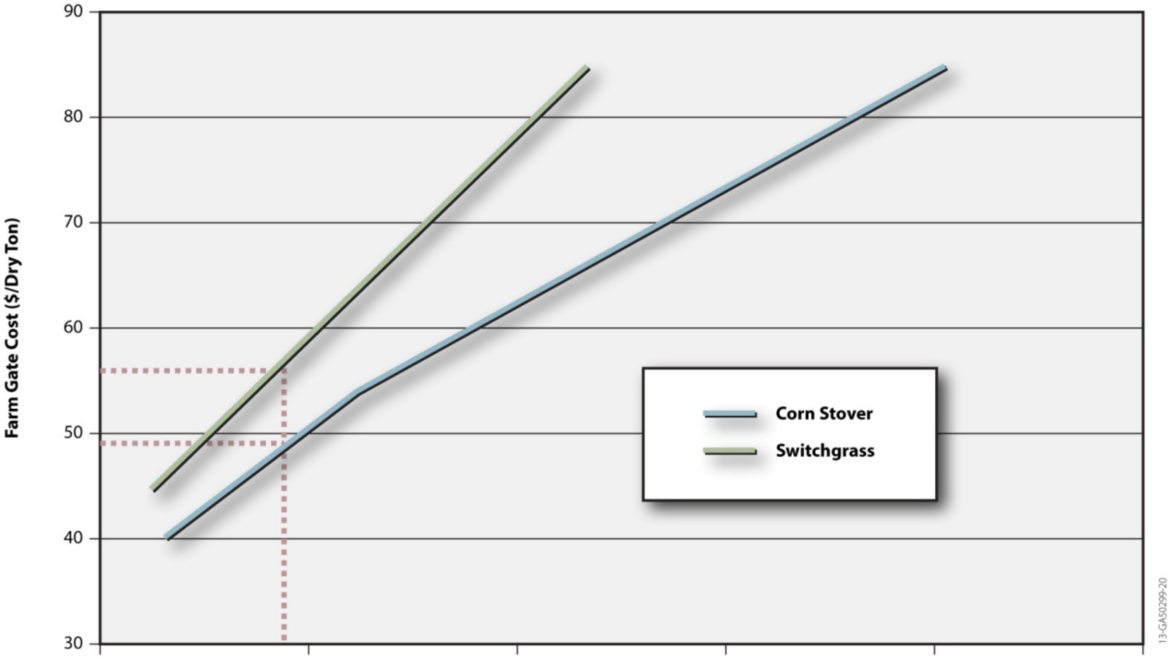

Figure 5. The farm gate cost curves would suggest that corn stover would be the preferred feedstock because it is available at a lower cost than switchgrass.

In order to account for losses throughout the supply chain, particularly dry matter losses in storage, a total of 870,000 dry T of biomass must be sourced in order to deliver 800,000 dry T to the biorefinery. According to the farm gate supply curves in Figure 5, sufficient quantities of both corn stover and switchgrass are available in this area at a cost of $49 and $57/dry T for corn stover and switchgrass, respectively. These farm gate supply curves indicate that even though switchgrass is available in this area, it cannot compete with the lower cost of corn stover.

However, when we consider the total delivered feedstock costs, which include both logistics costs and quality dockage costs (introduced in Section 1.1.2), then the dynamics of the biomass supply curve begin to change. These additional costs shift the farm gate supply curves upward; however, because these additional costs differ for corn stover and switchgrass, the curves do not shift the same amount (Figure 6). In the 2017 Design Case, the additional logistics and dockage costs are higher for corn stover than for switchgrass (see Section 4 for a cost summary). Logistics costs for switchgrass are lower primarily because of the higher yields, lower moisture, and improved preprocessing characteristics. In addition, the higher moisture and ash content of corn stover results in quality dockage costs (both ash and convertibility) for corn stover, where no dockage is applied to switchgrass. The result is that corn stover costs increase relative to switchgrass (Figure 6). Considering the total delivered feedstock costs, corn stover and switchgrass could each be supplied at the 870,000 ton quantity for about \$84 and \$85/dry T, respectively. This is only a \$1/ton difference compared to the \$8/ton difference when only farm gate price was considered.

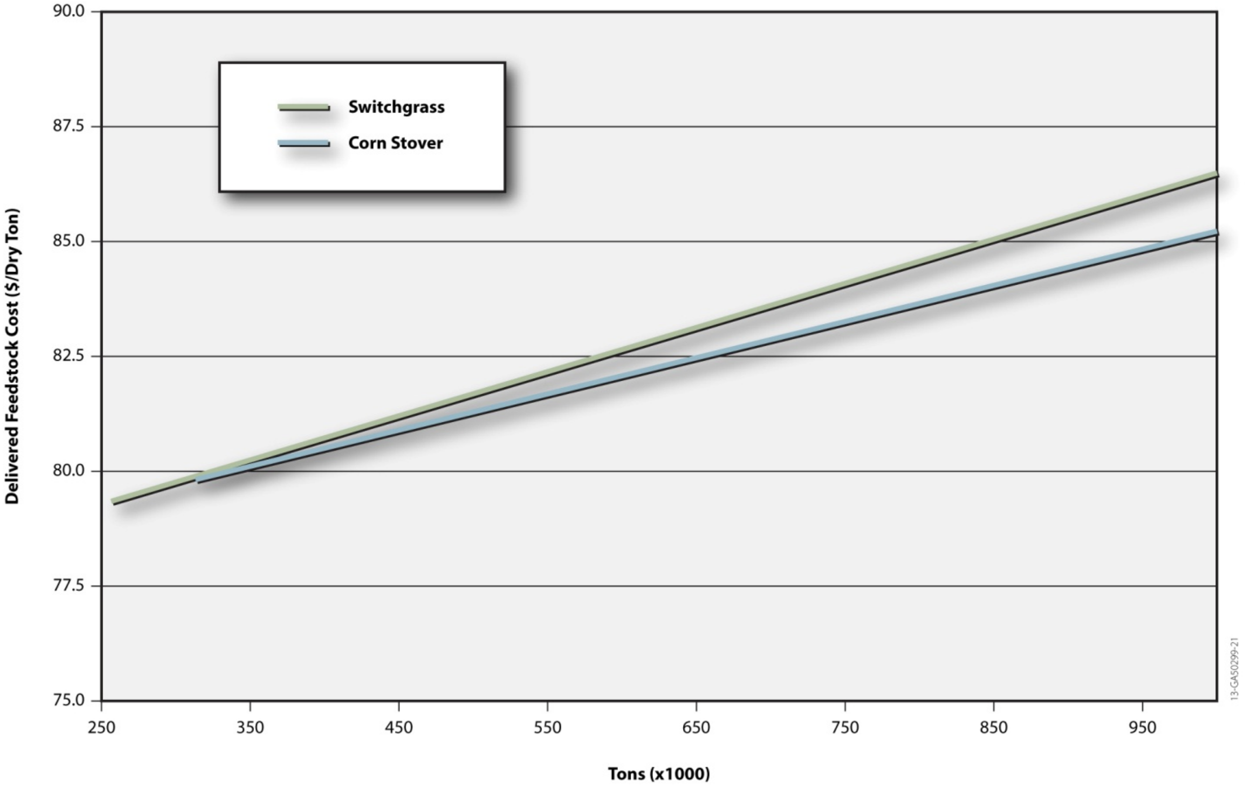

Figure 6. Accounting for logistics costs as quality (dockage)—the real cost to the biorefinery—shows that about 300,000 tons of switchgrass can be supplied at a lower cost than corn stover.

2.2 Resource Selection Design Basis

The feedstock supply curves in Figure 6 identify an opportunity for those not wed to a single feedstock. These supply/demand curves indicate that about 300,000 tons of switchgrass can be sourced at a lower cost than corn stover; however, beyond this amount, corn stove once again is more affordable. This gives rise to the least-cost formulation or blended feedstock strategy, which, in this case, replaces higher cost corn stover with lower cost switchgrass. By sourcing 300,000 tons of switchgrass and 550,000 tons of corn stover, a corn stover/switchgrass blend can be supplied and delivered at about \$81/dry T, compared to \$84/dry T for corn stover and \$85/dry T for switchgrass (Figure 7).

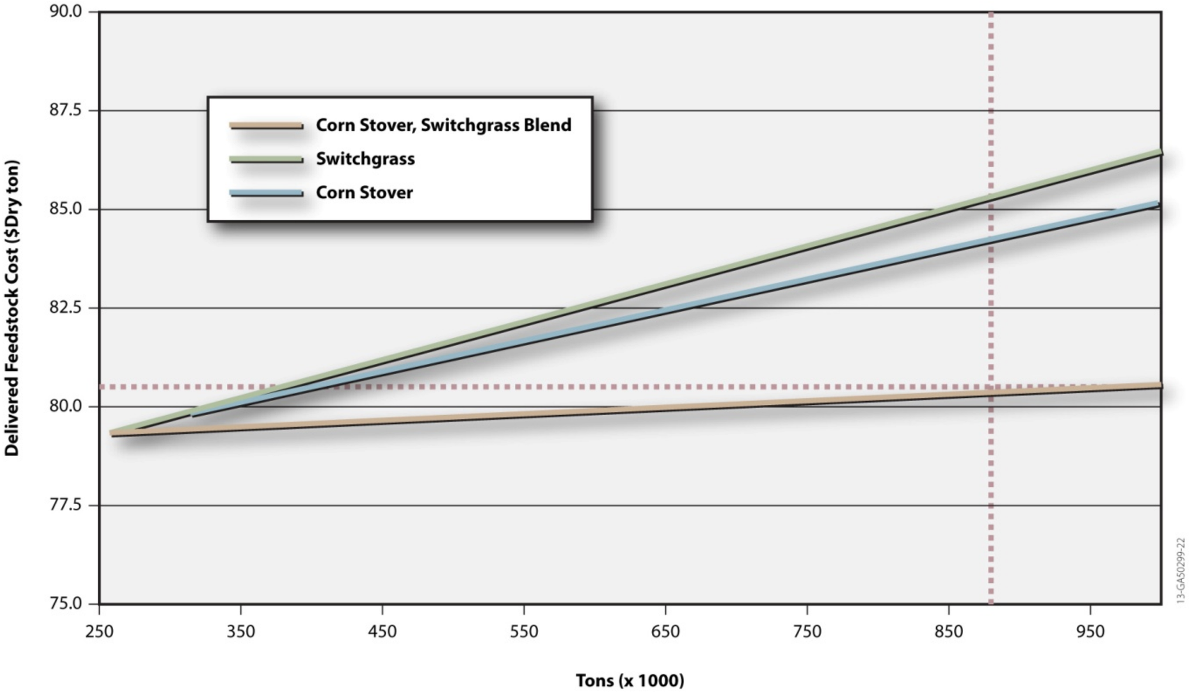

Figure 7. A corn stover/switchgrass blend that will deliver at about $81/dry T.

The least-cost formulation strategy would suggest that further reducing feedstock costs beyond what can be attained with the corn stover/switchgrass blend requires additional blendstock alternatives that can be accessed at lower costs than either switchgrass or corn stover. It is at this point that we introduce the potential of municipal solid waste (MSW) as a low-cost feedstock alternative. MSW is discussed in detail in Appendix A, where it is suggested that several MSW fractions are likely available at sufficiently low cost to be attractive blendstocks. Assuming an average access cost of $18/dry T (Shi et al. 2009) and logistics costs of about $44/ton (Section 4), MSW can be delivered for about $62/ton. At this cost, approximately 5% (44,000 dry T) of MSW added to the corn stover/switchgrass blend is sufficient to reduce the delivered feedstock costs an additional $1 to achieve the $80/dry T target (Figure 8). Recognizing that much uncertainty currently exists about the cost, availability, and conversion performance of MSW, a 5% MSW blend that contributes about $1/dry T to the $80/dry T target seems an acceptable level of risk until more research is completed to support higher blend levels.

The overall feedstock selection strategy of the 2017 Design Case is demonstrated in Figure 9. The supply curves in Figure 9 present the options available to a biorefinery in an area where a single, highly abundant, low-cost feedstock is not available. In the 2017 Design Case, the $80 feedstock cost target is only achieved by accessing multiple resources, including MSW. The least-cost formulation approach resulted in a feedstock blend consisting of 60% (522,000 dry T) corn stover, 35% (304,500 dry T) switchgrass, and 5% (43,500 dry T) sorted MSW.

The availability of these resources for the western Kansas scenario that was chosen to demonstrate the 2017 Design Case is illustrated in Figure 10. Corn stover and switchgrass are available within a 35-mile supply radius of the biorefinery. The source of MSW generally is tied to human generation; therefore, even 5% MSW requires a rather sizeable human population. This means that the MSW supply associated with this scenario comes out of the Denver, Colorado metropolitan area. It is not unusual for large metropolitan areas to ship their MSW to distant landfills; therefore, this scenario is likely replicable to many areas around the country.

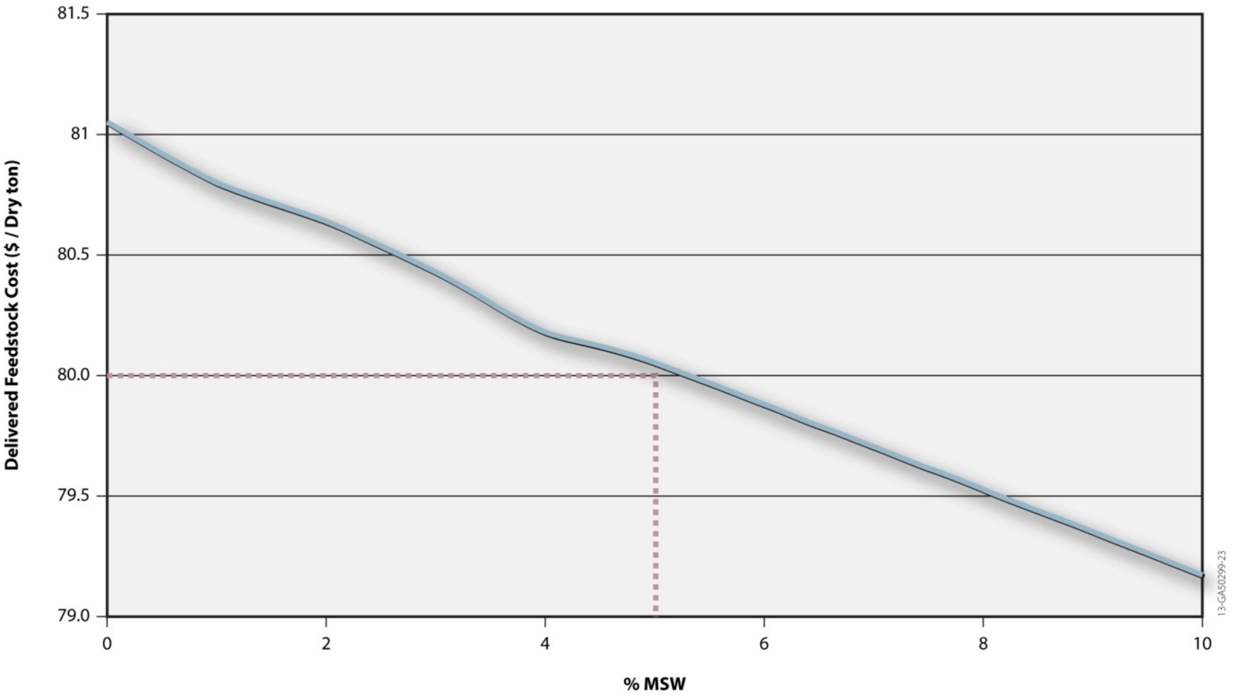

Figure 8. A minimum of 5% MSW (at $1/dry T) is needed to achieve the $80/dry T cost target with a corn stover, switchgrass, and municipal solid waste blend.

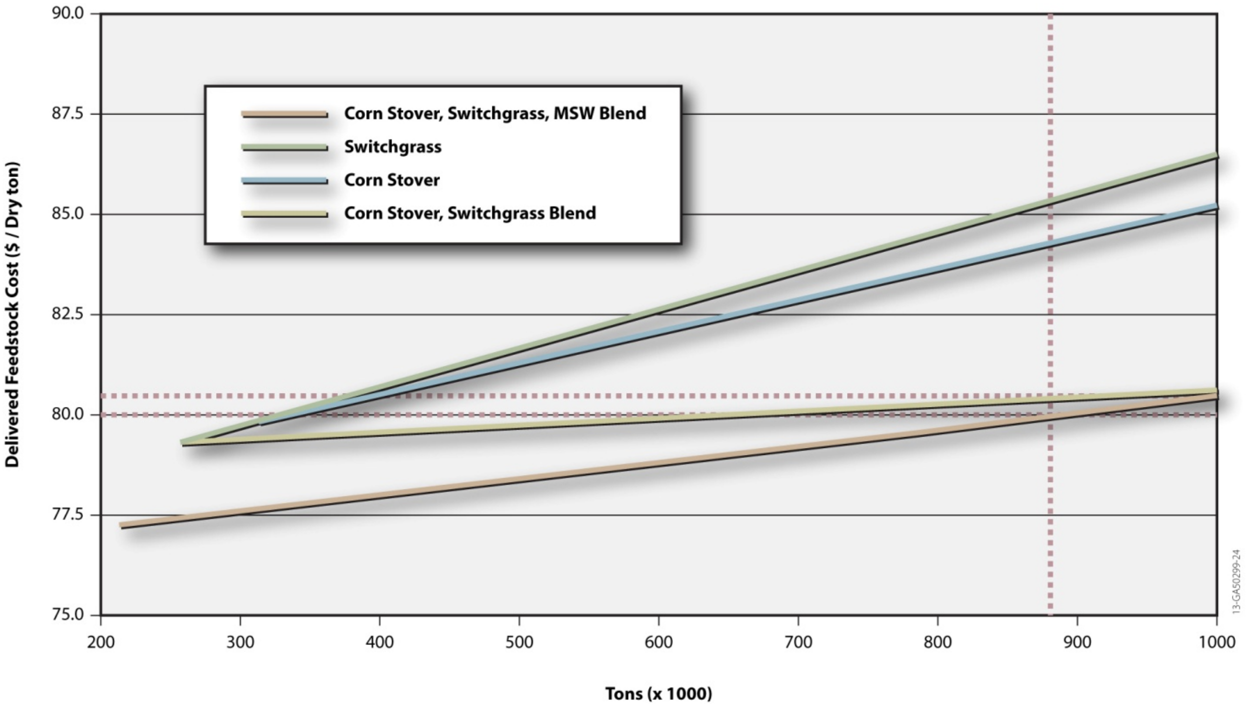

Figure 9. Comparison of individual and blended feedstock costs. A blend of 60% corn stover, 35% switchgrass, and 5% municipal solid waste is needed to hit the $80 feedstock cost target.

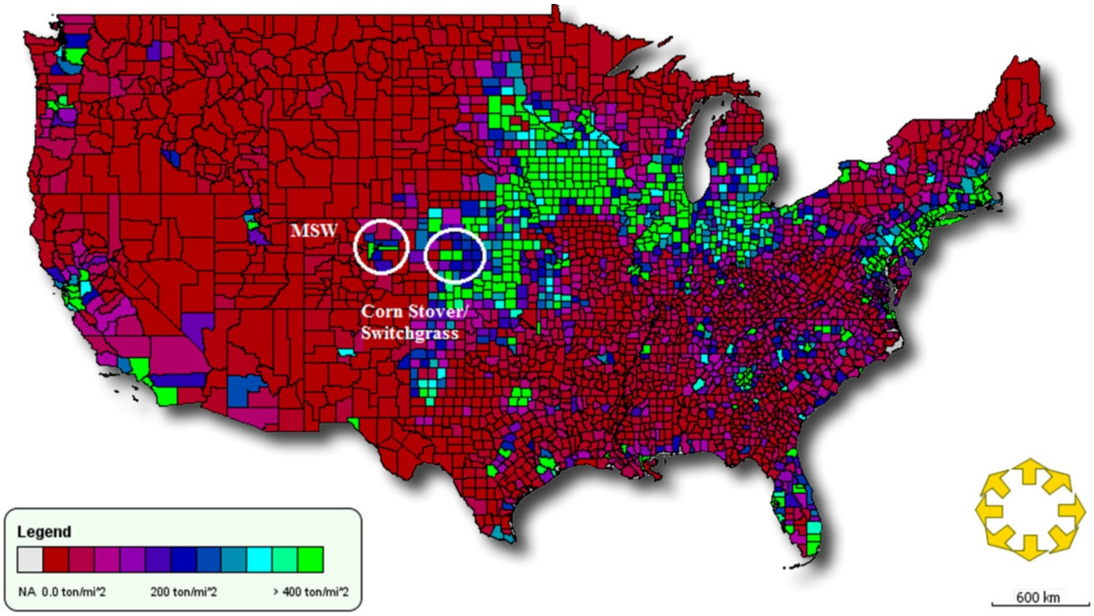

Figure 10. Resource selection for the 2017 Design Case to support biochemical conversion.

2.3 Resource Selection Cost Estimation

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

Access costs are calculated from the farm gate cost curves shown in Figure 6, which are derived from *The Billion Ton Update* (U.S. DOE 2011) data and are available from the Bioenergy Knowledge Discovery Framework (DOE 2013). Farm gate costs include nutrient replacement costs, harvest and collection costs, and an additional "profit" equal to 15% of nutrient replacement costs (Langholtz et al. 2011). Access cost is calculated by subtracting the biomass harvest and collection costs from the farm gate costs.

The 2017 Design Case basis discussion presented above provided the least-cost formulation approach for reducing access costs by accessing multiple feedstocks. With this approach, reduced quantities of each blendstock allows us to stay lower on the supply curve than if we had to supply the entire refinery with any single blendstock. The impact of this approach is shown in Table 3. The 2013 SOT assumes a 100% supply of corn stover and an access cost to supply 870,000 dry T estimated at $40/ton. In comparison, the 2017 Design Case blend of 60% corn stover, 35% switchgrass, and 5% MSW results in a weighted average feedstock cost that is nearly 30% lower than the access cost of stover alone.

Table 3. Resource access cost estimate.

	2013 SOT		2017 Target	
	Access Cost (2011 $/dry T)	*Tons*	*Access Cost* (2011 $/dry T)	*Tons*
Corn stover	40.00	870,000	27.20	522,000
Switchgrass	NA	0	29.80	304,500
MSW	NA	0	18.00	43,500
Totals	40.00	870,000	27.70	880,000

3. 2017 FEEDSTOCK SUPPLY SYSTEM DESIGN: ADDRESSING FEEDSTOCK LOGISTICS

Feedstock logistics is a highly complex organization of operations required to move and transform biomass from the point of production to the infeed system of the conversion reactor. Feedstock logistics encompass unit operations, including harvesting and collection, storage, transportation, preprocessing, and handling. Organizing feedstock logistics in a way that maintains economic and environmental sustainability, while providing necessary resource quantities, is a principal challenge that needs to be addressed before a self-sustaining industry can evolve. Feedstock logistics research aims to reduce delivered cost, improve or preserve feedstock quality, and expand feedstock access.

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

Biomass moisture content is a good example. The 2017 Design Case assumes that corn stover is harvested at 30% moisture content. This is not a typical scenario, but is likely to occur nonetheless. Considering a year-round supply chain, some feedstock will be processed on day one and some will remain in storage and not be processed until day 365. The two may be very different in composition and physical properties. Rather than including predictive functions to represent temporal variability, or even representing mean or median properties, the 2017 Design Case establishes the technical target for each unit operation based on worst case operational assumptions.

The major assumptions of the 2017 Design Case, compared to the 2012 Conventional Design and the Baseline Design developed in Section 1 are shown in Table 4. The implications of these assumptions on feedstock supply systems designs are discussed in this section of the report.

3.1 Harvest and Collection

3.1.1 Overview

Biomass harvest and collection encompass all activities required to gather and remove feedstock from the place of production to the first point of sale; this is often field side or at a nearby storage site and generally is referred to as the "farm gate." The 2012 Conventional Design focused on conventional multi-pass harvest methods (i.e., the mowing and/or windrowing operations are separate from the baling operation). Single-pass harvesting systems (such as those developed through the DOE-funded, high-tonnage, logistics projects) offer efficiency and quality improvements over conventional, multi-pass systems. The 2017 Design Case assumes that the immaturity of the biomass market will limit the farmer investment in advanced equipment options. Therefore, with the exception of a few proactive, early adopters, conventional, multi-pass systems will dominate the marketplace in the regions defined by the 2017 Design Case.

Table 4. Summary of assumptions underpinning progressive design implementations.

	2012 Conventional Design	Baseline	2017 Design Case
Feedstock(s)	Corn stover	Corn stover	Blended feedstock: corn stover, switchgrass, and select municipal solid waste (MSW)
Grower payment	Minimal	Increases based on marginal cost differential	Calculated and modeled according to specific location and resource blend/formulation
Moisture	Field dried to 12%	Arrives at 30% Dried to 20%	Arrives: corn stover 30%, switchgrass 20%, and MSW 20%; All dried to 7%
Ash	No ash management assumed	11%, dockage accessed for ash content Greater than 5% spec	Blended ash content of 4.9% Corn stover: multi-pass 7%; single-pass 3.5% Switchgrass: 4% MSW: 10%
Logistics	Uses existing systems	Uses existing systems	Fractional milling High-moisture densification Rail transportation for MSW
Quality controls (passive)	Field drying to meet moisture spec Ample available resource; quality spec manually selected	Dockage fee assessed to supplier for below-quality material	Multi versus single-pass harvest/ collection Harvest/collection and storage best management practices
Quality controls (active)	None assumed	Rotary drying	Multiple resource blending/formulation High-moisture densification High-efficiency pellet drying
Meets quality target	No	Yes	Yes
Meets cost target	Yes	No	Yes
Accesses dispersed resources	No	No	Yes

In the 2017 Design Case, corn stover is harvested using a flail shredder, which is commonly referred to as a stalk chopper. The ability of a stalk chopper to minimize soil pickup and contamination compared to alternate methods drives this decision (Bonner et al. 2013). Corn stover harvest occurs within a 6-week window that coincides with grain harvest. In this operation, stalk chopping and baling (i.e., 3×4×8-ft large, square bales) immediately follow grain harvest. The 2017 Design Case assumes a stalk chopper collection efficiency (i.e., removal rate) of about 40%, with a corn stover moisture content up to 30% (wet basis). It also assumes that field drying to a preferred moisture content (i.e., less than 20%) for long-term storage may not always be possible, resulting in corn stover bales with up to 30% moisture content that must be appropriately managed in storage. While drying in storage may occur, high-moisture biomass undergoes dry matter loss early in storage, resulting in both feedstock loss and compositional changes (Shinners et al. 2011).

Switchgrass harvest in the 2017 Design Case also follows conventional practices. Following plant senescence in the fall, when plant nutrients retreat into the root system and the plant naturally dries down, switchgrass is cut and windrowed using a self-propelled mower-conditioner; then it is subsequently baled using a large-square (i.e., 3×4×8-ft) baler. A collection efficiency of 90% and bale moisture content of less than 20% is assumed in cost estimation for switchgrass harvest and collection.

Improvements to multi-pass systems are described in the following section of the 2017 Design Case basis and focus on improving biomass quality through reduction of soil entrainment, while maximizing biomass yield and sustainability.

3.1.2 2013 State of Technology

Conventional harvest and collection employ multi-pass systems to process biomass. Existing multi-pass collection systems for agricultural residues typically involve cutting the feedstock, raking the material into a windrow, and baling the windrowed material. For corn stover, cutting may or may not be done at the time of corn harvest, which impacts material quality and removal yields. In multi-pass operations, raking is performed to facilitate baling and improve yield. No consideration is given to the impact of raking on soil entrainment in the final baled feedstock. In single-pass corn stover baling, the stover is fed directly into a baler towed by the combine. This harvesting method eliminates soil contact and results in a lower stover ash content. However, it also eliminates field drying, which results in a higher initial bale moisture content. This elevated moisture presents a challenge to feedstock stability and increases dry matter loss in storage.

The total ash content of research-grade corn stover samples has been reported to range from 0.8 to 6.6% across the Corn Belt of the Midwestern U.S. States (Templeton et al. 2009). Studies comparing single-pass to multi-pass harvest systems demonstrate total ash contents in the range of 5% to 10%, respectively (Shinners et al. 2012), which shows that single-pass harvest systems have the potential to minimize soil contamination in production harvest operations. Table 5 shows the mean and range of ash contents for selected feedstocks and includes the effects of feedstock ash and soil contamination from harvest and collection operations. Harvest methods for these feedstocks were not specified; however, average corn stover ash content in Table 5 feedstocks (from Turn et al. 1997) suggests that the majority of the reported values were obtained from research-grade samples. Switchgrass ash contents range from 2.7 to 10.6%, with an average of 5.8% (Turn et al. 1997). Minimum values correspond to physiological ash; therefore, for the purpose of this design, they are assumed to be the absolute minimum, practically obtainable values prior to further mechanical or chemical ash-reduction steps.

Table 5. Mean total ash values and ranges for selected lignocellulosic biomass.

	Feedstock	Average Ash (%)*	Reported Range (%)
Herbaceous	Corn Cob	2.9 (13)	1.0 to 8.8
	Corn Stover	6.6 (28)	2.9 to 11.4
	Miscanthus Straw	3.3 (13)	1.1 to 9.3
	Reed Canary Grass	6.7 (11)	3.0 to 9.2
	Rice Straw	17.5 (22)	7.6 to 25.5
	Sorghum Straw	6.6 (5)	4.7 to 8.7
	Sugarcane Bagasse	5.6 (27)	1.0 to 15.2
	Switchgrass Straw	5.8 (21)	2.7 to 10.6
	Wheat Straw	8.0 (50)	3.5 to 22.8
Woody	Oak Residue	2.5 (5)	1.5 to 4.1
	Oak Wood	0.6 (11)	0.2 to 1.3
	Pine Residue	2.6 (4)	0.3 to 6.0
	Pine Wood	1.0 (40)	0.1 to 6.0
	Poplar Wood	2.1 (14)	0.5 to 4.3
	Spruce Residue	4.3 (2)	2.2 to 6.4
	Spruce Wood	0.8 (5)	0.3 to 1.5
	Willow Residue	2.0 (1)	2.0 to 2.0
	Willow Wood	1.5 (18)	1.0 to 2.3

* Mean value presented with the number of reported samples in parenthesis.

Research to-date has shown herbaceous feedstock ash content as being highly dependent on harvest equipment (Turn et al. 1997). Traditional, multi-pass corn stover bales from Stevens County, Kansas, were found to range from 10 to 25% ash by mass (Figure 11), with quantities that represent increases in feedstock cost by 4.88 to 20.23 $/DMT compared to the baseline level of 5%. Feedstock replacement and ash disposal costs account for the change in value, which is on the order of $2.25/DMT for each 1% ash above the baseline.

In a separate study, field conditions and harvest efficiency were shown to impact stover bale ash content. Figure 12 shows the range of ash content measured in bales made within the same field using three different harvest methods with collection efficiencies in the range of 1 to 4 tons per acre. In this study, soil contamination was reduced through use of a flail shredder. However, for each equipment combination, ash content decreased at the expense of yield. The economic impact of yield, with the resultant increase in harvest, collection, and transportation costs, must be balanced with the need to deliver high-quality/low-ash feedstock.

Single-pass bales collected from the southwest region of Kansas contained only 4% ash (Figure 11), presenting a clear advantage to operational costs and biomass quality. Single-pass harvesting maximizes ash avoidance by preventing the biomass from contacting the soil; however, it results in increased moisture content because no in-field drying occurs. This collection method also can increase harvest yield compared to multi-pass systems, thereby decreasing the amount of acres harvested, but increasing the risk of erosion and soil carbon loss if stover removal exceeds the sustainability limits (Karlen et al. 2011).

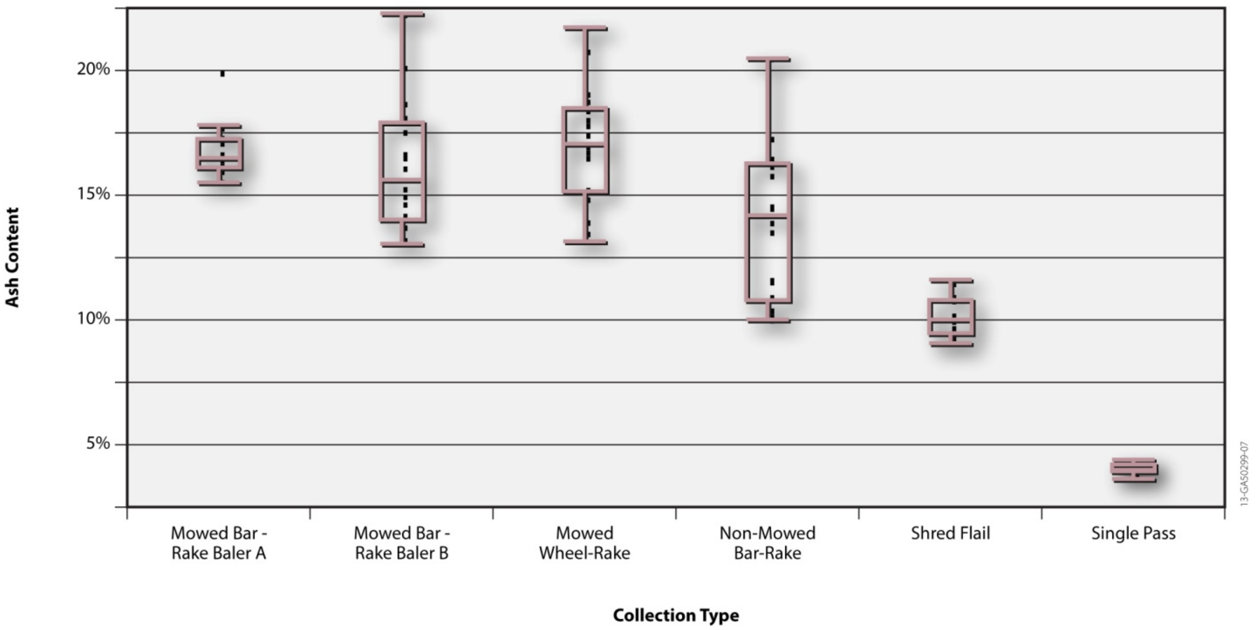

Figure 11. Ash content of corn stover bales from Stevens County, Kansas, that are collected using single-pass baling and a variety of multi-pass methods, including two rakes, two balers, a mower, and a flail shredding windrower.

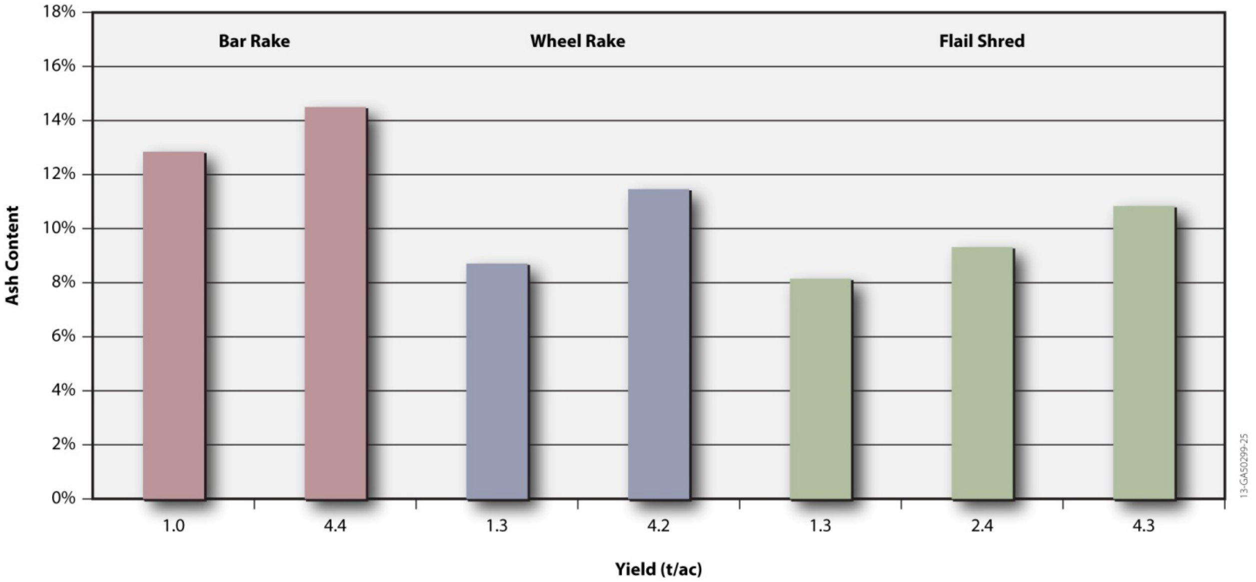

Figure 12. Ash content (bars) and yield (text) of corn stover bales from Stevens County, Kansas, show the impact of collection efficiency and windrowing equipment on yield and soil entrainment.

3.1.3 Harvest and Collection Design Basis

The 2017 Design Case will use traditional harvest and collection equipment (i.e., both multi-pass and single-pass methods); however, it will depend heavily on advancing operational strategy. Maintaining the design specifications shown in Table 6 for ash and moisture content requires a balance between harvested biomass quality, storage behavior, and final delivered feedstock specification. The blending strategy used by the 2017 Design Case will merge the benefits of multi-pass and single-pass systems to enforce ash avoidance during harvest and reduce ash enrichment throughout storage. To meet the delivered feedstock specifications, the harvest and collection task relies on the adjustment of pre-storage goals for ash content, moisture content, and biomass yield.

Table 6. Technical targets for harvest and collection of herbaceous resources in the 2017 Design Case.

	Ash Content		Baled Moisture		Bulk Density	
Process	2013 SOT	2017 Target	2013 SOT	2017 Target	2013 SOT	2017 Target
Multi-pass	10%	7%	30%	30%	12 lb/ft^3	12 lb/ft^3
Single-pass	6%	3.5%	30%	30%	12 lb/ft^3	12 lb/ft^3
Switchgrass	6%	4%	20%	20%	12 lb/ft^3	12 lb/ft^3

If the harvest and collection strategies can be improved to minimize the ash collected within herbaceous and woody biomass, a higher quality feedstock will be delivered to the conversion facilities, thus reducing preprocessing and pretreatment costs. Strategies for ash reduction in multi-pass corn stover and switchgrass focus on reducing soil disturbance during harvest such as reliance on mechanically driven rather than ground-driven rakes, using flail-shredding windrowers, and increasing cut height. These less-aggressive collection methods may sacrifice yield for reduced soil contamination. Research is necessary to find balanced solutions that optimize yield, ash content, and sustainability. Further ash reduction in switchgrass may come from delaying harvest until after the first freeze, or by overwintering (Adler et al. 2006). However, overwintering comes with the penalty of reduced yield because of leaf loss. Strategies for ash reduction in single-pass corn stover systems focus on harvest timing and cut height. To reduce moisture and ash contents, harvest may focus on the upper stalk, but at a concomitant decrease in yield (Hoskinson et al. 2007, Wilhelm et al. 2011), which will have an impact on transportation and handling costs (Hess et al. 2007). Delayed harvest results in lower stover moisture and ash content; however, harvest timing is driven by grain moisture and may be inflexible. Differences in the ash content of various anatomical fractions (Pordesimo et al. 2004) (such as cobs; see Table 5) may permit ash reduction by selective harvest at the expense of yield, but with benefits to sustainability. Further research is needed to better control biomass handling while minimizing ash and ensuring repeatable and reliable high-quality biomass is collected consistently, which enables blended feedstocks to be created with predictive certainty and operational confidence.

The 2017 Design Case focuses on improvements to and optimization of conventional equipment. Single-pass and advanced, multi-pass harvesting systems (i.e., specialized combine operation or windrowing equipment) that provide the lowest ash content feedstock will emerge first in the highly productive regions, where the economics of a single-feedstock market allow farmers to spread their investment across more acres and tons of biomass. In less productive areas, conventional multi-use systems will be operated with greater focus on reducing feedstock moisture content and improving storage stability to avoid ash enrichment throughout storage. Idaho National Laboratory (INL) research shows that stover ash content from conventional multi-pass collection equipment can approach the 2017 goal of 7.5% ash (Figure 12). However, additional improvements are required to stabilize the uncertainty of soil entrainment while maximizing biomass yield and sustainability.

3.1.4 Harvest and Collection Cost Estimation

Harvest and collection costs assume a removal rate of 1.2 dry T/acre for corn stover (both single and multi-pass) and 5-dry T/acre for switchgrass. These assumptions are consistent with those used in the *The Billion Ton Update* (U.S. DOE 2011). Cost reductions from the 2013 State of Technology (SOT) to the 2017 Design Case are largely attributed to the transition from multi-pass corn stover harvest in the 2013 SOT to single-pass harvest in the 2017 Design Case (Table 7). These cost reductions are attributed to both a reduction in as, and an improvement in the overall efficiency of the harvest operations that result from single-pass harvesting. The cost of ash is estimated from the ash dockage $2.25/dry T per percent ash presented in Section 1.1.2. Ash dockage contributed $14 to the 2013 SOT costs. However, the 2017 Design Case assumes that, with improvements to multi-pass harvest systems and through increased adoption of single-pass harvesting equipment, the blended feedstock ash content is within spec, thereby eliminating an ash dockage. Additional cost savings are realized through improved bale densities that result from anticipated improvements in the high-density baling technology.

Table 7. Biomass harvest and collection cost estimates.

Machine	2013 SOT (2011 $/dry T) *Total*	2017 Target (2011 $/dry T) *Total*
Multi-pass corn stover		
Combine*	0.00	0.00
Shredder	5.30	5.30
Baler	10.60	10.60
Bale collection/stacking	3.30	3.30
Ash dockage	14.00	0.00
Totals	33.20	19.20
Single-pass corn stover		
Combine*	0.00	
Baler	7.20	7.20
Bale collection/stacking	3.30	3.30
Totals	10.50	10.50
Switchgrass		
Mower-conditioner	4.80	4.80
Baler	7.30	7.30
Bale collection/stacking	3.30	3.30
Totals	15.40	15.40

* Costed to grain group.

3.2 Storage

3.2.1 Overview

Feedstock preservation in storage is necessary to enable year-round biorefinery operation using seasonally available feedstocks. Harvesting of herbaceous feedstocks, specifically agricultural residues such as corn stover and cereal straws, occurs within operational windows that may span weeks or months, yet conversion operations occur year-round. The goal of storage is to preserve the valuable qualities of the feedstock until they can be fully utilized within the conversion process.

Biomass is subject to degradation by fungi, yeast, and bacteria that alter the feedstock's composition through selective removal of valuable components (such as structural sugars). Consumption of these components results in dry matter loss and enrichment of other components (such as lignin and ash) within the remaining feedstock. These other components have low or no value within a sugar-based conversion process. Existing storage practices for feed and forage rely on drying (e.g., baled forage) or oxygen limitation (e.g., ensiling) to impart long-term stability. However, these operations have the potential to exceed the allowable storage and handling costs for biomass feedstocks. A more practical solution is to control biological degradation to limit storage losses and maintain acceptable feedstock characteristics such as specifications of component concentration or product yield. The relationship between feedstock properties, storage conditions, and dry matter loss forms the basis of a product shelf life, which allows perishable feedstocks to be used while they still retain their value.

The 2017 Design Case assumes that storage of corn stover and switchgrass will occur field side or at a similar unimproved storage site. Appropriate storage sites provide adequate drainage away from the stack to prevent the accumulation of moisture around the stack, provide year-round access, and preferably allow the stack to be positioned in a north-south orientation. Stacks are constructed with a bale wagon, are six bales high, and are covered with a high-quality hay tarp. In order to prolong tarp life, it also is important that adequate year-round maintenance be provided to periodically tighten the tarps. Biomass storage systems in the 2017 Design Case seek to provide a low-cost, low-maintenance, moisture-tolerant solution that focuses on the predictability of dry matter losses and compositional changes to inform an active inventory management approach to large-scale, long-term storage.

3.2.2 2013 State of Technology

The current industry standard for assessing storage performance entirely depends on the measure of dry matter loss. While losses do occur from physical handling, such sources of shrinkage are minimized by proper practice and are not considered a major factor for improvement. On the other hand, dry matter loss from biological degradation is highly variable, difficult to measure, and difficult to control. The major factors that drive biological dry matter loss are moisture content of the material entering storage and the habitability of the biomass for microbial organisms, which includes factors such as oxygen availability, pH, and inhibitory substances.

Conventional aerobic storage of biomass does little to limit any of these factors, because moisture contents often can be well within the range suitable for microbial growth (i.e., greater than20%) and raw biomass in a baled format presents a near-ideal environment for microbial growth and resulting degradation (e.g., ample oxygen and digestible substrate). Laboratory-scale storage experiments conducted at INL have shown significant contribution of moisture content to dry matter loss of aerobically stored corn stover, with losses ranging from as low as 6% to as high as almost 40% as moisture increases from 20 to 55%, respectively (Figure 13). Although the extent of dry matter loss in these experiments matches the field-run storage trials, the loss rates are increased by a factor of approximately three because of the temperature and moisture control in the laboratory system.

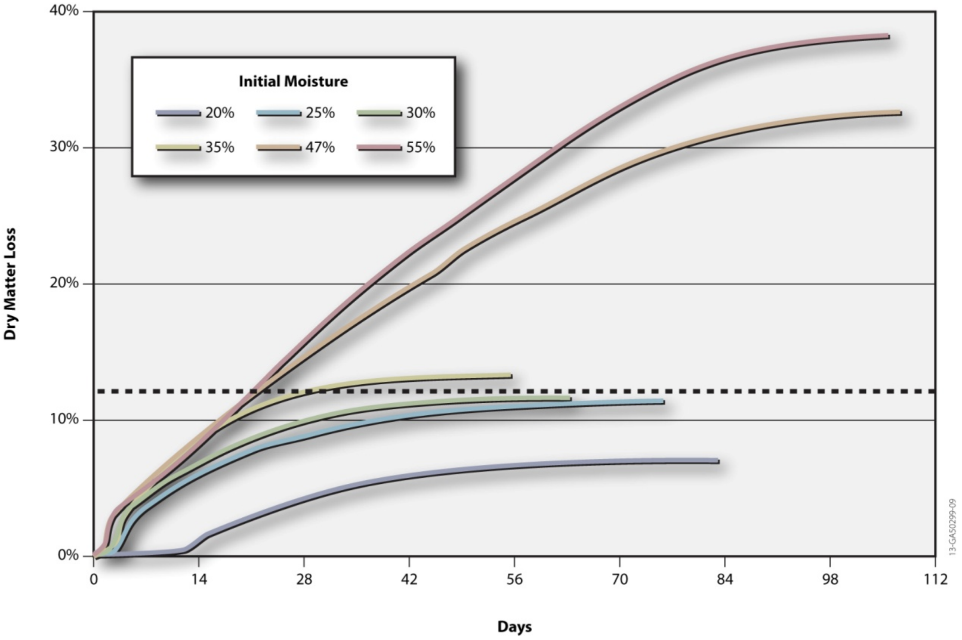

Figure 13. Dry matter loss of corn stover in laboratory storage conditions at fixed moisture contents.

Bale moisture tends to redistribute and even escape the stack during storage, ultimately contributing to significant moisture reduction throughout many of the bales within the stack (Figure 14; Smith et al. 2013). However, the end state of a stack of bales is no guarantee that its component bales did not suffer significant dry matter loss in storage or exit in a homogeneous state. The stack shown in Figure 14 was placed on a gravel pad, covered with a tarp, and ultimately dried to from 30 to 19% moisture; yet it still suffered 15% dry matter loss and portions of the stack remain at high moisture. An explanation for this is supported by the data in Figure 13, which indicate that the rate of dry matter loss is highest early in storage and decreases with time and stabilizing late in storage. Therefore, unless drying occurs rather rapidly (unlike the stack in Figure 14), moisture loss during storage is not likely to reduce storage losses significantly. The ultimate conclusion is that while field drying of stacked bales does occur, the rate at which drying occurs, the extent to which material may dry, and the extent of degradation that occurred along the way is largely uncontrollable using current practices.

In addition to management of moisture and the associated dry matter loss, design considerations for biomass storage systems must include the quality of the final material. Two main considerations for biomass quality include the convertibility of the remaining dry matter (e.g., sugar yield from pretreatment and enzymatic hydrolysis) and the enrichment of non-convertible components (e.g., lignin, ash, and formation of inhibitors). Figure 15 shows the change in the glucan and xylan contents of the corn stover that suffered 35% dry matter loss in the storage conditions reflected in Figure 13. Results show that xylan content decreased and glucan content increased in the remaining feedstock. The final compositions differ from the initial compositions, but are within the range reported for corn stover (26.5 to 37.6% glucan and 14.8 to 22.7% xylan; NREL/TP-5100-47764). Notably, no clear compositional signature of dry matter loss is seen, even with significant dry matter loss. However, composition alone is not a sufficient measure of convertibility.

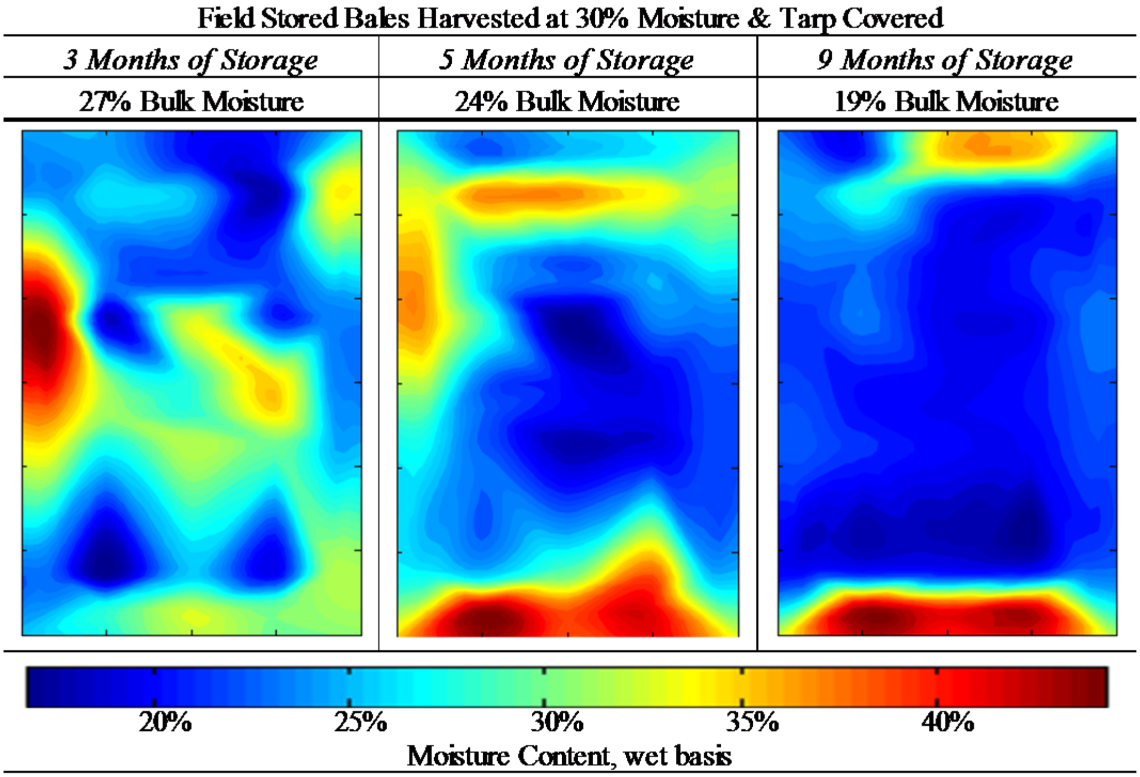

Figure 14. Change in moisture content of stacked corn stover bales in northern Iowa. Image depicts the variation in moisture content of a four-high column of bales stored outdoors for up to 9 months.

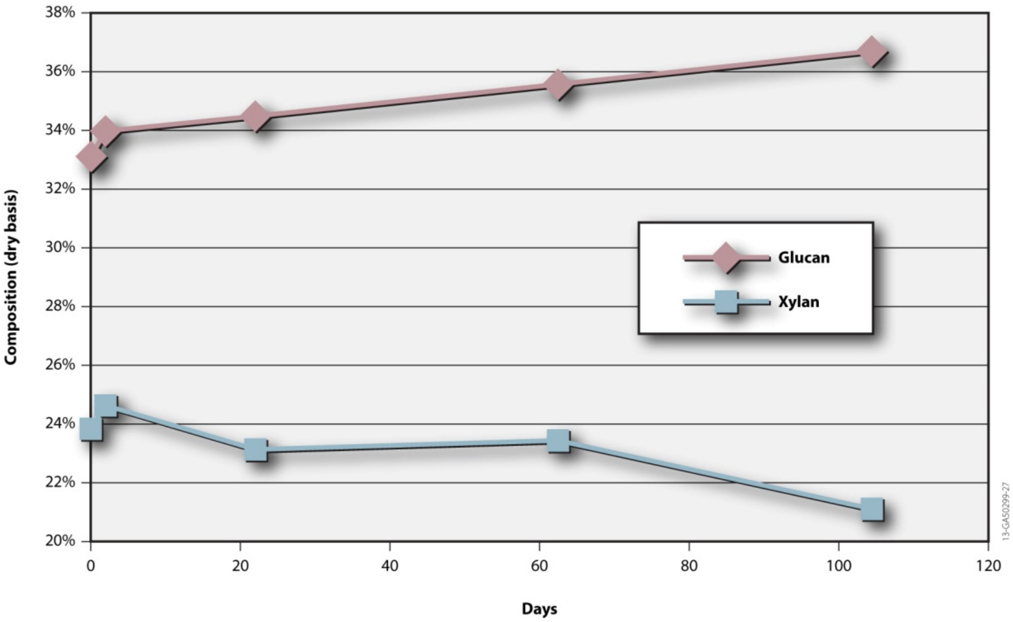

Figure 15. Change in glucan and xylan over time as corn stover is stored in laboratory reactors.

Preliminary results suggest that losses that occur in storage result in a decreased sugar yield following pretreatment, despite this minor composition change. Storage-induced losses may occur as a result of resistance to pretreatment, over-pretreatment (conversion to furfuraldehyde and HMF in a dilute-acid pretreatment), and/or reduced enzymatic hydrolysis. Decreased sugar yields in these processes may result from the selective removal of more easily converted forms of xylan and glucan during dry matter loss. Over-pretreatment may result from the partial hydrolysis of structural sugars and formation of lower molecular weight polymers and oligomers, which are susceptible to oxidation during pretreatment. In each instance, replacement feedstock is necessary to offset the loss of available sugar in order to maintain production. Ongoing research is evaluating the impact of dry matter loss relative to the intermittent and final product yields of the remaining dry matter. Research in Fiscal Year 2014 will quantify the impacts of storage on the xylose yields during pretreatment and the glucose yields during enzymatic hydrolysis. This assumption of decreased convertibility due to degradation in storage has been applied to the 2013 SOT (Table 2) and is explained in more detail in Section 3.2.3.

3.2.3 Biomass Storage Design Basis

The 2017 Design Case is based on material entering storage with 30% moisture. While it is recognized that this condition is not the norm for many areas and that storage performance will vary accordingly, use of this approach ensures the supply system will be capable of dealing with unstable, non-ideal feedstock. According to INL data shown in Figure 13, we assume that 30% moisture corn stover accumulates, at-worst ,12% dry matter loss after about 150 days in storage (adjusted for time scale) if additional moisture is not inserted. This upper limit for dry matter loss was assumed for the entire year’s lot of feedstock. As discussed in terms of the 2013 SOT, the passive loss of moisture during storage using conventional practice cannot be depended on as means to safely store wet feedstock. Therefore, storage practices developed by 2017 must be capable of limiting dry matter loss and its associated impact on convertibility, even when moisture contents entering storage are not favorable. To this end, the reduction of dry matter loss will be achieved through actively controlled improvements to storage in a way that moisture loss can be reliably achieved and/or oxygen availability can be limited in baled storage; both of which effectively limit microbial growth. Laboratory testing at INL has demonstrated that the availability of oxygen (while maintaining an aerobic storage environment) can effectively reduce the rates of dry matter loss in storage (Figure 16). These high-moisture corn stover samples (i.e., 50% wet basis) demonstrate how oxygen limitation can extend the shelf life in aerobic storage. Ongoing research will determine how practical measures, such as increasing bale density, high-density stacking configurations, and tarping, can be used to limit oxygen availability and improve storage stability in high-moisture, baled, and bulk stored feedstocks.

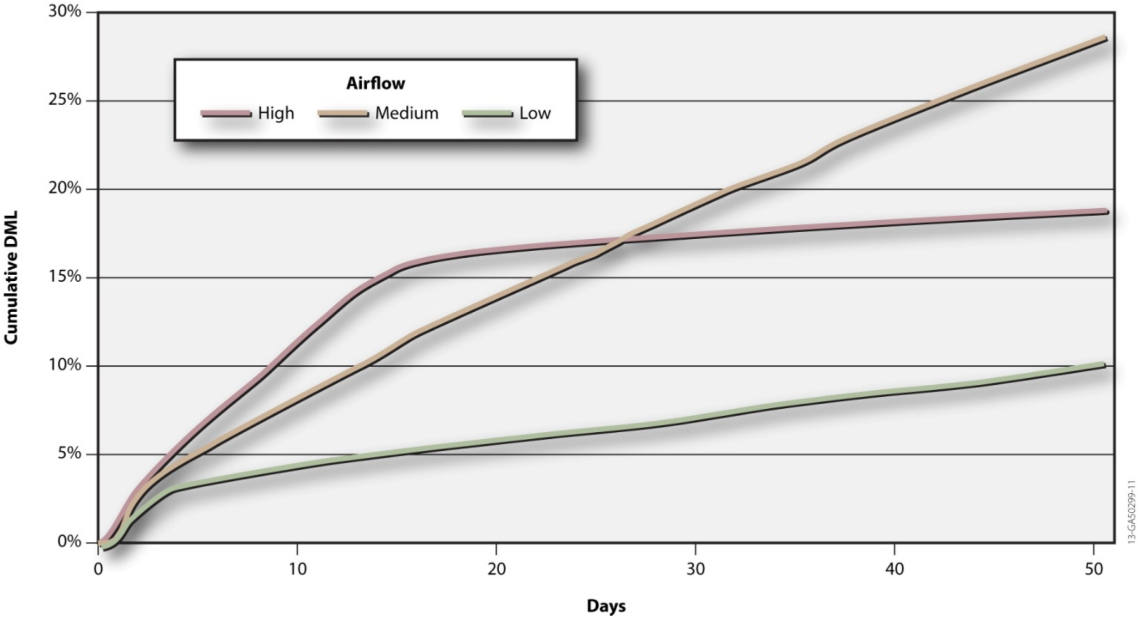

Figure 16. Dry matter loss of corn stover in the simulated storage conditions, with three air flows simulating three different oxygen availabilities.

The 2017 Design Case shifts the traditional focus of storage management away from a singular goal of minimizing dry matter loss to a more informed focus on the final material's convertibility. This approach allows the conversion yield, reasonably derived from stored biomass, to be assessed in addition to the mass loss incurred. The 2017 Design Case assumes that structural carbohydrates consumed during storage leave the remaining dry matter less convertible than the starting material. As an example of this effect, a hypothetical analysis of a storage scenario using the 2013 Base Case feedstock (30% moisture and 11% ash) was cast in terms of the existing biochemical ethanol conversion pathway (Humbird et al. 2011). Regardless of final product class (e.g., ethanol versus bio-based hydrocarbon fuels), it is assumed the decreased conversion performance due to degradation in storage will have comparable impacts on the feedstock supply system, with actual impacts dependent on product-specific conversion specifications. For the purpose of this analysis, calculation in terms of ethanol presents the opportunity for a direct comparison of feedstock performance and should not be inferred as yield goals for 2017. The analysis shows a conversion efficiency drop to 70 gal/dry T, which is an 11% reduction compared to the baseline of 79 gal/dry T (Figure 17). The analysis assumes that (1) dry matter losses are confined to the non-ash biomass fraction, (2) dry matter loss occurs proportionally across all non-ash components, and (3) for each 1% dry matter lost, there is a 0.25% decrease in conversion efficiency, which is defined as a reduction in final product yield. As a result, when dry matter loss is accumulated over time in storage (Figure 17, top), several important behaviors and interactions are occurring, primarily the relative ash content of the material is becoming enriched (Figure 17, middle), causing the carbohydrate fraction of the biomass respectively diminish (deviance from carbohydrate quantity spec), and the conversion performance of the remaining biomass is being reduced (deviance from the carbohydrate quality spec; Figure 17, bottom). These actions impact replacement costs, operational costs, and disposal costs for the refinery because more biomass must to be procured (replacement costs), more biomass must be handled and treated throughout the conversion process (operational costs), and more waste is being generated (disposal costs). In the 2013 Base Case, where feedstock price is $121.60/dry T, these costs result in a total feedstock dockage of $18.93/dry T, comprised of $12.48/dry T from feedstock replacement, $4.16/dry T from operational costs, and $2.28/dry T from disposal costs. Of these costs, dry matter loss is responsible for $6.10/dry T.

The technical targets for 2017 reduce this cost through decreases in dry matter loss (i.e., structural sugar quantity and quality preservation) and the ash entering storage (described in Section 3.1). When the above simulation is applied to the 2017 Design Case specifications (i.e., 30% moisture, 4.9% ash, annual dry matter loss of 7%, and a $81.60/dry T feedstock price), the dry matter loss results in a total convertibility dockage of $3/dry T (Table 8). These reductions in storage-related losses will be achieved by 2017 through the minimization of microbial activity in storage; principally, through controlled limitation of moisture content and/or oxygen in stored herbaceous feedstock.

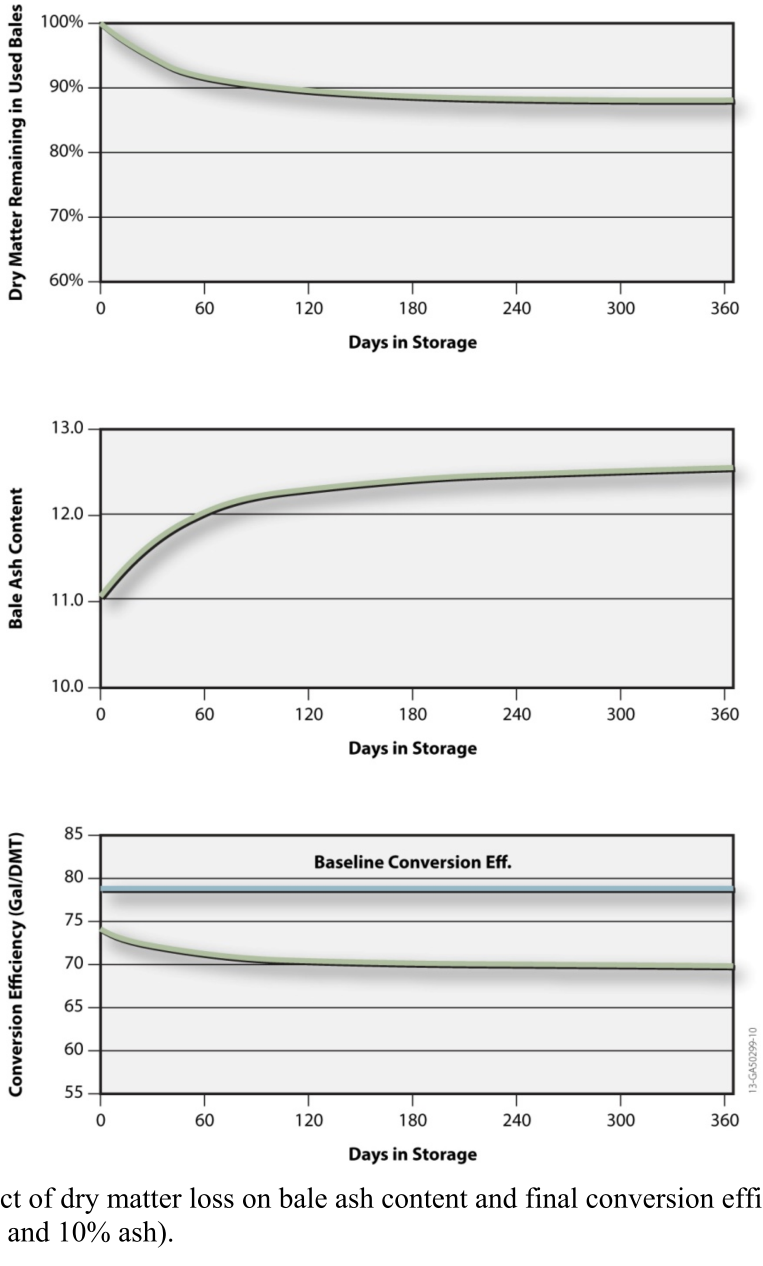

Figure 17. The impact of dry matter loss on bale ash content and final conversion efficiency (based on a 35% initial moisture and 10% ash).

Table 8. Biomass storage design basis.

	SOT Dry Matter Loss	Target	SOT Convertibility[a]	Targets
Corn Stover	12%	8%	59 gal/dry T	79 gal/dry T
Switchgrass	NA	6%	NA	79 gal/dry T

[a] Convertibility calculated in terms of the currently established cellulosic ethanol conversion pathway for a relative comparison between material performance for the current SOT and the 2017 Target, because the 2017 Design Case produces a hydrocarbon fuel.

3.2.4 Biomass Storage Cost Estimation

Cost estimations for biomass storage were calculated based on the storage cover vendor's information and laboratory and field level experiments (Table 9).

Table 9. Field-side storage cost estimation.

SOT (2011 $/dry T)			Design Target (2011 $/dry T)		
Storage	Dockage	*Total*	Storage	Dockage	*Total*
4.30	6.10	10.40	3.50	3.00	6.50

3.3 Preprocessing

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

Biomass preprocessing operations of the 2017 Design Case (Figure 18) differ substantially from the current state of technology, including improvements to size reduction (milling) and drying processes and the inclusion of new preprocessing operations (e.g., chemical preconversion and formulation) for ash reduction and feedstock blending. Biomass preprocessing begins with a coarse (i.e., Stage 1) size reduction to break the bale and facilitate the subsequent separations process. The objective of biomass separations is to reduce the quantity of material that requires further preprocessing, differentiating among anatomical or size fractions based on size, material properties (e.g., moisture and density), and/or composition. In the 2017 Design Case, substantial cost savings in size reduction are realized by separating the fraction of the biomass that meets the particle size specification as it exits the Stage 1 size-reduction process, passing only the remaining over-sized materials on to the Stage 2 size-reduction process.

Separation/sorting of MSW is required to remove recyclables (e.g., metal, paper, and cardboard), contaminants (e.g., plastics and concrete), and other unusable fractions to isolate only those fractions that meet the cost and quality requirements for biofuel feedstocks. In the 2017 Design Case, MSW is sorted to supply only yard and construction/demolition waste, which consists mainly of wood waste (e.g., tree trimmings and lumber), as a feedstock to be blended with corn stover and switchgrass. The ash content of these select MSW fractions is estimated to be about 10%. Chemical preconversion will be necessary for additional ash reduction (see Appendix B).

Following final milling of over-sized materials to the particle-size specification (i.e., 1/4-in. minus), feedstocks are pelletized. Pelletization enables the use of more efficient dryer designs, improves stability for long-term storage, eliminates handling and feeding problems often encountered with bulk biomass, and facilitates feedstock blending.

The 2017 Design Case incorporates many improvements in preprocessing, including fractional milling, chemical preconversion, high-moisture densification, and formulation/blending. Figure 18 demonstrates the material flow given for these improvements.

The logistics of a blended feedstock scenario are certainly more complex than a single-feedstock scenario. The 2017 Design Case assumes that preprocessing of MSW will occur at a preprocessing depot located at the source landfill or refuse transfer station, and MSW pellets will be shipped from the depot to the blending depot located within proximity of the biorefinery. Corn stover and switchgrass that is formatted in large square bales will be delivered to the blending depot, where they will be processed into pellets. Corn stover, switchgrass, and MSW pellets will be queued up in blending bunkers or silos. The pellets of the three blendstocks (i.e., corn stover, switchgrass, and MSW) are then metered from the blending bunkers in the ratios required of the blended feedstock and are conveyed from the preprocessing facility/depot to the conversion facility.

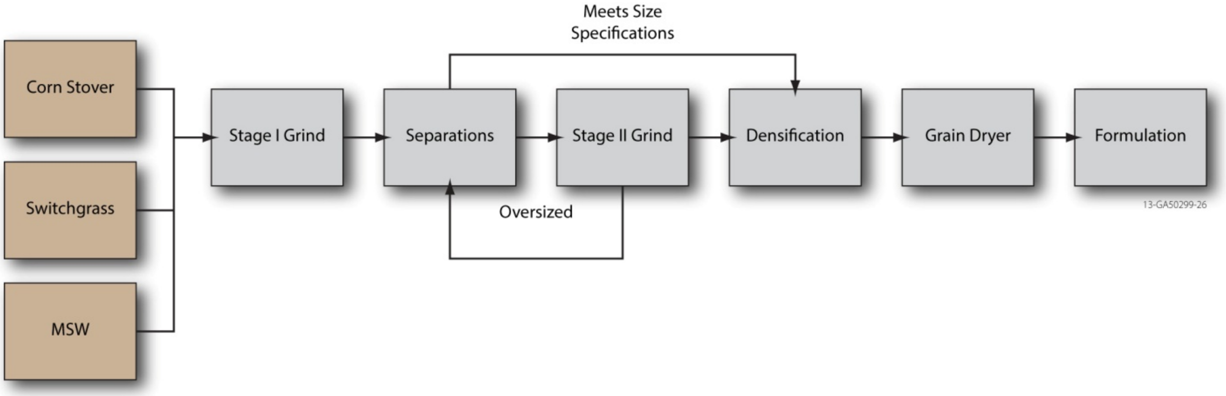

Figure 18. Material flow in the 2017 Design Case that incorporates many improvements in preprocessing, including fractional milling, chemical preconversion, high-moisture densification, and formulation/blending.

3.3.1 Size Reduction

The objective of biomass size reduction, or comminution, systems is to take biomass from its as-received condition (i.e., baled, log, or coarse shredded) to the final particle size specification required by the end user. Design and performance considerations include the size distribution of the final milled feedstock and the energy required to process the material.

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

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

3.3.1.1 2013 State of Technology: Sequential Two-Stage Grinding. Conventional milling operations involve two sequential size-reduction steps to arrive at the final particle size specification. The first stage of the size reduction process takes the as-received biomass and converts it (through grinding or chipping) into a product that can be further preprocessed. In the 2013 SOT scenario, the first-stage size reduction is followed by drying and second-stage size reduction. The 2013 SOT configuration of the first-stage grinding/chipping process uses a 2 to 3-in. screen for coarse size reduction. This size and type of screen provides enough size reduction for subsequent drying and final grinding.

The role of the second-stage grinder is to reduce the particle size further in order to meet particle size distribution requirements. A typical second-stage size reduction process will use a 19 to 25-mm screen to produce a mean particle size of 2.75 to 3.25 mm. While conventional milling processes achieve the desired mean particle size, they often have wide particle size distributions, with a large percentage of undersized particles referred to as fines.

3.3.1.2 Fractional Milling Design Basis. An analysis of the particle size distributions of the milled biomass after first-stage grinding shows that much of the material already meets particle size specifications. With the conventional, two-stage grinding approach, the material is further processed through the second-stage grinder, which results in over processing, generation of more fines, and needless consumption of additional grinding energy.

The fractional milling design solves this problem by introducing a separations step between the first and second-stage grinding operations to remove the material that already meets the size specification, thereby passing on only the remaining oversized material for further size reduction. As an example, consider the sieve analysis of the corn stover grind fractions shown in Figure 19. This chart shows the sieve fractions that result from hammer mill screen sizes ranging from 1 to 6 in. Assuming a particle size specification of 1/4-in. minus (i.e., all material passing a through a 1/4-in. screen), the data show that over 75% of the material processed through a 1-in. screen and about 45% of the material processed through a 6-in. screen can bypass the second-stage grinder. The result of this approach is a tighter particle size distribution, reduced fines, and reduced grinding energy consumption.

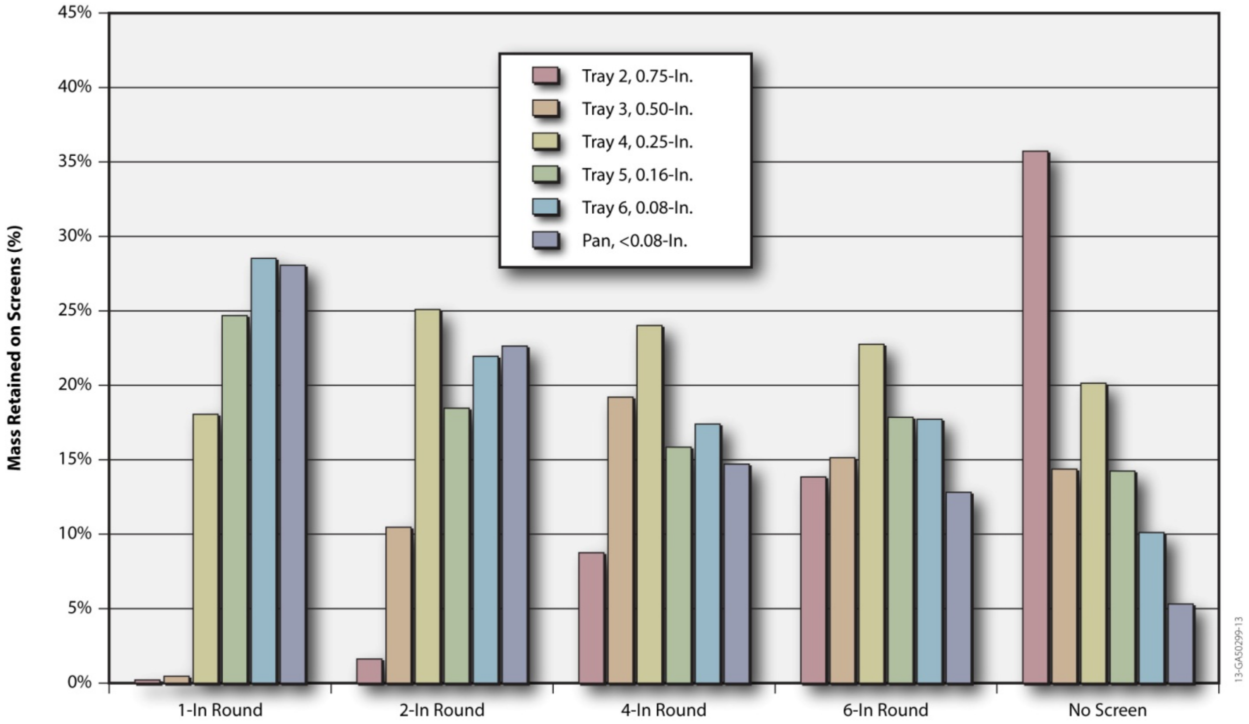

Figure 19. Particle-size distributions for five grinding scenarios.

With conventional, two-stage milling, the choice of the screen size in the first-stage mill is based on balancing energy consumption and mass flow rates through the two operations. Figure 20 shows the specific energy consumption (i.e., total consumed power) data for milling corn stover through a combined two-stage process. In these tests, the screen size of the first-stage hammer mill grinder was varied from 3/16 to 6 in. as shown on the chart. The second-stage hammer mill grinder was configured with a 3/16-in. screen for all tests. The highest energy consumption is observed when size reducing in a single pass through the first-stage grinder. These tests reveal that it often is very difficult to optimize a coupled, two-stage-size reduction process, because the second-stage mill often regulates the capacity of the first-stage mill. For a specific material and moisture content, the system, whose results are shown in Figure 20, was operating in “a sweet spot” (where capacities are evenly matched and grinding efficiencies are the greatest) when either a 1 or 2-in. screen in the first-stage grinder was used. The data show that with larger first-stage screen sizes, the second-stage grinder has to work harder, reducing the capacity of both itself and the upstream grinder feeding.

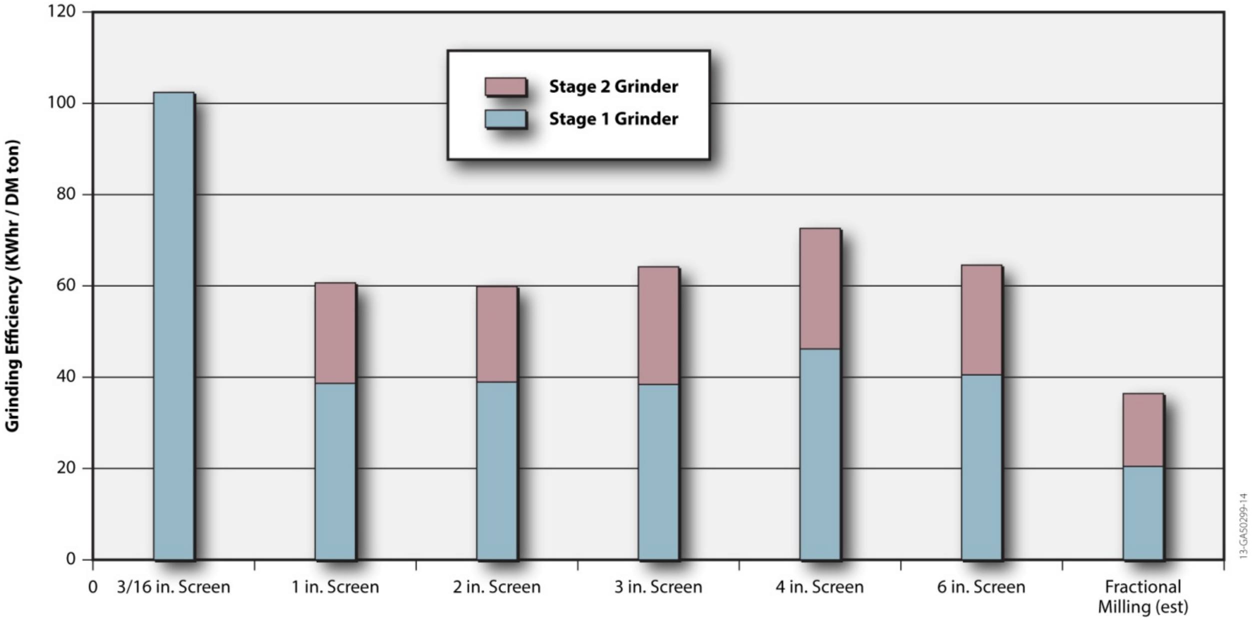

Figure 20. Comparison of conventional, two-stage grinding and fractional milling.

Decoupling the two sequential grinding operations provides an opportunity to optimize the two systems independently. For example, when the first-stage grinder is operated alone and the throughput is not constrained by the throughput of the second-stage grinder, the specific energy consumption of the first-stage grinder is reduced substantially (Figure 21). Optimization of the first-stage grinder for the fractional milling design is accomplished by using a 6-in. screen to maximize throughput and to minimize the amount of fines produced. Extrapolation of the specific energy data shown in Figure 21 to estimate a design basis for operating with a 6-in. screen provides an estimated specific energy of 12 kW-hr/ton. This is about a 70% reduction in energy compared to the current 2013 SOT.

Hammer mill systems tend to be highly sensitive to biomass moisture content, with energy consumption increasing dramatically as moisture content increases. This is illustrated in Figure 22, which shows that the sensitivity to moisture also varies with screen size. The majority of the data used in this design to support technical targets for fractional milling was derived from hammer milling of dry (i.e., approximately 15% moisture) biomass. Therefore, when establishing the fractional milling design basis, it is necessary to first develop the targets based on a dry biomass scenario and extrapolate using more limited data sets to a higher moisture scenario.

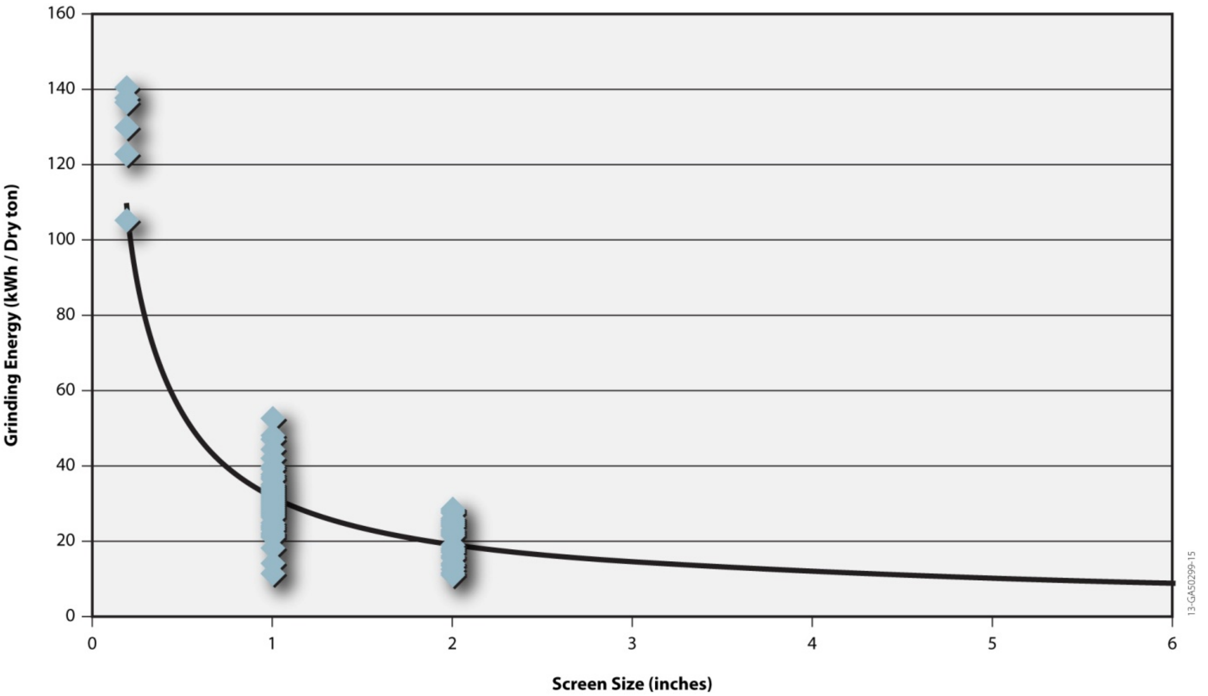

Figure 21. Grinding energy and throughput is highly dependent on screen size.

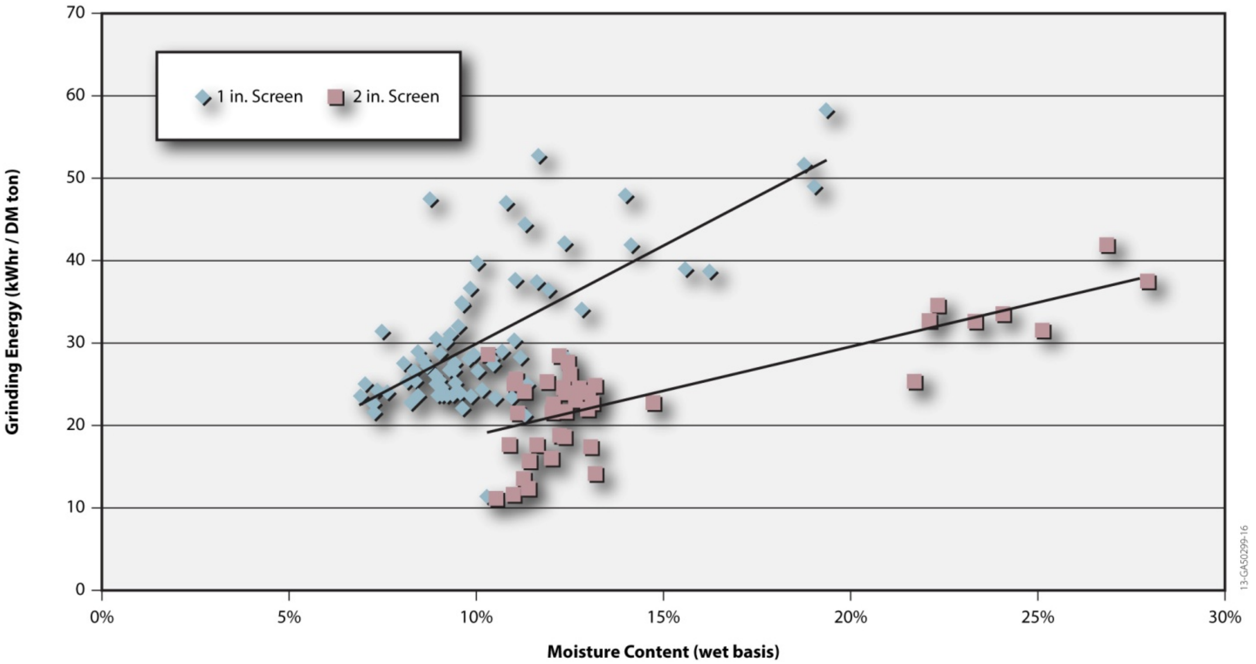

Figure 22. Hammer mill energy consumption is highly dependent on biomass moisture content.

3.3.1.3 ***Fractional Milling Dry Biomass.*** In this scenario, the data presented in Figures 19, 20, and 21 are used to estimate the expected performance of a fractional milling design for processing dry (i.e., approximately 15% moisture) herbaceous biomass.

First-stage size reduction: As explained above, decoupling the first and second-stage size reduction processes allows us to independently optimize the two systems. This is accomplished using a first-stage hammer mill with a 6-in. screen to maximize throughput and to reduce the amount of fines that are typically generated when using smaller screens. According to Figure 21, we estimate that the energy consumption for first-stage milling to be about 10 kWhr/ton.

Second-stage size reduction: The design basis of the second-stage grinding process in this scenario assumes that the decoupled fractional milling process will allow the second-stage grinder to operate at the minimum energy requirements (21 kWhr/ton) shown in Figure 20.

Separation: The fractional milling design inserts a separator between the first and second-stage comminution processes to separate the material from the first-stage comminution process that meets the size specification from those that are oversized and require further processing through second-stage comminution. Based on a 0.25-in. particle size specification, the separator will be configured with a 0.25-in. screen; therefore, only the material that is retained on the screen will be conveyed to the second-stage mill. Using the particle-size distribution data shown in Figure 19, we assume that following the first-stage hammer milling through a 6-in. screen, approximately 45% of the material will pass through the 0.25-in. separator screen, and the remaining 55% will be passed to the next mill. With only 55% of the material requiring further processing through the second-stage grinder, the estimated effective specific energy consumption for second-stage fractional milling is 12 kWhr/ton (21 kWhr/ton multiplied by 0.55).

3.3.1.4 Fractional Milling High-Moisture Biomass. Considering that the 2017 Design Case includes preprocessing of higher-moisture biomass, the design basis for fractional milling of dry biomass requires an additional adjustment of the specific energy assumptions for both the first-stage and the second-stage to account for the increased energy requirements due to moisture.

First-stage size reduction: Data for single-stage grinding (Figure 22) shows that the sensitivity of energy consumption to moisture content decreases with an increasing screen size. According to Figure 22, as moisture increases from 15 to 30%, grinding-specific energy increases by 85 and 65% for 1-in. and 2-in. screen sizes, respectively. Assuming this trend continues, a 6-in. screen will be much less sensitive to moisture content than the 1 and 2-in. screens shown. We estimate that energy consumption with a 6-in. screen will increase by about 50% as moisture content increases from 15 to 30%. Applying this to the first-stage energy consumption assumed in the dry scenario above, the estimated specific energy consumption for first-stage hammer milling increases from 10 kWhr/ton at 15% moisture to 15 kWhr/ton at 30% moisture.

Second-stage size reduction: A limited INL data set indicates that the 21-kWhr/ton energy consumption measured for hammer milling corn stover at 15% moisture (Figure 20) increases to about 60 kWhr/ton at 30% moisture. For the 2017 Design Case, we assert that improvements to comminution systems are achievable to reduce the sensitivity of these systems to biomass moisture content. While improvements to hammer mill systems may be achieved, shear milling technology generally is considered a better option for higher-moisture materials. A preliminary data set obtained from testing at INL of a prototype shear mill from an industry collaborator suggests that shear mill technology may be capable of reducing comminution energy requirements at higher moisture contents to the level achieved with hammer milling at the lower moisture levels. Accordingly, a technical target of 21 kWhr/ton is established for the 2017 Design Case second-stage size reduction process (taken from the 2-in. screen data shown in Figure 20).

Separation: The separations target for the high-moisture scenario is the same as the low-moisture scenario discussed above. Achieving this target may be more difficult at higher moisture levels, because the higher-moisture material will likely be tougher and less prone to shattering than the low-moisture material. Nonetheless, 45% of the material passing through the 1/4-in. separator screen is established as the target for the 2017 Design Case separation design basis. As was described for the dry fractional milling scenario, this separations target results in effective energy consumption for second-stage comminution of 15 kWhr/dry T (calculated as 21 kWhr/dry T times 0.55); the total effective energy consumption target for fractional milling is 35 kWhr/ton.

The fractional milling design basis is summarized in Table 10. Preprocessing starts with an initial (Stage 1) coarse size reduction using a 400-hp horizontal grinder configured with a 6-in. screen. Upon exiting the first-stage grinder, the coarse-ground material passes through a separator that is configured with a 1/4-in. screen. The fraction that meets the size specification will pass through the screen and move onto densification, while the fraction that is retained on the screen will be conveyed into the second-stage size-reduction process for final milling to the particle size specification. The fractional milling process will reduce the total effective energy consumption for biomass size reduction by about 60 and 70% for dry (15%) and wet (30%) biomass, respectively. Note that this calculation is based on the effective energy consumption for second-stage comminution (see footnote to Table 10).

Table 10. Size-reduction design basis.

	2013 SOT		2017 Target	
	Stage 1	Stage 2	Stage 1	Stage 2
Screen size	2 in.	1 in.	6 in.	1 in.
Comminution energy at 15% moisture (kWhr/dry T)	39	21	10	21*
Comminution energy at 30% moisture(kWhr/dry T)	40	60	15	21*
Separations at 15% moisture (percent passing 1/4-in. screen)	100	100	100	55
Separations at 15% moisture (percent passing 1/4-in. screen)	100	100	100	55

* The effective specific energy is reduced by 45% (to 12 kWhr/dry T), because only 55% of the material is processed in Stage 2 due to fractional milling.

3.3.1.5 *Fractional Milling Cost Estimation.* Factional milling cost estimation is based on vendor-supplied information and equipment performance from typical machine performance and process demonstration unit data (Table 11).

Table 11. Fractional milling cost estimates.

	2013 SOT (2011 $/dry T)	2017 Target (2011 $/dry T)
	Total	*Total*
Grinder 1	16.80	5.10
Separations	NA	5.00
Grinder 2	11.60	2.40
Total	28.40	12.50

3.3.2 Drying and Densification

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

3.3.2.1 2013 State of Technology: Conventional Pelletizing. Conventional biomass pellet production (Figure 23) includes initial size reduction to a 2- in. particle size, followed by drying to 10 to 12% moisture content (wet basis) using a rotary drier. The dried biomass is then passed through a second-stage grinding process to reduce the particle size to less than 3/16-in. (typically to 2 mm), steam conditioned, and pelletized (Tumuluru et al. 2010, 2011). Drying is the major energy consumption unit operation in this process, accounting for about 70% of the total pelletization energy.

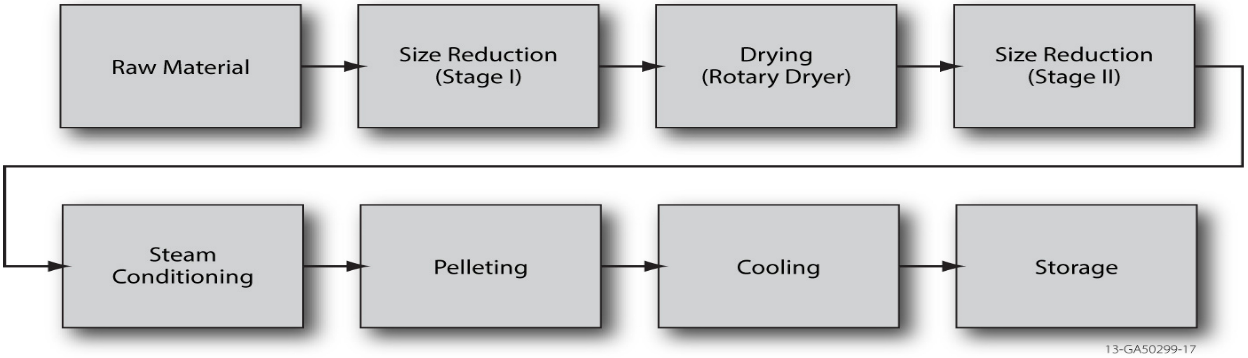

Figure 23. Conventional pelletization process.

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

This process has been demonstrated at INL where corn stover, ranging in moisture from 28 to 38%, was preheated at 110°C for 3 to 4 minutes prior to pelleting in a laboratory flat-die pellet mill using both 8 and 6 mm dies. The pellets exited the mill at 20 to 30% moisture content and, after drying, exhibited densities greater than 30 lb/ft^3 and durabilities greater than 95%. The specific energy consumption was found to be in the range of 40 to 100 kWhr/ton (U. S. DOE Bioenergy Technologies Office Peer Review 2013).

The reduction in drying energy is the key advantage of this approach (Figure 24). First, the process uses the heat generated in the pellet die to partially dry the material. Second, drying the pellets offers cost and energy advantages over drying loose, bulk biomass. Loose biomass typically is dried in a concurrent-flow rotary dryer. Rotary biomass dryers typically operate at temperatures of about 150 to 160°C, have greater particulate emissions, greater volatile organic compound emissions, greater fire hazard, a large footprint, and often have difficulty in controlling the material moisture. With the increased density, the reduced tendency for material to become entrained in the air flow, and the increased heat transfer coefficients compared to loose biomass, more efficient drying technologies options are available for drying pellets. A cross-flow dryer (common in grain drying) operates at temperatures less than 100°C, reduces the particulate and volatile organic compound emissions, and will have better temperature distribution. A comparison of pellet properties and energy balances for conventional and high-moisture pelletization processes is given in Table 12. The table shows 2017 Design Case targets to achieve a 40 to 50% reduction in the total pelletization and drying energy.

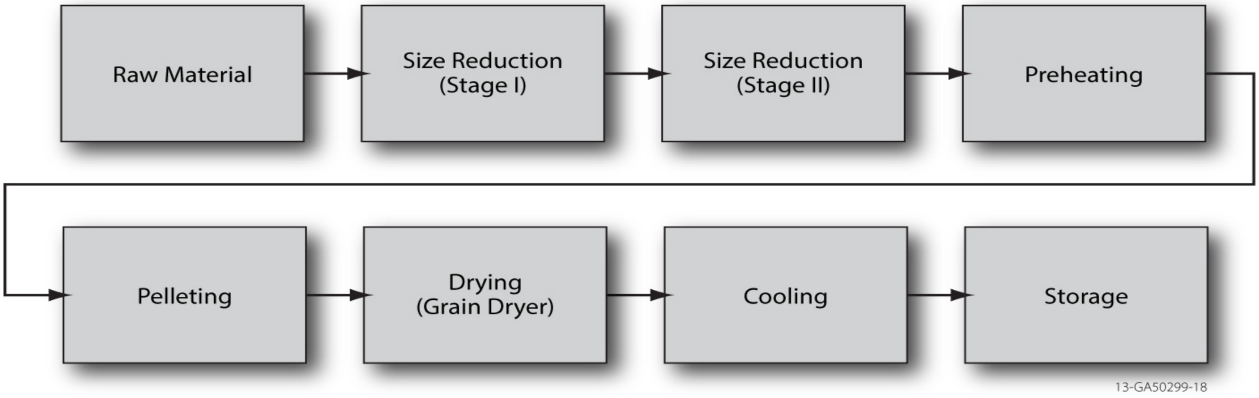

Figure 24. High-moisture pelletization process.

Table 12. Drying and densification design basis.

	2013 SOT	2017 Target
Infeed Moisture	30%	30%
Dryer Moisture Reduction	18%	11%
Densification Moisture Reduction	3%	10%
Final Pellet Moisture	9%	9%
Densification Energy	75 kWhr/dry T	50 kWhr/dry T
Drying Energy	350 kWhr/ton	100 kWhr/ton
Pellet Properties		
Unit Density	70 lb/ft^3	65 lb/ft^3
Bulk Density	40 lb/ft^3	35 lb/ft^3
Durability	Greater than 97.5%	Greater than 97.5%

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

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

3.3.2.3 Cost Estimation for High-Moisture Densification. The cost of densification was estimated using vendor-supplied information and the capacity and energy assumptions shown in Table 13.

Rotary drying costs associated with the 2013 SOT were based on data supplied by Anco-Eaglin, Inc. As described above, because of the similarity of pellets and grain, grain drying technology is the basis of the 2017 Design Case. Accordingly, grain drying costs also EW the source of the pellet drying cost estimate. Using a grain drying calculator found at Iowa State (Iowa State University 2013), we estimate the cost of drying grain of a similar moisture content to be $10 to $14/ton. Estimated pellet drying costs were reduced from these values because we assume that the porous nature of pellets and less structural heterogeneities in pellets will promote more rapid and uniform drying compared to grain that has the outer pericarp layer that limits moisture transfer.

Table 13. Drying and densification cost estimates.

	2013 SOT (2011 $/dry T) *Total*	2017 Target (2011 $/dry T) *Total*
Drying	15.20	5.60
Densification	7.70	4.40
Totals	22.90	10.00

3.3.3 Formulation/Blending

3.3.3.1 Overview. Feedstock formulation is not a new concept in many market sectors. For example, different grades of coal are blended to reduce sulfur and nitrogen contents for power generation (Boavida et al. 2004, Shih and Frey 1995), grain is blended at elevators to adjust moisture content (Hill 1990), animal feeds are blended to balance nutrient content (Reddy and Krishna 2009), and high-ash biomass sources are mixed with low-ash coal to allow their use in biopower (Sami et al. 2001). However, blending/formulation is not part of the baseline design.

3.3.3.2 Formulation Design Basis. To meet feedstock specifications required for various conversion pathways, formulation of specific mixtures of feedstocks will likely be required. Examples include mixing high and low-cost feedstocks to meet cost targets, mixing high and low-ash feedstocks to meet an ash target, mixing of high and low-carbohydrate feedstocks to meet a yield target, and mixing easily and poorly reactive feedstocks to meet a convertibility target. An example of blending to meet an ash and moisture specification is shown in Table 14.

Table 14. Feedstock formulation/blending of ash and moisture contents*.

Content Delivered to Biorefinery Infeed	Multi-pass	Single-pass	Switchgrass	MSW	Final Blend
Ash content (wt. %)	3.5	7	4	10	**4.9**
Moisture content (%, wet basis)	9	9	9	9	**9**
Carbohydrate content (wt. %)	64	57	57	57	**59**

*Corn stover and switchgrass composition data were obtained from the INL Biomass Library. See Appendix A for MSW ash and carbohydrate data.

Assumptions for the formulation design basis are as follows:

1. Blended feedstocks will be selected and developed to achieve conversion yield specifications. It currently is unknown how blended feedstocks will perform in the conversion pathways. The simplest assumption is that the performance of the blended feedstocks would be the sum of performances of each individual component. However, two, small-scale studies demonstrated that the performance of blended feedstocks ranged from under to over performance, depending on the conditions assessed. In the first study, Yu and Chen (2009) examined a blend of wheat straw, barley straw, hardwood, and softwood subjected to three different types of pretreatments: dilute acid, lime, and soaking in aqueous ammonia. After pretreatment, the feedstocks were hydrolyzed using commercial cellulose enzymes

(NREL LAP-009) and sugar yields were measured. Ethanol yields also were determined using simultaneous saccharification and fermentation (NREL LAP-008).

For the dilute acid and soaking in aqueous ammonia treatments, the yields of C6 sugars were lower than would be predicted by simple summation, while the C6 sugar yield was slightly higher than predicted for the lime treatment. However, the opposite trends were observed for ethanol production, with higher ethanol production for dilute acid and soaking in aqueous ammonia and lower production for lime treatment. It is not clear from the report whether or not these differences were statistically significant. It also was shown that yields of both C6 sugars and ethanol were lower than predicted for non-optimized pretreatments. This may indicate that the pretreatment has to be optimized for the most recalcitrant component, which may lead to formation of sugar degradation products and fermentation inhibitors. In the second study, Arora et al. (2012) examined a mixture of corn stover, switchgrass, eucalyptus, and lodgepole pine. This mixture was pretreated with an ionic liquid (i.e., 1-ethyl-3-methylimidazolium acetate) and the resulting sugars measured. The mixed feedstock released more glucose than would be expected from the sum of the individual feedstocks.

2. Individual feedstocks will be pelleted at depots for shipment to biorefineries. At the biorefinery, the pelleted feedstocks will be unloaded and conveyed into individual bunkers for storage. Pellets of the different blendstocks will be metered out into the bunkers in the ratios required of the blends, crushed (using a pellet crusher), and then mixed prior to insertion into the conversion process.
3. Material will be metered from individual bunkers onto a conveyer and will be thoroughly homogenized during this process with no segregation. Mixing of solids occurs in many industries and is often problematic when solids of varying density, shape, and size are blended. This often leads to segregation, either during the mixing or while being transported to its destination. Mixing of solids is considered a trial-and-error process due to these issues.
4. The expected unit operations for formulation are shown in Table 15.

Table 15. Feedstock formulation design basis.

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

Research currently is ongoing at INL to examine the compatibility of various feedstocks in formulated blends, with an initial focus on the reactivity of blends versus the individual feedstocks. Blends will be developed for several regions of the United States using the least-cost formulation model as a starting point and will incorporate feedstocks with varying levels of reactivity (e.g., herbaceous, woody, and MSW). Reactivity for the fermentation pathway will be investigated first, with expansion into the other DOE conversion pathways in later fiscal years. Reactivity for the fermentation conversion pathway will be measured as production of sugars using dilute acid pretreatment followed by enzymatic hydrolysis. Production of sugar decomposition products and other inhibitors also will be monitored. Hydrolysis conditions will be optimized for each feedstock and then each of the optimum conditions used on the formulated feedstock. Research is planned to examine mixing issues associated with blended feedstocks. A survey of current state-of-the-art mixing technologies will be conducted, and those technologies relevant to feedstocks will be further examined to determine the best technology to ensure thorough homogenization without segregation.

While the costs for preprocessing of herbaceous feedstocks (e.g., grinding, chemical preconversion, pelleting, and drying) are addressed in other parts of the 2017 Design Case, MSW will require a different set of preprocessing options to produce a stable, high-quality feedstock.

3.3.3.3 Cost Estimation for Formulation. Formulation cost estimation was based on existing technology, vendor-supplied information and equipment performance (Table 16).

Table 16. Formulation cost estimation.

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

3.4 Transportation and Handling

3.4.1 Overview

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

Lignocellulosic feedstock handling operations currently operate at 40 to 50% of the design capacity. Handling operations depend on many factors, including biomass chemical composition, bulk density, and particle size and shape distribution. Lignocellulosic feedstocks inherently possess characteristics that inhibit handling (such as high cohesivity, low density, high compressibility, and high variability in particle size and shape uniformity). There are two main approaches to solving material handling problems: (1) engineer systems to specific materials or material properties and (2) engineer materials to feed into the equipment systems (Kenney et al. 2013).

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

3.4.2 Transportation and Handling Design Basis

As stated in Section 3.3, the 2017 Design Case includes formulation and densification to meet feedstock specifications and costs targets. Both of these active processes will improve feedstock handling operations through active controls. See Section 3.3.3 for further discussion on feedstock formulation and costs estimates for handling included in formulation estimates.

Given formulation and the specific quantities of individual feedstocks required, the average transportation distance (and even mechanism) will change based on feedstock type. In the 2017 Design Case, corn stover will be trucked from a local draw radius of about 25 miles (compared to 35 miles) while switchgrass will be trucked 15 miles. MSW will need to be transported from a larger metropolitan area to obtain the required quantities; therefore, it will be transported by rail (either by unit train or single car) from as far as 200 miles away. Corn stover and switchgrass will be loaded and unloaded at each location using a telehandler capable of moving 12-lb/ft^3 bales at 30 and 20% respective moisture contents. A 53-ft trailer and 800,000-GVW limits were assumed in all trucking operations. Transportation for corn stover and switchgrass will occur from a field side stack to a densification facility completely separate from the conversion location, but is within a minimal conveyor distance. MSW transportation will occur from the waste transfer station to a densification facility. Further transportation and handling assumptions are given as follows:

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

3.4.3 Cost Estimation for Transportation and Handling

The cost estimation for transportation and handling was based on vendor-supplied information and equipment performance from typical machines (Table 17).

Rail transportation costs were based on work from Searcy using a jumbo hopper car (Searcy et al. 2007) adjusted for U.S. conditions.

Table 17. Transportation cost estimates.

	2013 SOT (2011 $/dry T)	2017 Target (2011 $/dry T)
	Total	*Total*
Truck	11.50	8.30
Rail*	0.00	18.00

*For specific feedstocks only to obtain required quantity.

4. SUPPLY SYSTEM ECONOMICS

4.1 Delivered Feedstock Costs

Two requirements for the 2017 Design Case that were established early in this report are (1) achieving the $80 cost target when located outside the Midwest Corn Belt and (2) achieving biorefinery quality specifications within the $80 cost target. In Section 2, feedstock curves were developed for the 2017 Design Case scenario located in western Kansas. These curves included access costs (i.e., grower payment), logistics costs, and dockage costs (e.g., ash and carbohydrate dockage). Using these curves, it was determined that a feedstock blend of 60% corn stover, 35% switchgrass, and 5% MSW would meet the $80 delivered feedstock cost target, thus satisfying the cost criterion of the 2017 Design Case (see Table 18).

Table 18. Biochemical conversion feedstock design cost analysis.

Cost Element	Single-pass Corn Stover	Multi-pass Corn Stover	Switchgrass	MSW	Blend
Formulation Contribution	*35%*	*25%*	*35%*	*5%*	–
Grower payment/Access Cost	27.20	27.20	29.80	18.00	**27.70**
Harvest and collection ($/dry T)	10.50	19.20	15.40	–	**13.90**
Transportation ($/dry T)	8.70	8.30	7.20	18.00	**8.60**
Preprocessing ($/dry T)	23.40	23.40	19.70	19.70	**21.90**
Storage ($/dry T)	6.50	6.50	5.50	4.50	**6.10**
Handling ($/dry T)	1.90	1.90	1.90	1.90	**1.90**
Total Delivered Feedstock Cost ($/dry T)	**78.30**	**86.60**	**79.60**	**62.10**	**80.00**
Delivered Feedstock Specifications*					
Ash content (wt. %)	3.5	7	4	10	**4.9**
Moisture content (%, wet basis)	9	9	9	9	**9**
Carbohydrate content (wt. %)	64	57	57	57	**59**

*Corn stover and switchgrass composition data were obtained from the INL Biomass Library. See Appendix A for MSW ash and carbohydrate data.

Even though feedstock quality is represented in the cost curves with a dockage fee (in this case, ash dockage for multi-pass corn stover and MSW ash content in excess of the 5% ash specification [shown in Table 1]), the least-cost formulation approach does not guarantee that the lowest-cost feedstock meets spec. In fact, the 60% corn stover, 35% switchgrass, and 5% MSW blend actually exceeded the ash specification with a blended ash content of 6.1%. As a result, it was necessary to replace some of the higher-ash, multi-pass stover with lower–ash, single-pass corn stover in order to meet the ash specification (Table 18). The rationale for including both single and multi-pass stover is that because single-pass technology is a new technology requiring additional investment by farmers, it is unlikely it will fully replace multi-pass harvest by 2017. Sourcing 35% single-pass and 25% multi-pass corn stover assumes that about 60% of the stover will be single-pass and 40% will be multi-pass. This seems to be a reasonable assumption considering that the 60% may be harvested by a custom harvester and 40% by local farmers.

For the 2017 Design Case scenario located in western Kansas, it worked out that both the cost and quality criteria could be achieved through blending. However, there may be other scenarios where reaching the 5% ash specification for biochemical conversion will require the removal of silica. Methods for accomplishing silica removal include both fine grinding followed by triboelectrostatic separation and alkali-based processes that dissolve silica (CENNATEK 2011). A recent analysis for non-woody feedstocks estimated a net cost of $39.93 to $60.80/dry T for removal of alkali metals (up to 95%) by leaching, followed by removal of silica (up to 75%) by triboelectrostatic separation (CENNATEK 2011). With an $80/dry T feedstock cost target, these costs are too high to allow the use of chemical preconversion as an added unit operation in the current design; the existing feedstock supply chain operations and the grower payment leave little room for added cost. A detailed discussion of a chemical preconversion for ash removal is included in Appendix B. Therefore, for this report, we have selected feedstocks that can meet the ash specification in a blend with MSW.

The moisture and carbohydrate content of the blended feedstock also meet the specification for moisture content (i.e., less than 20%) and carbohydrate content (i.e., at least 59%). Because each blendstock is pelletized prior to blending, the pellets are dried to about 9 to 10% during pellet production, thereby fixing the moisture content of the blend. Similar to ash content, the carbohydrate specification is met by blending. The carbohydrate content of MSW varies depending on the particular fraction, ranging from 46% for yard waste to 64% for food waste. The MSW carbohydrate content shown in Table 18 is the average of yard waste (46%), food waste (64%), non-recyclable paper (55%), and C&D waste (61%). Because MSW is such a small fraction of the overall blend, even food waste blends out to a carbohydrate content of 59%.

5. CONCLUSIONS

This report establishes a plausible case for achieving the 2017 cost goals of delivering a biomass feedstock to the throat of the conversion facility at a cost of $80/dry T. The least-cost formulation approach that was presented in Section 2 illustrates the importance of solid cost estimates for determining the total cost of feedstock to a biorefinery, including grower payment (access costs), logistics costs, and quality/dockage cost. It also illustrates the importance of refining and updating these costs as analyses and data improve to better inform the estimates. The following conclusions are presented to document the specific areas that require additional attention to further strengthen and support the feedstock design detailed in this report.

Continued refinements of the biomass supply curves to represent the latest estimates for biomass grower payment are needed to support the least-cost formulation approach. Ultimately, translating *The Billion Ton Update* (U.S. DOE 2011) data from farm gate price to grower payment is necessary to establish better grower payment estimates. The grower payment estimates included in this report were calculated by subtracting our harvest and collection costs from the farm grate price. This erroneously varies grower payment inversely with harvest and collection costs (i.e., the higher our harvest collection costs, the less the grower is paid). Separating grower payment from farm gate price in *The Billion Ton Update* data would fix this problem.

As noted by reviewers, logistics costs are considered low because we do not include the cost of various business elements that would, in reality, be involved throughout a biomass feedstock supply chain. This was of little consequence to the Conventional Design case target that intentionally focused only on logistics costs. The 2017 Design Case, on the other hand, is meant to encompass total delivered feedstocks costs. Further, the complexity of a blended feedstock approach may introduce multiple business elements into the supply chain; therefore, it is important that logistics costs be updated to include the true cost of these business elements, including a return on investment.

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

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

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Appendix A

Municipal Solid Waste

MSW is attractive as a feedstock because it is available year-round, it already has an established infrastructure for collection and handling, and it has the potential to be low cost. MSW currently is a negative cost feedstock because municipalities paid an average of $49.27/ton in 2012, with a range from $18.43 in Idaho to $105.40 in Massachusetts for landfilling (Waste and Recycling News, July 20, 2012). While it is unlikely that MSW will be available to the biorefinery at negative costs because MSW will require processing to separate out the fractions of interest and will require other types of preprocessing to upgrade the quality, it likely will still be available at lower cost than other herbaceous feedstocks. An average composition of MSW is provided in Table A-1.

Table A-1. National average municipal solid waste composition.

Material	% Total MSW
Paper and paperboard	28.5%
Glass	4.6%
Steel	6.8%
Aluminum	1.4%
Other nonferrous metals	0.8%
Plastics	12.4%
Rubber and leather	3.1%
Textiles	5.3%
Wood	6.4%
Other materials	1.9%
Food	13.9%
Yard trimmings	13.4%
Misc. inorganic waste	1.5%

Candidate materials for the biochemical pathway include paper and paperboard, food, and yard waste. Of these, paper and paperboard are likely to have more value when recycled than as a feedstock for fuels; however, there is still a significant fraction of paper and paperboard that is non-recyclable, including coated paper and cardboard, polycoat material, glossy papers such as magazines, food-contaminated papers and cardboards, and any material with binders such as phone books.

Table A-2 shows generation rates for these fractions for 14 different state and/or regions. Of these fractions, food waste has the highest rate of generation and will be available year-round. Non-recyclable paper has the next highest generation rate and also would be available year-round. Yard waste has the lowest rate of generation and may not be available year-round depending on location.

Table A-2. Per capita generation rates for various fractions of municipal solid waste and construction and demolition waste (lb/person/day).

Location	Yard waste	Food waste	Non-recyclable paper	Untreated wood C&D waste
AZ – Phoenix[1]	0.40	0.29	0.11	0.03
CO - Boulder Co.	0.52	0.58	0.33	0.07
CO - Larimer Co.	0.19	0.39	0.34	0.12
CT	0.27	0.50	0.44	0.10
DE	0.46	0.66	0.61	0.38
HI	0.16	0.72	0.16	0.09
IA	0.18	0.53	0.40	0.22
IL	0.14	0.95	0.47	0.15
MA -eastern	0.17	0.89	0.47	0.15
MA-central	0.10	0.40	0.19	0.06
MN	0.07	0.41	0.40	0.15
PA	0.06	0.50	0.52	0.24
WA	0.17	0.54	0.22	0.14
WI	0.06	0.49	0.41	0.61
Average	0.21	0.56	0.36	0.18

[1] See references for information on the individual waste characterization studies.

Construction and demolition (C&D) waste is also a potential feedstock. This stream consists of waste materials generated during construction, renovation, and demolition from both residential and non-residential sources. In a 2009 report (EPA530-R-09-002), the Environmental Protection Agency (EPA) estimated that approximately 170 million tons of C&D waste was generated in 2003 in the United States, going to an EPA-estimated 1,900 C&D landfills, although more recently many localities are setting recycling targets for C&D projects (http://www.nyc.gov/html/ddc/downloads/pdf/waste.pdf). The composition of this waste stream is primarily wood, drywall, metal, plastics, roofing, masonry, glass, cardboard, concrete, and asphalt debris. The relative amounts of these materials vary greatly depending on the relative percentages of new construction versus renovation and demolition, as well as the type and size of structures being built, renovated, or demolished. The only fraction relevant to a biorefinery would be the woody material that consists of both untreated and treated (e.g., painted, stained, or varnished) materials. In this report, only untreated woody material is assumed to be used, because it is unknown whether the treated material would affect downstream processing of these materials. The per capita generation rate for untreated, woody C&D waste is shown in the last column of Table A-2. This rate is comparable to the yard waste generation rate and would be available only seasonally depending on location.

A feedstock that contains 5% MSW requires that 40,000 tons of MSW material be generated yearly for an 800,000-ton biorefinery. Using the generation rates from Table 1, yard waste, food waste, non-recyclable paper, and untreated C&D wood waste would require population centers of 1 million; 390,000; 610,000; and 1.2 million people, respectively, to support this amount of material. For yard waste and woody C&D waste, this could only be accomplished near fairly large metropolitan areas and would require that other herbaceous resources be available within that area. Food waste and non-recyclable paper waste relaxes this constraint with their smaller population requirements. A more likely scenario would be to use more than one of these fractions in the MSW portion of the feedstock.

Other considerations for these MSW fractions include moisture content, ash content, carbohydrate content, compatibility with other biorefinery operations, and obtaining a clean feedstream of these fractions from mixed MSW (Table A-3).

Table A-3. Physical parameters of solid waste.

Fraction	Moisture (%)	Ash (%)	Carbohydrate (%) (glucan+xylan)	Pretreatment Severity	Sorting Required?
Yard waste	43[1]	28[2]	463	More severe pretreatment may be needed[3]	No, if curbside recycling is in place
Food waste	37[1]	NA	644	No pretreatment needed[4]	Yes
Non-recyclable paper	51	19[5]	555	Lower severity pretreatment needed[5]	Yes
Untreated C&D wood	13[1]	6.5[2]	616	Higher severity pretreatment required[6]	Yes, unless onsite sorting occurs

[1] Valkenburg et al. 2008

[2] Shi et al. 2009

[3] Gustafson et al. 2009

[4] Yan et al. 2012

[5] Unpublished data generated at INL

[6] Cho et al. 2011 (includes mannan content)

Both yard waste and food waste tend to be high moisture materials; keeping the carbohydrate content stable during collection, storage, and preprocessing will be a challenge. These materials are above the target moisture content of 20% and will require drying. The non-recyclable paper and untreated C&D wood are both below the target moisture content and can be readily blended with other herbaceous materials. With a final ash specification of 5% for the blended feedstock, only the woody waste could be readily used without ash reduction if blended with lower ash materials. The yard waste and non-recyclable paper would likely need some kind of chemical preconversion treatment (such as leaching) to remove ash prior to blending (see Appendix B). The carbohydrate target for the blended feedstock is 59% total glucan plus xylan. Both food waste and untreated C&D woody waste have carbohydrate levels above the target and could be utilized in the blend to increase total carbohydrates if needed. However, in the case of the untreated C&D waste the carbohydrate content also includes mannan content. Without the mannan content, the glucan plus xylan is 52%. The non-recyclable paper is close to the specification, but would need to be blended with higher carbohydrate-containing materials. The yard waste had the lowest carbohydrate content and may not be suitable as a blend because of this low carbohydrate content.

Currently, it is unknown how any of these materials will respond to downstream biorefinery operations such as pretreatment, saccharification, and fermentation. Gustafson et al. (2009) examined yard waste as a potential feedstock for ethanol production. They found that the sugar yields from after the saccharification were very low and attributed this to insufficient pretreatment severity due to the presence of woody materials in the waste stream. It is unclear if this also would be the case if just grass waste were utilized. Kim et al. (2011) examined ethanol production from food waste and determined that a chemical pretreatment step was not needed and got good yields of carbohydrates after enzymatic saccharification. However, due to the nature of food waste, they found it necessary to add an amylase to the enzyme mixture to release sugars from starchy food sources and also speculated that a protease would help with sugar yield. Paper waste has much of the lignin and xylose removed during the pulping process and would not require as severe of pretreatment conditions as required for herbaceous material such as corn stover. If paper waste is pretreated at the same severity as herbaceous materials, there is a likelihood that acid degradation products could form and reduce carbohydrate yields and cause inhibition during saccharification and fermentation. Conversely, woody C&D waste consists primarily of softwoods and requires higher-severity pretreatment to get comparable yields to herbaceous materials. A recent study with C&D woody waste required a two-stage acid hydrolysis, with concentrated acid in the first stage and diluted acid in the second stage to achieve a 90% yield of ethanol (Cho et al. 2011).

An established infrastructure is in place for collection and handling of MSW, which is already paid for by the waste generators. In many locations, recycling programs also are in place to separate out various materials by consumers. Additionally, many municipalities transport MSW to material recovery facilities for further sorting to increase recycling. In these locations, fractions considered here would likely be available at low cost to the biorefinery. Yard waste, in particular, is often collected separately by communities and would need no further separation. Non-recyclable paper would require some sorting to remove it from recyclable materials in areas where curbside paper recycling occurs. In other areas where MSW is in a single stream, the costs of sorting may be prohibitive. Food waste is generally always part of the general MSW stream and would require sorting, although sourcing materials from restaurants, grocery stores, and so forth may help with this. C&D waste generally is not part of the residential MSW stream and is handled by construction contractors. In some locations, onsite sorting occurs by the contractors and the untreated woody fraction would be readily available. An internet survey of landfills and transfer stations showed that those facilities will only receive untreated woody material and generally compost these materials. These facilities also would be a source for this material. In areas where onsite sorting does not occur, some type of sorting to remove treated wood and non-woody materials would be required.

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Appendix B

Chemical Preconversion

What Is Chemical Preconversion?

Chemical preconversion is an element of advanced preprocessing that utilizes physical, chemical, or biological modifications of the biomass to allow more stable, more consistent, cheaper, and/or more easily converted biomass feedstock to bioconversion facilities. Methods of chemical preconversion may include low-temperature solvent or catalyst washes; low-severity, liquid-phase catalytic reactions that effect changes in the structure of the lignocellulose but avoid production of soluble saccharides; and low-severity, gas phase reactions or polymer solvation and redistribution. Deployment methods include leaching by spraying, in slurry tanks with subsequent clarification, static treatment in wet storage, and liquid or gas phase reactors (Thompson et al. 2013).

Chemical preconversion can accomplish a number of important benefits for both the feedstock interface and for ultimate end users, including (a) ash reduction via removal of structural ash and/or soluble and insoluble nonstructural ash; (b) feedstock cost reduction by improving densification, reducing grinding energy requirements, and/or improving the flowability; (c) improving feedstock storage stability by decreasing wettability; and (d) reducing biorefinery pretreatment severity by partially depolymerizing hemicellulose and/or lignin (Thompson et al. 2013). The long-term goals of chemical preconversion at INL are to improve feedstock characteristics for supply chain logistics, reduce the cost of feedstock, and improve feedstock characteristics for the end user.

Estimated Cost of Feedstock Ash to the Biorefinery's Bottom Line

For the sugars/fermentation pathway to ethanol, Bonner et al. (2013) estimated increased feedstock costs of \$4.88 to \$20.23/dry T of processed corn stover, compared to biorefinery processing costs arising from corn stover ash levels that range from 10 to 25% (this compares to design base case levels of 5% ash; Humbird et al. 2011). While the analysis did not include the additional capital and operating costs due to the higher amount of throughput required and the larger amounts of ash to be disposed, it showed that the added biorefinery costs from ash in the feedstock can amount to as much as \$1 per dry matter ton per percentage point of ash above 5%. In the study, two-thirds of the cost increase was attributed to feedstock replacement costs to maintain throughput of convertible material and one-third of the increase was attributed to increased ash disposal costs, indicating that the added costs can be traced primarily to silica content, because silica comprises 60 to 70% of the ash in corn stover. The pretreatment employed in the biochemical conversion design case was dilute acid pretreatment; it is notable that the costs of other pretreatment technologies (e.g., low-solids alkaline pretreatments at higher temperatures) may not be as sensitive to ash content.

For comparison, Jones et al. (2013) estimate that increasing ash content from the fast pyrolysis/hydrotreating bio-oil design base case of 0.9 to 1.9 wt% leads to a \$0.21/gallon of gasoline equivalents (gge) increase in the minimum fuel selling price, which translates to an additional cost of nearly \$19/dry T of feedstock processed for a single percentage point increase in ash content. Additional simulations were not performed to determine the potential linearity of product fuel cost with additional increases in ash content, nor were the contributions of specific ash constituents considered with regard to reactivity, choosing rather to focus only on total ash content. The difference primarily was due to product yield losses because of the higher content of alkali metals. Ash disposal costs were insignificant compared to the increase in price due to yield losses at about \$0.01/gge or about \$0.90/dry T of feedstock processed. Therefore, cost increases owing to ash sensitivity in the pyrolysis/case for woody feedstocks are not derived from silica content, but from side reactions catalyzed by alkali metals and to a lesser extent alkaline earth metals (Vamvuka and Sfakiotakis 2011).

Clearly, there is justification for ash removal early in the feedstock supply chain provided it can be removed at or below the added costs at the biorefinery, depending on the feedstock or feedstock blend components, the specific ash components that lead to the increased costs, and the conversion technology being utilized at the biorefinery.

Chemical Methods for Ash Removal

Chemical preconversion treatments for ash reduction include leaching, chelation, and chemical treatments applied to remove contaminants and toxins (INL 2012), to reduce grinding (Zhu et al. 2010) and densification costs (Eranki et al. 2011), and to improve the pretreatability and/or bioconvertability of the feedstock for the end user (Zhu et al. 2010). Enzymatic (Smith et al. 2009) and whole-cell biocatalyst treatments (Tian et al. 2012) also can be considered to be chemical preconversion. Thermal treatments such as torrefaction, which causes chemical modification of the biomass, also is a form of chemical preconversion, although not generally suited for downstream bioconversion processes (Tumuluru et al. 2011).

An example breakdown of ash composition for corn stover is shown in Table B-1. Data in Table B-1 show the oxide composition in the final ash after ignition. Ash components include soluble ions originating from physiological activity, insoluble minerals from entrained soil and from silica deposition, and heteroatoms present in biomolecules. Methods for removal of these are presented in the following subsections.

Table B-1. Ash composition of initial, untreated corn stover. Chlorine was detected using a halogen test for chloride, bromide, and iodide. The results are reported as wt% chloride with respect to dry biomass. The ash components are reported as percent of total ash by mass in oxide form.

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Average	95% CI
Cl^- (ug/g)	414	410	409	410	408	411	410	1.61
Total Ash (%)	8.07	8.69	7.46	8.20	8.25	8.50	8.20	0.31
Composition of ash by %								
Al_2O_3	2.83	3.27	2.55	2.83	2.82	3.08	2.90	0.18
CaO	8.37	7.71	7.38	7.52	7.62	7.55	7.69	0.26
Fe_2O_3	2.90	2.88	2.02	2.40	1.99	2.95	2.52	0.33
MgO	4.14	3.97	4.14	4.07	4.04	3.95	4.05	0.06
MnO	0.08	0.08	0.07	0.07	0.07	0.08	0.08	0.00
P_2O_5	1.49	1.45	1.55	1.58	1.58	1.53	1.53	0.04
K_2O	11.59	10.91	11.74	11.33	11.17	11.17	11.32	0.22
SiO_2	65.90	66.82	65.02	67.75	68.28	65.90	66.61	0.90
Na_2O	0.45	0.52	0.44	0.48	0.49	0.49	0.48	0.02
SO_3	1.85	1.89	1.61	1.90	1.63	1.81	1.78	0.09
TiO_2	0.14	0.15	0.13	0.13	0.14	0.15	0.14	0.01

Soluble Ash Components

Soluble ash components, both introduced and physiological, can be removed from biomass by low-temperature leaching with water, dilute acids, or dilute alkali. These include Cl^-, K^+, Na^+, Mg^{2+}, Mn^{2+}, Ca^{2+}, and abiologic P^{5+} (Werkelin et al. 2010). Low-solids treatments are better for ash removal because ash solubility can be an overriding factor; however, large volumes of briny water must be recovered and treated. High-solids treatments have the benefit over low-solids treatments because they do not immediately generate a waste stream, and they do not offer the opportunity to dissolve significant ash (Thompson et al. 2013). It is notable that some high-solids treatments require significant washing to remove reacted biomass fragments; those high-solids treatments also would achieve some ash removal. After leaching is completed, the brine solution must be disposed (Thompson et al. 2013). Because of the large volumes of brine produced, reverse osmosis has been considered as a cost-effective method to reduce brine volume (Jenkins et al. 2003); however, mild hydrothermal treatment with chelation does provide an opportunity to mitigate ash with little effect on cellulose and hemicellulose (Reza et al. 2013).

Insoluble Ash Components and Heteroatoms

Insoluble ash constituents (such as silica and other metal oxides) and intracellular (structural) salts and protein and DNA-derived heteroatoms (including nitrogen, phosphorus and sulfur) require chemical preconversion treatments that utilize more severe conditions of higher (or lower) pH and elevated temperatures (Thompson et al. 2013). The added catalyst is necessary to disrupt cell wall structure, allowing the release and dissolution of the ash components. In general, acids are more effective at removing structural salts, while alkali is required to solubilize silica. Alkali is more effective at disrupting cell wall structure than acids at low temperatures; however, it is both more costly and more expensive to recover (Thompson et al. 2013).

Different types of biomass or different biomass tissues or fractions will require different methods of preconversion because of their different chemical and structural characteristics (Thompson et al. 2013). Hardwoods and softwoods are high in lignin; therefore, they are susceptible to oxidative preconversion methods, whereas grasses with high acetyl content can be modified with mild acid or alkaline treatments. Agricultural residues may contain a high ash content and, thus, a mild liquid treatment could act as a leaching process. In the case of different plant tissues or fractions of a given biomass type, differences can be significant. For example, leaves and sheaths of corn stover would require less severe chemical preconversion conditions than stems because of their higher surface-to-weight ratio. Similarly, bark contains much higher ash concentrations than do clean wood chips and is more recalcitrant. Depending on the feedstock and preconversion chemistry employed, lower-severity chemical preconversion may be better suited to highly digestible feedstocks. In any event, structural modification of the lignocellulose matrix without significant removal of convertible organics is preferred.

Chemical Preconversion Design Basis

Leaching Technologies for Soluble Ash

Alkali metals can be removed easily from biomass after grinding with simple water leaching. Alkaline earth metals can be effectively leached with the addition of acid and heat. Simple leaching with water can be accomplished by spraying while in-field (after windrowing), with detraction of the potential for high losses of convertible sugars. Engineered systems for leaching are typically simple in design, allowing for solvent (water or dilute catalyst solutions) addition, collection, and recycle (if necessary); leachate neutralization and treatment (or disposal); and drying. A simple design for leaching in a depot is a drain and fill leaching system (Jenkins et al. 2003). In this design, chopped or ground biomass is conveyed into a leach tank and leach solution (with or without catalyst) is added to achieve the desired percentage solids. Because leaching is solubility limited, lower percentage solids are preferred; however, if more than one leach cycle can be accommodated, then higher percentage solids could be used, thereby reducing water usage. After leaching, the leach solution is drained to a waste tank, and fresh water is introduced to wash the remaining soluble ash from the biomass (this may occur in several cycles as well). The wash liquid is drained to the waste tank as well. Once washing is completed, the solids are conveyed from the leach tank through a roller press, which mechanically dewaters the biomass. The solids are conveyed to a wet mill and then to a wet pelleting mill. The liquids in the waste tank are neutralized and processed by reverse osmosis, from which the permeate is recycled to the makeup water and the retentate is pumped to wastewater treatment. These operations and the accompanying assumptions are summarized in Table B-2.

Table B-2. Expected unit operations and assumptions for the application of a drain and fill leaching system for the removal of soluble ash from biomass in a feedstock depot.

Expected Unit Operation	Assumptions
Convey chopped herbaceous biomass or shredded MSW to leach tank	• Herbaceous: 2-in. screen • MSW: 6-in. screen
Leaching (water or dilute acid, steam heat with agitation)	• Volume tied to depot throughput • Fill and drain leach tank with agitation • 10 wt% solids • 5 cycles of 1 hour • 95% reduction of alkali metals and alkaline earth metals • Sulfuric acid at 0.5 wt% • Heated to 40°C
Drain leach solution to waste tank	• Pump not needed
Add water, agitate, and drain liquids to waste tank	• Pump not needed • 5 cycles of 30 minutes
Convey leached solids through roller press, send expressed water to drain tank	• Exiting solids are 50% moisture • Greater than 95% recovery of solids
Dry solids	• Exiting solids are 30% moisture
Convey wet solids to wet mill	• Particle size 6 mm or less for herbaceous and MSW
Convey wet solids to wet pelletization	NA
Neutralize liquids in waste tank	• Final pH 6-8 • Bicarbonate used for acid
Pump neutralized liquids to reverse osmosis unit and recycle permeate to makeup water	• 90% removal of ions • 90% recovery of permeate water • Flux = 40 L m^{-2} h^{-1}
Pump retentate to wastewater treatment	NA

Ash Removal Technologies for Non-Leachable Ash Components

Silica typically is the largest ash component in biomass and is insoluble in acid and water (it cannot be leached). Hence, physical and/or chemical methods are required to remove silica from biomass with minimal loss of organic material. Technologies that can potentially accomplish this goal include grinding to micron-size particles followed by triboelectrostatic separation and alkali-based processes that dissolve silica (CENNATEK 2011). Methods for lignin recovery and precipitation must be employed in the latter case to avoid significant losses of organic material. These methods would add unit operations to the feedstock supply chain that exists today, thereby increasing costs.

Increased costs would arise in the triboelectrostatic separation pathway through increased grinding cost and the requirement that ground biomass be completely dry, as well as through losses of some of the convertible matter with the silica. If considered as an addition to the existing feedstock supply unit operations, the silica dissolution method would increase costs through the requirement for alkali recovery and the requirement for lignin recovery via acid precipitation, ultrafiltration, or triboelectrostatic separation from the lignin after concentration and drying. Acid-soluble lignin also could be lost.

However, it is notable that the severity of alkaline treatment required to solubilize the silica would likely disrupt the structure of herbaceous biomass sufficiently to greatly reduce grinding and pelletization energy requirements. In any event, if silica or heteroatoms must be removed for a given conversion process, it may be more cost effective to design the feedstock supply system around the removal processes rather than vice versa.

Cost Estimation for Chemical Preconversion

Few economic analyses are available in the literature for ash removal. The following provides overall costs for two systems that are found in the literature and include a technoeconomic analysis of leaching of alkali metals from rice straw for combustion and a technoeconomic analysis of removing both alkali metals and silica from non-woody residues (also for combustion). The cost of 95% alkali metal removal from rice straw by leaching was estimated in 2000 to be $13.61 to $16.33/dry T (Bakker 2000). A more recent analysis for non-woody feedstocks estimated a net cost of $39.93 to $60.80/dry T for removal of alkali metals (up to 95%) by leaching, followed by removal of silica (up to 75%) with triboelectrostatic separation (CENNATEK 2011).

Utilizing mechanical and chemical ash removal technologies in tandem to reduce the amount of non-spec feedstock blend components requiring further preprocessing to meet ash specifications is a strategy for reducing ash while still meeting cost targets. This can be accomplished by utilizing fractional grinding to take advantage of the skewed distribution of ash toward smaller particle sizes for corn stover. Therefore, the performance target for chemical preconversion is to produce on-spec feedstocks below the biorefinery's added costs for off-spec feedstock by either reducing the amount of feedstock requiring chemical ash removal, reducing the cost of chemical ash removal, or both.

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