

Feedstock Supply System Design and Analysis

***“The Feedstock Logistics Design Case for
Multiple Conversion Pathways”***

*Idaho National Laboratory
Bioenergy Program
Idaho Falls, Idaho 83415
<http://www.inl.gov>*

September 2014

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



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Executive Summary

The U.S. Department of Energy (DOE) aims to make cellulosic biofuels competitive with petroleum-based fuels at a modeled cost of mature bio-oil technology of \$3/gallon gasoline equivalent (gge) (\$2011) by the year 2022. The DOE Bioenergy Technologies Office (BETO) Terrestrial Feedstock Technology Area supports this goal by demonstrating a modeled delivered feedstock cost of \$80/dry T (dry U.S. short ton) by the year 2017. The purpose of this report is to document a feasible feedstock supply system for various conversion pathway designs capable of achieving this 2017 target. This design is referred to in this report as the “2017 Design Case.” Idaho National Laboratory (INL) supports the U.S. Department of Energy’s bioenergy research program. As part of the research program INL investigates the feedstock logistics economics and sustainability of these fuels. A series of reports were published between 2000 and 2013 to demonstrate the feedstock logistics cost. Those reports were tailored to specific feedstock and conversion process. Although those reports are different in terms of conversion, the strategies to improve logistics operations are similar at each conversion process. Therefore, this report is designed in such a way that it can capture different feedstock logistics cost while eliminating the need of writing a conversion specific design report.

This report provides feedstock design cost analysis for five conversion pathways: 1) Biological Conversion of Sugars to Hydrocarbons, 2) Lignocellulosic Biomass conversion to Hydrocarbon Fuels via Fast Pyrolysis and Hydrotreating Bio-Oil Pathway, 3) Catalytic Conversion of Sugars to Hydrocarbons ,4) Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels via Thermochemical Pathways with In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors, and 5) Conversion of Lignocellulosic Biomass to High Octane Gasoline via Indirect Gasification and Methanol Intermediate. The delivered feedstock composition assumed at the process design for Biological Conversion of Sugars to Hydrocarbons and Catalytic Conversion of Sugars to Hydrocarbons is the same. Therefore, feedstock supply chain design cost analysis will be the same for these two conversions pathways. Similarly the delivered feedstock composition assumed at the process design for conversion of Lignocellulosic Biomass to Hydrocarbon Fuels via 1) Fast Pyrolysis and Hydrotreating Bio-Oil Pathway, 2) Thermochemical Pathways with In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors, and 3) Indirect Gasification and Methanol Intermediate is the same. As a result feedstock design cost analysis is the same for these three conversion pathways. As each of these conversion pathways mature and additional information is added to the feedstock in-feed specifications the chapters for each pathway will be updated based on the new information.

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/dry ton target encompasses total delivered feedstock cost, including both grower payment and logistics costs, while meeting all conversion in-feed quality targets. The 2012 programmatic target of \$35/dry ton included only logistics costs with a limited focus on biomass quality.

The 2017 Design Case explores two approaches to addressing the logistics challenge: one is an agronomic solution based on blending and integrated landscape management and the second is a logistics solution based on distributed biomass preprocessing 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 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 and handling. 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 T. delivered cost.

Table E-1. Summary of assumptions underpinning progressive design implementations for biological conversion of sugars to hydrocarbons and catalytic conversion of sugars to hydrocarbons.

	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 9%
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

Table E-2. Summary of assumptions underpinning progressive design implementations for thermochemical conversion(Fast Pyrolysis and Hydro treating Bio-Oil Pathway, Thermochemical Pathways with In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors, Indirect Gasification) (INL 2017 Design Case).

	2012 Conventional Design	Baseline	2017 Design Case
Feedstock(s)	Pulpwood	Pulpwood	Blended feedstock: pulpwood, wood residues, switchgrass, and select construction and demolition wastes (C &D)
Grower payment	Breakeven cost of production	Increases based on marginal cost differential	Calculated and modeled according to specific location and resource blend/formulation
Moisture	Field dried to 40%	Field dried to 40%	Arrives: Pulpwood chips 30% wood residue chips 30%, switchgrass 20%, and C & D ground 20%; All dried to 9% pellets
Ash	Debark/delimb	Debark/delimb	Debark/delimb pulpwood Trommel screen residues Wash and sort C& D waste Blended ash content of <1% Debarked pulpwood <1%, screened wood residues 1.4%; washed and sorted C&D 1.0 %
Logistics	Uses existing systems	Uses existing systems	Pneumatics attached to hammermill High-moisture densification
Quality controls (passive)	Field drying to reduce moisture Ample available resource; quality spec manually selected	Field drying to meet moisture spec	Harvest/collection and storage best management practices for pulpwood and switchgrass More rigorous field drying of pulpwood and residues
Quality controls (active)	Waste heat dryer	Rotary drying	Multiple resource blending/formulation High-moisture densification High-efficiency pellet drying
Meets quality target	Yes	Yes	Yes
Meets cost target	Yes	No	Yes
Accesses dispersed resources	No	No	Yes

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Table of Contents

EXECUTIVE SUMMARY	2
AUTHORS AND CONTRIBUTORS	6
TABLE OF CONTENTS	7
FIGURES	12
TABLES	15
LIST OF ACRONYMS	18
1. 2017 DESIGN CASE	19
2. LIMITATIONS OF CONVENTIONAL SUPPLY SYSTEM DESIGNS	20
2.1 Expansion Beyond Highly Productive Regions	21
2.2 Feedstock Quality Specifications	22
2.2.1 Moisture Specification	24
2.2.2 Ash Specification(s)	25
3. MOVING BEYOND THE 2012 CONVENTIONAL DESIGN	28
4. APPROACH OF THE 2017 DESIGN CASE	30
4.1 Addressing the Farm Gate Price Challenge	30
4.2 Addressing the Feedstock Specification Challenge	32
4.3 Addressing the Logistics Challenge	33
5. 2017 FEEDSTOCK SUPPLY SYSTEM DESIGN	35
5.1 2013 State of Technology	35
5.2 Resource Selection Cost Estimation	36
6. FEEDSTOCK SUPPLY SYSTEM UNIT OPERATIONS	38
6.1 Harvest and Collection Operations	38

6.1.1	State of Technology	38
6.1.2	Improvement of Harvesting and Collection	41
6.2	Storage.....	42
6.2.1	State of Technology Herbaceous Residues/Energy Crops	42
6.2.2	State of Technology Woody Biomass	45
6.3	Preprocessing.....	47
6.3.1	Comminution	47
6.3.1.1	<i>Sequential Two-Stage Grinding</i>	47
6.3.1.2	<i>Pneumatic separation</i>	48
6.3.1.3	<i>Fractional Milling Design Basis</i>	49
6.3.1.4	<i>Fractional Milling Dry Biomass</i>	53
6.3.1.5	<i>Fractional Milling High-Moisture Biomass</i>	54
6.3.2	Drying	54
6.3.3	Densification	55
6.3.3.1	<i>Conventional Pelletizing</i>	55
6.3.3.2	<i>High-Moisture Densification Design Basis</i>	56
6.4	Transportation	58
6.5	Handling and Queuing.....	58
7.	SUPPLY SYSTEM DESIGN: ARRANGEMENT OF UNIT OPERATIONS	59
7.1	Conventional Feedstock Supply System	59
7.2	Advanced Supply System	59
8.	BIOLOGICAL CONVERSION OF SUGARS TO HYDROCARBONS.....	61
8.1	Summary.....	61
8.2	Feedstock Composition (In-feed quality specifications).....	64
8.3	Feedstock Selection Cost Estimation	65
8.4	Quality Specification and Design Assumptions	67
8.5	Feedstock Logistics	67
8.5.1	Harvest and Collection	67
8.5.1.1	<i>Overview</i>	67
8.5.1.2	<i>Harvest and Collection Design Basis</i>	68
8.5.1.3	<i>Harvest and Collection Cost Estimation</i>	69
8.5.2	Storage	70
8.5.2.1	<i>Biomass Storage Design Base</i>	70
8.5.2.2	<i>Biomass Storage Cost Estimation</i>	73
8.5.3	Preprocessing	73
8.5.3.1	<i>Size Reduction</i>	75
8.5.3.2	<i>Fractional Milling Cost Estimation</i>	76
8.5.3.3	<i>Drying and Densification</i>	76

8.5.3.4	<i>Cost Estimation for High-Moisture Densification</i>	76
8.5.3.5	<i>Formulation/Blending</i>	78
8.5.3.6	<i>Formulation Design Basis</i>	78
8.5.3.7	<i>Cost Estimation for Formulation</i>	80
8.5.4	Transportation and Handling.....	80
8.5.4.1	<i>Cost Estimation for Transportation</i>	81

8.6	Life Cycle Assessment:.....	81
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9. CONVERSION OF LIGNOCELLULOSIC BIOMASS TO HYDROCARBON FUELS: FAST PYROLYSIS AND HYDROTREATING BIO-OIL PATHWAY.....83

9.1	Summary.....	83
9.2	Feedstock Composition (In-feed quality specifications).....	85
9.3	Feedstock Selection Cost Estimation	86
9.4	Quality Specification and Design Assumptions.....	88
9.5	Feedstock Logistics	90
9.5.1	Harvest and Collection	90
9.5.1.1	<i>Harvest and Collection Design Basis</i>	90
9.5.1.2	<i>Harvest and Collection Cost Estimation</i>	92
9.5.2	Storage	93
9.5.2.1	<i>2013 State of Technology</i>	93
9.5.2.2	<i>Storage Design Basis</i>	94
9.5.2.3	<i>Biomass Storage Cost Estimation</i>	94
9.5.3	Preprocessing	94
9.5.3.1	<i>State of Technology:</i>	96
9.5.3.2	<i>Size Reduction Cost Estimation</i>	96
9.5.3.3	<i>Drying and Densification</i>	97
9.5.3.4	<i>Cost Estimation for High-Moisture Densification</i>	98
9.5.3.5	<i>Formulation/Blending</i>	98

10. CONVERSION OF LIGNOCELLULOSIC BIOMASS TO HYDROCARBON FUELS: THERMOCHEMICAL PATHWAYS WITH IN SITU AND EX SITU UPGRADING OF FAST PYROLYSIS VAPORS98

10.1	Summary.....	99
10.2	Feedstock Composition (In-feed quality specifications).....	101
10.3	Feedstock Selection Cost Estimation	102
10.4	Quality Specification and Design Assumptions.....	104
10.5	Feedstock Logistics	106
10.5.1	Harvest and Collection.....	106
10.5.1.1	<i>Harvest and Collection Design Basis</i>	106
10.5.1.2	<i>Harvest and Collection Cost Estimation</i>	108

10.5.2	Storage	109
10.5.2.1	<i>2013 State of Technology</i>	109
10.5.2.2	<i>Storage Design Basis</i>	110
10.5.2.3	<i>Biomass Storage Cost Estimation</i>	110
10.5.3	Preprocessing	110
10.5.3.1	<i>State of Technology:</i>	112
10.5.3.2	<i>Size Reduction Cost Estimation</i>	112
10.5.3.3	<i>Drying and Densification</i>	113
10.5.3.4	<i>Cost Estimation for High-Moisture Densification</i>	114
10.5.3.5	<i>Formulation/Blending</i>	114
10.5.3.6	<i>Cost Estimation for Formulation.</i>	116
10.5.4	Transportation and Handling Design Basis	116
10.5.4.1	<i>Cost Estimation for Transportation and Handling</i>	117
10.6	Life Cycle Analysis	117
11.	DILUTE-ACID CONVERSION OF LIGNOCELLULOSIC BIOMASS TO HIGH OCTANE GASOLINE VIA INDIRECT GASIFICATION AND METHANOL INTERMEDIATE	119
11.1	Summary.....	119
11.2	Feedstock Composition (In-feed quality specifications).....	121
11.3	Feedstock Selection Cost Estimation	122
11.4	Quality Specification and Design Assumptions	124
11.5	Feedstock Logistics	126
11.5.1	Harvest and Collection	126
11.5.1.1	<i>Harvest and Collection Design Basis</i>	126
11.5.1.2	<i>Harvest and Collection Cost Estimation</i>	128
11.5.2	Storage	129
11.5.2.1	<i>2013 State of Technology</i>	129
11.5.2.2	<i>Storage Design Basis</i>	130
11.5.2.3	<i>Biomass Storage Cost Estimation</i>	130
11.5.3	Preprocessing	130
11.5.3.1	<i>State of Technology:</i>	132
11.5.3.2	<i>Size Reduction Cost Estimation</i>	132
11.5.3.3	<i>Drying and Densification</i>	133
11.5.3.4	<i>Cost Estimation for High-Moisture Densification</i>	134
11.5.3.5	<i>Formulation/Blending</i>	134
11.5.3.6	<i>Cost Estimation for Formulation.</i>	135
11.5.4	Transportation and Handling Design Basis	136
11.5.4.1	<i>Cost Estimation for Transportation and Handling</i>	136
11.6	Life Cycle Analysis	137
REFERENCES	139
APPENDIX A	143

APPENDIX B.....	147
APPENDIX C.....	153
APPENDIX D.....	156
APPENDIX E.....	159

Figures

Figure 1. Total tons per county of available pulpwood at \$60/dry T farm gate price. Yellow circles show areas represented in the 2012 Conventional Design and the Relocated (2013) Design Case ⁵	21
Figure 2. Total tons per county of available corn stover at \$40/dry T farm gate price. Circles show areas represented in the 2012 Conventional Design and the Relocated (2013) Design Case.	22
Figure 3. Flow diagram of the 2012 Relocated (Baseline) Design Case to supply thermochemical conversion refineries ¹²	28
Figure 4. Marginal and average farm gate costs versus supply quantities derived from BT2 data for the U.S. predicted out to 2022 ¹	31
Figure 5. U.S. Marginal farm gate prices projected for 2022 by POLYSYS ¹	32
Figure 6. Historical pulpwood stumpage prices for the southern U.S. in \$/dry Ton (http://www.timbermart-south.com/prices.html).	36
Figure 7. National estimated pulpwood stumpage prices ¹	36
Figure 8. 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.	40
Figure 9. 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.	41
Figure 10. Dry matter loss of corn stover in laboratory storage conditions at fixed moisture contents 32.....	43
Figure 11. 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 ³²	44
Figure 12. Change in glucan and xylan over time as corn stover is stored in laboratory reactors ³²	45
Figure 13. Dry matter loss and self-heating of 50% initial moisture pine chips stored under aerobic conditions using laboratory scale reactors at INL.....	46
Figure 14. Comparison of comminution capacities (tons of through put per operating hour) for woody biomass as a result of adding pneumatic transfer assist (PTS) ³⁸	48
Figure 15. Change in moisture content during comminution using pneumatic transfer assist (PTS) ³⁸	48
Figure 16. Ash content in various screen sizes for pinyon-juniper biomass ^{38 41}	49
Figure 17. Particle-size distributions for five grinding scenarios ⁴¹	50
Figure 18. Comparison of conventional, two-stage grinding and fractional milling ⁴¹	51
Figure 19. Grinding energy and throughput is highly dependent on screen size ⁴¹	52
Figure 20. Hammer mill energy consumption is highly dependent on biomass moisture content (INL PDU Data).	53

Figure 21. Conventional pelletization process.....	56
Figure 22. High-moisture pelletization process.....	57
Figure 23. Conventional feedstock system for herbaceous lignocellulosic biomass.....	59
Figure 24. Advanced supply system designs (Advanced Uniform) follow the model of the current grain commodity supply system, which manages crop diversity at the point of harvest and/or depot, allowing all subsequent feedstock supply system infrastructure to be similar for all biomass resources ⁴	60
Figure 25. 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.....	63
Figure 26. Resource selections for the 2017 Design Case to support biochemical conversion. Figure shows tonnages available at \$40/dry ton. Green represents higher amounts of tonnage available, red represents no available tonnage available at \$40/dry ton ⁴⁷	66
Figure 27. The impact of dry matter loss on bale ash content and final conversion efficiency (based on a 30% initial moisture and 12% ash).....	71
Figure 28. Dry matter loss of corn stover in the simulated storage conditions, with three air flows simulating three different oxygen availabilities.....	72
Figure 29. Material flow in the 2017 Design Case that incorporates many improvements in preprocessing, including fractional milling, chemical preconversion, high-moisture densification, and formulation/blending.....	74
Figure 30. Total tons per county of available pulpwood at \$60/dry T farm gate price. Yellow circles show areas represented in the 2012 Conventional Design and the Relocated (2013) Design Case ⁵	87
Figure 31. Conventional (left) and high-capacity grapple skidder (right) for transporting small diameter pulpwood from the forest to the landing. Photo credit: Auburn University High Tonnage Forest Biomass Project ⁵⁸	91
Figure 32. Ash and moisture content of switchgrass harvested in Oklahoma, 2010 by Oklahoma State University. Error bars represent one standard deviation. Ash samples for October, December, and January are three samples comprised of six individual core samples composited.....	92
Figure 33. Material flow in the 2017 Design Case that incorporates many improvements in preprocessing, including pneumatics, high-moisture densification, and formulation/blending	95
Figure 34. Total tons per county of available pulpwood at \$60/dry T farm gate price. Yellow circles show areas represented in the 2012 Conventional Design and the Relocated (2013) Design Case ⁵	103
Figure 35. Conventional (left) and high-capacity grapple skidder (right) for transporting small diameter pulpwood from the forest to the landing. Photo credit: Auburn University High Tonnage Forest Biomass Project ⁵⁸	107
Figure 36. Ash and moisture content of switchgrass harvested in Oklahoma, 2010 by Oklahoma State University. Error bars represent one standard deviation. Ash samples for October,	

December, and January are three samples comprised of six individual core samples composited.....	108
Figure 37. Material flow in the 2017 Design Case that incorporates many improvements in preprocessing, including pneumatics, high-moisture densification, and formulation/blending	111
Figure 38. Total tons per county of available pulpwood at \$60/dry T farm gate price. Yellow circles show areas represented in the 2012 Conventional Design and the Relocated (2013) Design Case ⁵	123
Figure 39. Conventional (left) and high-capacity grapple skidder (right) for transporting small diameter pulpwood from the forest to the landing. Photo credit: Auburn University High Tonnage Forest Biomass Project ⁵⁸	127
Figure 40. Ash and moisture content of switchgrass harvested in Oklahoma, 2010 by Oklahoma State University. Error bars represent one standard deviation. Ash samples for October, December, and January are three samples comprised of six individual core samples composited.....	128
Figure 41. Material flow in the 2017 Design Case that incorporates many improvements in preprocessing, including pneumatics, high-moisture densification, and formulation/blending	131
Figure B 1.The farm gate cost curves suggest that corn stover is the preferred feedstock because it is less expensive than switchgrass.....	148
Figure B 2. Accounting for quality (dockage)—shows that about 300,000 tons of switchgrass can be supplied at a lower cost than corn stover	149
Figure B 3. A corn stover/switchgrass blend that will deliver at about \$81/dry T	150
Figure B 4. 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.....	151
Figure B 5. 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.....	151
Figure C 1. Sensitivity of dockage by altering feedstock ash content relative to the baseline ash content of 4.9% ⁸³	153
Figure C 2. Sensitivity of the costs impacts to altering feedstock price relative to the base case of 58.50 \$/dry T for a delivered feedstock with 10% ash ⁸³	154
Figure C 3. Total dockage based on shifting baseline ash content for a range of received materials at a feedstock price of 58.50 \$/dry T ⁸³	155

Tables

Table E-1. Summary of assumptions underpinning progressive design implementations for biological conversion of sugars to hydrocarbons and catalytic conversion of sugars to hydrocarbons	4
Table E-2. Summary of assumptions underpinning progressive design implementations for thermochemical conversion(Fast Pyrolysis and Hydro treating Bio-Oil Pathway, Thermochemical Pathways with In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors, Indirect Gasification) (INL 2017 Design Case).	5
Table 1. Delivered woody feedstock composition and processing assumptions for the fast pyrolysis and hydrotreating design report ⁶	23
Table 2. Potential effect of higher biomass ash content.....	26
Table 3. Costs and specifications for woody feedstocks and blends (INL analysis).	27
Table 4. 2013 SOT cost estimate (all costs are in 2011 USD).....	29
Table 5. Resource access cost estimate ⁵ and INL Material Solid Waste (MSW Data)	37
Table 6. Mean total ash values and ranges for selected lignocellulosic biomass.....	39
Table 7. Drying and densification design basis.	57
Table 8. Biochemical conversion feedstock design cost analysis.....	62
Table 9. Delivered Feedstock Composition Assumed in the Present Design ⁴⁴	65
Table 10. Resource farm gate price.	66
Table 11. Summary of assumptions underpinning progressive design implementations.	67
Table 13. Biomass harvest and collection cost estimates.	70
Table 14. Biomass storage design basis.....	73
Table 15. Field-side storage cost estimation.....	73
Table 16. Size-reduction design basis.....	76
Table 17. Fractional milling cost estimates	76
Table 18. Drying and densification design basis.	77
Table 19. Drying and densification cost estimates.....	78
Table 20. Feedstock formulation/blending of ash and moisture contents*.....	78
Table 21. Feedstock formulation design basis.	79
Table 22. Formulation cost estimation.....	80
Table 23. Transportation cost estimates.....	81
Table 24. Energy consumption for Biochemical conversion supply chain design.	82
Table 25. GHG contribution for biochemical conversion supply chain design.	82
Table 26. Thermochemical feedstock design cost analysis for 2017.....	84

Table 27. Delivered woody feedstock composition and processing assumptions for the fast pyrolysis and hydrotreating design report ⁶	86
Table 28. Resource access cost estimate (U.S. DOE 2011 ⁵ and INL MSW Data)	88
Table 29. Summary of assumptions underpinning progressive design implementations ⁵⁷	89
Table 30. Biomass harvest and collection cost estimates derived from INL analysis.	93
Table 31. Technical targets for biomass field storage of resources in the 2017 Design Case.	94
Table 32. Field-side storage cost estimation.	94
Table 33. Size-reduction design basis.....	96
Table 34. Size reduction cost estimates.	96
Table 35. Drying and densification design basis.	97
Table 36. Drying and densification cost estimates.	98
Table 37. Feedstock formulation/blending of ash and moisture contents*.	98
Table 39. Delivered woody feedstock composition and processing assumptions for the In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors ⁶	102
Table 40. Resource access cost estimate (U.S. DOE 2011 ⁵ , and INL MSW Data).	104
Table 41. Summary of assumptions underpinning progressive design implementations ⁵⁷	105
Table 42. Biomass harvest and collection cost estimates derived from INL analysis.	109
Table 43. Technical targets for biomass field storage of resources in the 2017 Design Case.	110
Table 44. Field-side storage cost estimation.	110
Table 45. Size-reduction design basis.....	112
Table 46. Size reduction cost estimates.	113
Table 47. Drying and densification design basis.	113
Table 48. Drying and densification cost estimates.	114
Table 49. Feedstock formulation/blending of ash and moisture contents*.	115
Table 50. Feedstock formulation design basis.	115
Table 51. Formulation cost estimation.....	116
Table 52. Transportation cost estimates.....	117
Table 53. Energy Consumption for Thermochemical conversion supply chain design.....	118
Table 54. GHG contribution for thermochemical conversion supply chain design.....	118
Table 55. Thermochemical feedstock design cost analysis for 2017.....	120
Table 56. Delivered woody feedstock composition and processing assumptions for the fast pyrolysis and hydrotreating design report ⁶	122
Table 57. Resource access cost estimate (U.S. DOE 2011 ⁵ , and INL MSW Data).	124
Table 58. Summary of assumptions underpinning progressive design implementations ⁵⁷	125
Table 59. Biomass harvest and collection cost estimates derived from INL analysis.	129

Table 60. Technical targets for biomass field storage of resources in the 2017 Design Case.	130
Table 61. Field-side storage cost estimation.	130
Table 62. Size-reduction design basis.	132
Table 63. Size reduction cost estimates.	132
Table 64. Drying and densification design basis.	133
Table 65. Drying and densification cost estimates.	134
Table 66. Feedstock formulation/blending of ash and moisture contents*.	134
Table 67. Feedstock formulation design basis.	135
Table 68. Formulation cost estimation.	136
Table 69. Transportation cost estimates.	137
Table 70. Energy Consumption for Thermochemical conversion supply chain design.	137
Table 71. GHG contribution for thermochemical conversion supply chain design.	138
Table A 1. Potential C&D available in select counties in western South Carolina.	143
Table A 2. National average municipal solid waste composition.	144
Table A 3. Per capita generation rates for various fractions of municipal solid waste and construction and demolition waste (lb/person/day).	145
Table A 4. Physical parameters of solid waste	146
Table D 1. 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.	157

List of Acronyms

C&D waste	Construction and demolition waste
Dry T	Dry Ton
MSW	Municipal Solid Waste
BETO	Bioenergy Technology Office
BT2	Billion Ton Study Update
DMT	Dry Matter Ton (U.S. short ton)
DOE	U.S. Department of Energy
GGE	Gallon Gasoline Equivalent
I&D	Interest and Depreciation (costs)
IH&T	Insurance Housing and Taxes (costs)
INL	Idaho National Laboratory
MC	Moisture Content
MESP	Minimum Ethanol Selling Price
ORNL	Oakridge National Laboratory
PDU	Process Demonstration Unit (at INL)
R&M	Repairs and Maintenance (costs)
TEA	Techno-Economic Analysis
LCF	Least Cost formulation
PNNL	Pacific Northwest National Laboratory
NREL	National Renewable Energy Laboratory

1. 2017 Design Case

The success of the earlier logistic pathway designs (Biochemical and Thermochemical) from a feedstock perspective was that it demonstrated that through proper equipment selection and best management practices, conventional supply systems (referred to in this report as “conventional designs,” or specifically the 2012 Conventional Design) can be successfully implemented to address dry matter loss, quality issues, and enable feedstock cost reductions that help to reduce feedstock risk of variable supply and quality and enable industry to commercialize biomass feedstock supply chains. The caveat of this success is that conventional designs depend on high density, low-cost biomass with no disruption from incremental weather. In this respect, the success of conventional designs is tied to specific, highly productive regions such as the southeastern U.S. which has traditionally supported numerous pulp and paper industries or the Midwest U.S for corn stover.

The goal of the 2017 Logistics Design Case is to increase availability of affordable biomass beyond only highly productive resource areas. The 2017 programmatic target is to supply the conversion facility with a feedstock that meets the conversion feedstock specifications at a total delivered cost of \$80/dry T. This design document describes a feedstock logistics design capable of achieving this goal, discusses the limitations of the conventional supply systems when applied outside of highly productive resource areas and 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.

The \$80/dry T target encompasses a total delivered feedstock cost, including both grower payment and logistics, and meeting all conversion in-feed quantity and quality targets. The 2012 \$55/dry T target for the thermochemical conversion pathway and the \$35/dry T biochemical conversion pathway target included only logistics costs and only included passive quality control methods. An estimated grower payment associated with the 2012 Conventional Design was \$15.20/dry T based on the break-even cost of production¹. Adding grower payment and logistics, the total delivered feedstock cost was \$70.20/dry T for thermochemical conversion and \$50.20/dry T for biochemical conversion in 2007 dollars. Translating the \$70.20/dry T to 2011 dollars, the total delivered feedstock cost of the 2012 Conventional Design scales to about \$80/dry T. This demonstrates that for a conventional supply system it is possible to deliver feedstock to various conversion pathways for \$80/dry T or less, but only for of tightly coupled set of designs that require high quality, low moisture harvested material. First, the 2012 Conventional Design assumed field drying the material. Next, it was assumed that waste heat from the conversion facility would be available for further drying requirements. And finally, the design assumed that biomass was available in high yield regions, minimizing transportation distances. Each of these assumptions limits the size and location of conversion facilities and assumes that weather will not impact biomass quality. Achieving the goals of the 2017 Design Case will require innovative solutions and significant technological advancements as pivotal assumptions within the 2012 Conventional Design are removed.

This report is intended to describe the feedstock logistic pathway for supplying biomass to a conversion facility. The logistic designs are not conversion pathway specific, but discuss in general the methods and processes necessary to stabilize and densify large volumes of biomass

that can then be delivered to the specific conversion pathways at a specified quality level. Sections 8–11 will then outline the costs and quality impacts for the current conversion pathways. Feedstock design reports associated with alternate hydrocarbon pathways of BETO will be published subsequent to this report.

2. Limitations of Conventional Supply System Designs

Conventional design is based on the supply system where corn stover or other herbaceous residues are procured through contracts with local growers, harvested, stored at field side, and delivered in bale format to the conversion facility. A detailed description of conventional supply system is provided in section 7.1. Conventional designs are the backbone of an emerging biofuels industry. In fact, conventional designs have been successfully implemented by pioneer (1st of a kind, small capacity) biorefineries currently in operation. However, conventional supply systems have limitations^{2,3} that prohibit them from being broadly implemented to access the diverse set of resources needed to support a national biorefinery capability. These limitations, including biomass availability, feedstock quality and high costs, are discussed in this section.

The viability of the 2012 Conventional Design is rooted in areas that have a concentrated supply of 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 likely to be small due to the high cost of transportation of low density biomass, limiting their ability to achieve economies of scale, because feedstock costs and risks are likely to be prohibitive⁴.

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, and harvest technique. 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. Additional work needs to be done both on the conversion side as well as the feedstock side to identify additional quality specifications and to align them with the various feedstocks which match up with the conversion process including woody, herbaceous residues, energy crops and various municipal solid wastes (MSW). The new quality specifications could include breaking down total ash by species (e.g. potassium and other alkali), cellulose, hemicellulose, lignin, and other extractives. Each conversion pathway will have a select set of quality specifications that may very well dictate regions of the country that are better aligned to supply feedstocks.

Two requirements that distinguish the 2017 Design Case from the 2012 Conventional Design are first expansion beyond highly productive resource areas and second adherence to feedstock specifications. These requirements are discussed in detail in the following subsections.

2.1 Expansion Beyond Highly Productive Regions

Expansion beyond highly productive resource areas has significant implications to the feedstock supply chain. Sparse areas, 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 yields increase the supply radius and biomass transportation distances. Under the 2012 Conventional Design, higher yield areas allow refinery to be selective on the resource that they access.

Consider, for example, pulpwood farm gate (farm gate prices include harvest, collection and revenue to the owner) prices depicted in Figure 1. This resource map illustrates a county-level resource assessment of pulpwood farm gate at \$60/dry T prices (this includes grower payment, harvest, collection, and chipping costs). Farm gate price data were extracted from *The Billion Ton Update* (BT2)⁵ data supplied from Oak Ridge National Laboratory.

The cost competitiveness of the 2012 Conventional Design was demonstrated³ in the scenario located in southern Alabama, a high biomass yielding area (2012 Design in Figure 1). We further suggest, based on the consistency of farm gate (i.e., landing) prices shown in this map, that the 2012 Conventional Design can be deployed cost effectively in South Carolina (2013 Design in Figure 1).

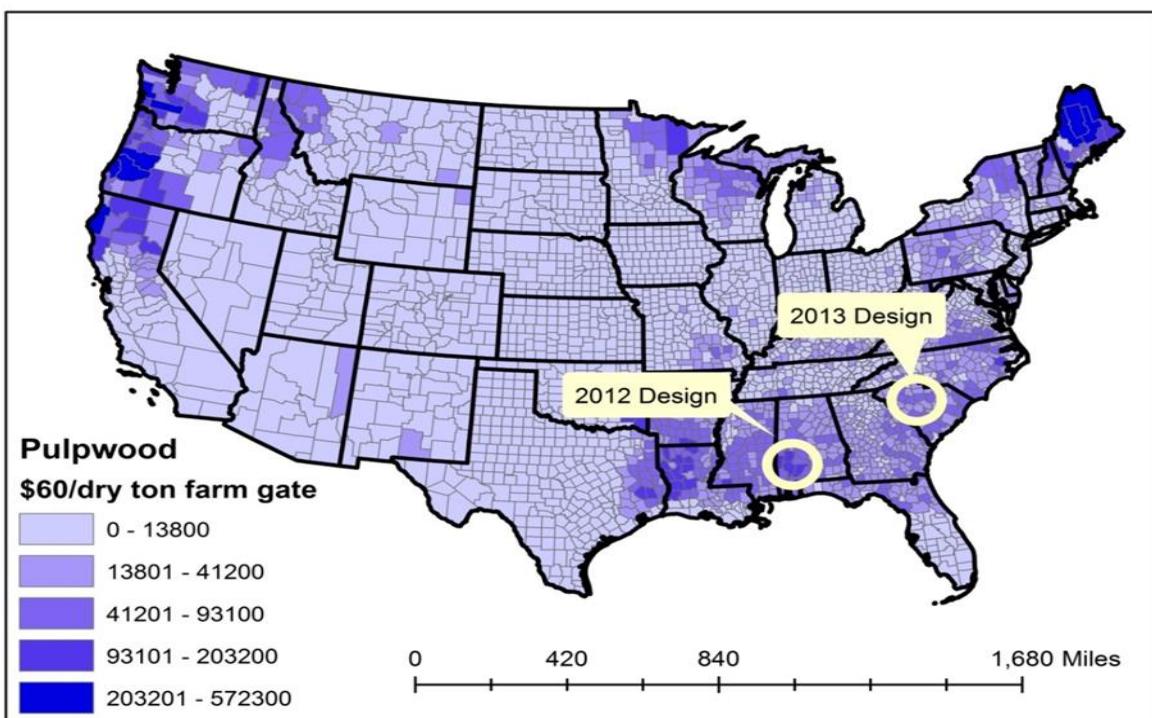


Figure 1. Total tons per county of available pulpwood at \$60/dry T farm gate price. Yellow circles show areas represented in the 2012 Conventional Design and the Relocated (2013) Design Case⁵.

The map depicts a fairly steep gradient where resource available at \$60/dry T farm gate price rapidly decreases (lighter colors) for areas outside the southern area that traditionally supported a thriving pulp and paper industry. Significant county-to-county fluctuations in available resources are seen as well. In these areas, as in the scenario depicted in western South Carolina, sufficient pulpwood exists to support an 800,000 ton per year biorefinery; however resource selectivity to passively mitigate quality will be constrained due to the limited amount of biomass (i.e., selecting only the higher quality material and leaving the low quality material behind). In this scenario, a more dispersed pulpwood resource, due to lower yields in these regions, also results in increased harvest, collection, and transportation costs compared to the lower-cost scenario.

To reinforce this concept and to expand the analysis to other feedstocks, Figure 2 depicts farm gate price for corn stover in the Midwest for two areas. The first is in Iowa where corn yields are high and the second area moves to western Kansas with lower yields. The map also depicts (as in the pulpwood case) a fairly steep gradient where at \$40/dry T farm gate price resources rapidly decrease toward the fringes of the Corn Belt. Significant county-to-county fluctuations in resources 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 biorefineries 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.

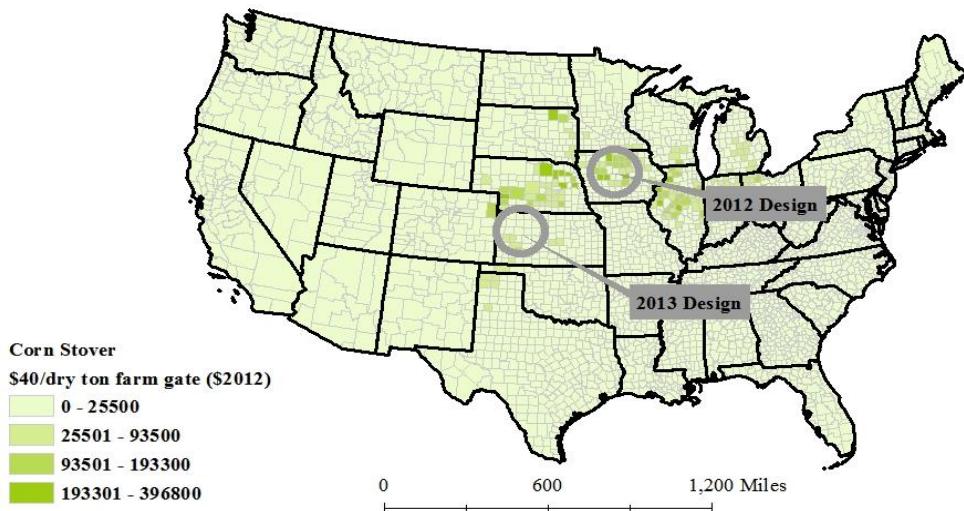


Figure 2. Total tons per county of available corn stover at \$40/dry T farm gate price. Circles show areas represented in the 2012 Conventional Design and the Relocated (2013) Design Case.

2.2 Feedstock Quality Specifications

Techno-economic models often involve process simulations wherein mass and energy balances converged across a number of unit operations to assess the entire system as a whole. Feedstock compositions and heating values are required inputs to these balances. The fast pyrolysis and hydrotreating conversion pathway (Section 9) feedstock specifications are shown in Table 1.

These assumptions were based on the composition of low ash, woody biomass delivered at 30% wt moisture⁶. Currently within the feedstock logistic system the only quality specifications that are actively being managed are ash, particle size and moisture. Other components, such as lignin, low and high heating values, may be included in future revisions as their quality impacts are identified. A combination of passive methods such as, selective biomass selection, applying best management practices that preserve material, and harvest practices that minimize introduced ash (soil) were implemented in the 2012 Conventional Design. However, quality “specifications” were not actively enforced in the 2012 Conventional Design. In other words, the specifications were acknowledged and attempts were made to match up the biomass with the specifications, but no active management was installed to enforce expectations and it was assumed that the passive controls were enough to insure the quality specifications were met.

Table 1. Delivered woody feedstock composition and processing assumptions for the fast pyrolysis and hydrotreating design report ⁶.

Component	Composition (dry wt. %)
Carbon	50.94
Hydrogen	6.04
Nitrogen	0.17
Sulfur	0.03
Oxygen	41.90
Ash	0.90-1.0
Heating Value (Btu/lb)	8,601 HHV 7,996 LHV
Moisture (Bulk Wt. %)	10.0
Particle Size (inch)	1/4

Table 1 illustrates the feedstock conversion specifications for one particular conversion pathway, fast pyrolysis and hydrotreating. Each conversion pathway under consideration has its own set of feedstock conversion specifications. The impacts of the in-feed specifications for each conversion pathway are addressed later in this report in chapters specific to each pathway. The 2017 Design Case introduces the expectation that the feedstock supply system will be held accountable to deliver feedstocks that meet these quality assumptions.

The passive approaches (i.e., biomass selection and best management practices) implemented in the 2012 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 feedstock costs and supply risk to biorefineries by making them dependent on limited specific feedstocks. Case in point, there may be years where due to rainy weather biomass does not undergo any field drying, thereby increasing biomass

moisture which results in decreased harvest yields, increased dry matter loss, transportation costs, grinding costs and drying costs each of which increase the cost to the biorefinery.

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 system. The 2017 Design Case 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 adding in additional processes adds cost to an already cost-constrained system. Therefore, the insertion of active controls into the 2017 Design Case must balance the cost/benefit of mitigation in the feedstock supply system and the cost of further biorefinery processing of off-spec feedstock.

In commercial practice, this normalization function is implemented through a dockage fee. A dockage fee is the penalty a feedstock supplier incurs from payment by the biorefinery for delivery of off-specification feedstock. The dockage fee is established based on the additional cost the biorefinery incurs to process off-specification feedstock; the dockage fee is subtracted from the contracted feedstock payment the biorefinery agreed to pay a supplier. If the pre-delivery cost of mitigation by the feedstock supplier exceeds the dockage fee, the dockage fee is the lowest cost option; otherwise, the feedstock supplier could 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 system costs the supplier \$15/dry T, but the biorefinery is able to mitigate the ash for \$10/dry T, the feedstock supplier may choose to accept the \$10/dry T dockage fee rather than implement ash reduction, for a net \$5/dry T savings. For further discussion on dockage see Appendix C

Implementation of a dockage-based quality assurance approach, much like in the grain industry, 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 and ash content.

2.2.1 Moisture Specification

For some conversion processes, i.e. thermochemical processing, feedstock moisture content has a strong influence on the process economics. High quality heat in the reactor will be required to evaporate the extra moisture which can be a significant penalty on the process depending on how it is configured⁷. The reality is that the moisture has a high impact on both the feedstock supply system as well as the conversion process. In addition to its implications on storage stability, biomass moisture content can significantly affect transportation, preprocessing, and feedstock handling⁸. These logistics-related costs are discussed in Section 3. Since the logistics supply system is designed to meet the moisture target there will not be a dockage assessed by the biorefinery for excessive feedstock moisture content.

2.2.2 Ash Specification(s)

Feedstock ash content has a big impact on liquid yields for most conversion processes. Ash in this context is a combination of inorganic material that has two parts: (1) the mineral matter taken up from the soil and retained as part of the plant or tree; (aka physiological ash), and (2) inorganic material that was collected with the biomass during harvesting/collection (e.g. soil matter, dirt, etc.). Both parts are not converted during conversion and represent solid input that goes through the process and requires disposal. This extra inert mass causes a decrease in conversion efficiency and creates a waste stream that needs additional removal costs. Current predicted disposal costs are \$18/T for pyrolysis ⁹. The cost for other conversion processes may be different.

The goal of implementing improved feedstock supply system design is to minimize the inorganic material collected during harvest/collection and not address the physiological ash in the plants. In future supply systems, advanced preprocessing may be required to address physiological ash. Another option worth pursuing is that feedstock with higher ash is purchased at a low enough price to compensate for the losses in fast pyrolysis liquid yield or an added cleanup process to bring it in on specification. INL, in collaboration with NREL and PNNL, are researching the benefits/costs of both methods. Table 2 illustrates the effect of ash content on fast pyrolysis liquid yield. Additionally, feedstock ash content represents an additional variable operational cost to the biorefinery, because it reduces pretreatment efficacy, increases wear in handling and feeding systems, accumulates as a waste stream that requires disposal, and increases water treatment costs ¹⁰. While ash entrained in the liquid could impact downstream catalysis, it is unknown at this time if the ash is soluble or attached to the char. There is a filtration step prior to condensed-phase upgrading that can help reduce the impacts. If the ash is soluble, it may impact the catalyst life.

Limited understanding is known about the efficiency of upgrading high-ash feedstock pyrolysis oils. Preliminary efforts indicate that oil produced from high-ash feedstocks actually performs better during hydrotreating. This would indicate that the loss of efficiency during pyrolysis is balanced by improved efficiency during hydrotreating. This might actually be an improved scenario because lost efficiency during hydrotreating is typically related to small molecular weight acids that consume hydrogen before being lost to the fuel gas ¹¹.

Table 2. Potential effect of higher biomass ash content ⁶.

Cost and Consumption	Base Case	Base Case
	with 0.9% wt Ash	with 1.9% wt Ash
Fuel yield, gal/dry T. biomass	84	75
Natural gas usage, scf/gal	19.3	5.9
H₂ demand, MMscfd	44.5	40
TCI, million \$	700	672
MESP, \$/gge	3.39	3.55

Note: TCI (Total Cost Indicator), scf = standard cubic feet

Crop residues forest thinnings, logging residues, and construction and demolition (C&D) wastes are low cost resources to procure, but also have unfavorable quality specifications, specifically ash content. It should be noted that the ash type and quantity may have an effect on the yield of fast pyrolysis oil as certain ash constituents can cause an increase in the gas production at the expense of condensable liquids; however more research is needed to understand the impacts of ash on conversion.

Because these biomass resources are low cost, supply chains that include active ash management preprocessing unit operations can be purchased. Prior to preprocessing, certain resources can be blended to reduce the overall percentage of ash and moisture, thereby reducing the costs and severity needed to reduce the ash to in-feed specifications. Table 3 shows an example formulation.

Table 3. Costs and specifications for woody feedstocks and blends (INL analysis).

Feedstock	Reactor Throat Feedstock Cost (\$/dry T) ²	Formulation Fraction (%)	% Ash Delivered to Throat of Conversion Reactor
Pulp	99.49	45	0.5
Wood Residues¹	67.51	32	1
Switchgrass	66.68	3	4.0
C&D Wastes	58.12	20	1.0
Formulation Totals	80.00	100	<1

¹ residues do not include costs for harvest and collection; they are moved to landing while attached to the merchantable portion of the tree (for example, timber or pulpwood)

² includes ash mitigation

The C&D wastes are incorporated because of its low access fee cost and assumed low ash content. C&D wastes were limited in quantity due to the uncertainty of available supplies. Current research shows significant quantities of C&D, but there are uncertainties with EPA qualifying C&D waste for credit for RIN's and competition from other markets. This is only an example; the actual blends will be regionally based designs that take advantage of local feedstocks and their biomass characteristics. Additionally the ability to blend feedstocks to a specification has the potential to reduce some of the risks associated with the seasonality of feedstocks.

3. Moving beyond the 2012 Conventional Design

With the 2012 Conventional Design Case (e.g. thermochemical conversion pathway) located in a highly productive pulpwood production area, the main constraint of the design was that the biorefinery could be selective in contracting pulpwood that was <1% ash content (Table 1). In the 2013 State of Technology (SOT), the assumption that the biorefinery can be selective is unlikely because there will most likely not be enough resource available to maintain the volumes required.

The feedstock supply system unit operations modeled in the 2013 SOT case for the thermochemical conversion path are shown in Figure 3. These unit operations are identical to those in the 2012 Conventional Design¹², with the exception of the removal of the waste heat drying. The new assumption is that waste heat drying will not be available to support feedstock drying but will be used elsewhere inside the conversion facility. The details of these unit operations are discussed in the design basis sections of this report.

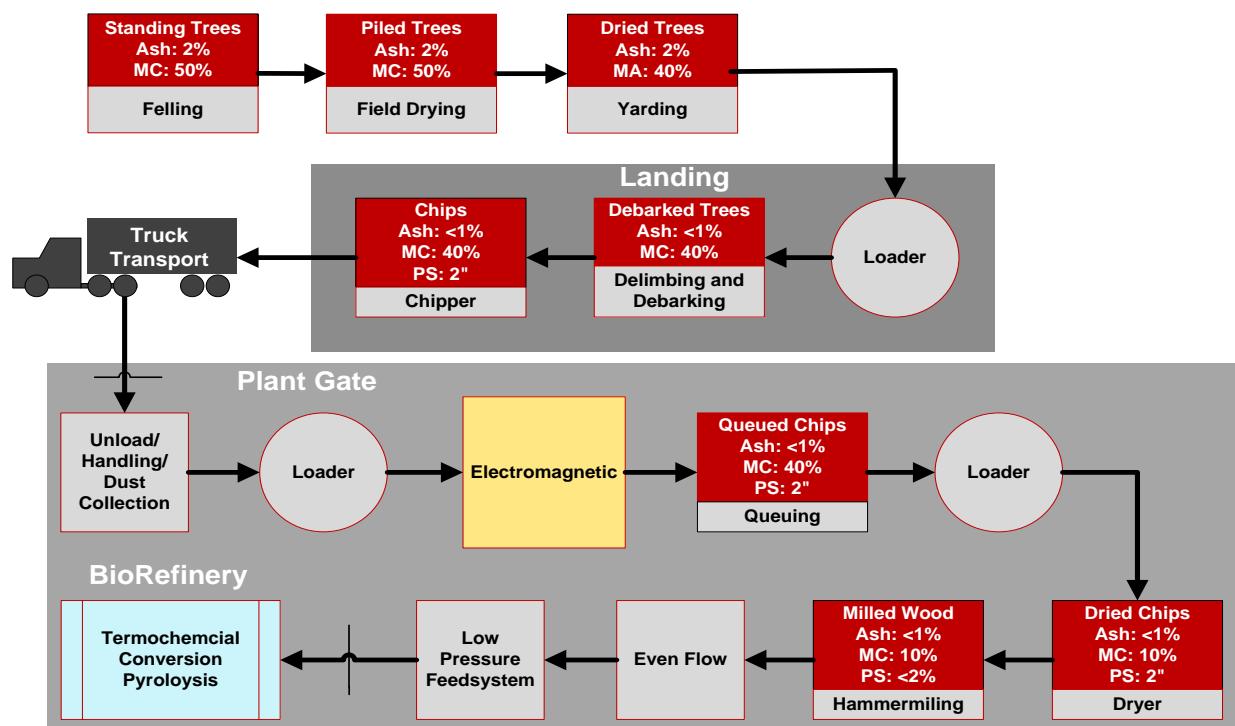


Figure 3. Flow diagram of the 2012 Relocated (Baseline) Design Case to supply thermochemical conversion refineries¹².

The cost estimate of the 2013 SOT supply system (Table 4) shows a logistics costs total of \$77.90/dry T, compared to \$55/dry T for 2012 Conventional Design. Increased costs of the baseline system are attributed to the following:

- Cost escalation from 2007\$ to 2011\$ cost year
- Lower resource yields (90% to 67%), which increases harvest, collection and transportation costs
- Switch from waste heat dryer to natural gas dryer due to the separation of the depot from the conversion facility which eliminates the ability to make use of waste heat.
- Increased grower payment from the \$15.70/dry T to \$25.00/dry T based on the BT2 data ⁵.

Escalation was estimated using the Chemical Engineering Plant Cost Index and Producer Price Index from 2007 to 2011. The Chemical Engineering Index is published in each issue of Chemical Engineering (www.che.com/pci). The Producer Price Index includes commercial and industrial machinery and equipment repair and maintenance costs (www.bls.gov/ppi/ppinaics811310.htm).

Table 4. 2013 SOT cost estimate (all costs are in 2011 USD).

Cost Element	Cost by Operation (\$/dry T)	Cumulative Cost (\$/dry T)	Report Section
Farm Gate Price	25.00	25.00	Section 4.1
Harvest and Collection	22.20	47.20	Section 6.1
Landing Preprocessing			Section 6.3
Debark/Delimb	6.10	53.30	
Size Reduction	6.10	59.40	
Storage	3.80	63.20	Section 6.2
Preprocessing			Section 6.3
Size Reduction	5.40	68.60	Section 6.3.1
Drying	17.20	85.80	Section 6.3.2
Dust collection and miscellaneous equipment	0.80	86.60	
Handling	1.50	88.10	Section 6.5
Transportation	14.80	102.90	Section 6.4
Ash Dockage	0.00	0.00	Section Appendix C
Total Delivered Feedstock Cost		102.90	
Delivered Feedstock Specifications			
Ash Content	<1%		
Moisture Content	9%		

4. Approach of the 2017 Design Case

The 2013 SOT Design presented above illustrates the barriers of the conventional biomass supply system that will limit expansion of a national biorefinery industry. This section will address three specific challenges for reducing the current estimated feedstock costs to achieve the \$80/dry T cost target. These challenges include price of biomass resources (grower payment), feedstock quality, and the ability of the logistics system to handle increased volumes at reduced costs. First, cumulative grower payment (access costs) must be reduced. This does not suggest that the per producer payment will decrease; rather it will be shown that the grower payments can be reduced by selecting multiple feedstocks, thereby decreasing the total amount of any single feedstock, thus working lower on the supply curve and reducing the access cost. Second, the conventional biomass supply system has no mechanisms for preserving or addressing feedstock quality. Biorefinery conversion efficiency is tightly coupled to the quality of the feedstock⁶. There are operations that can be included in the feedstock logistic supply system that address these quality issues and deliver a feedstock that meets the in-feed quality specifications. Third, technological improvements in all supply chain unit operations must occur to reduce logistics costs and handle larger more dispersed volumes of biomass material. This section discusses the general approach of the 2017 Design Case for addressing these challenges.

4.1 Addressing the Farm Gate Price Challenge

The Billion Ton Update (BT2)⁵, 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, collection and chipping at the landing, compensation for soil nutrient removal, and grower profit. However, feedstock logistics designs also consider harvest, collection, and chipping operations within logistics costs, therefore it is necessary to subtract harvest, collection, and landing preprocessing costs from the reported farm gate price and refer to difference as the grower payment. The grower payment would then consist of feedstock production, soil nutrient replacement, and profit margin.

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 from that area. BT2 scenarios provide projected farm gate prices for each county in the United States for all available feedstocks for the years 2012 through 2030. When examines the BT2 results, very little biomass is accessible until farm gate prices reach \$40/dry T. This means that producers are not willing to allow access to their biomass until they are offered at least \$40/dry T farm gate price.

Figure 4 below shows the step-wise supply curve for marginal and average feedstock costs versus supply quantities accessible from the BT2 scenario. These cost curves are used to determine the quantity of biomass that can be accessed at the different farm gate prices. The BT2 data is generated in increments of \$10/T cost targets, hence the step functions. It is important to note the difference in marginal versus average costs. The width of the boxes displays the increased amount in total tons that shows up for each type of biomass as the price increases, these incremental costs represent the marginal costs. Looking at Figure 4, at \$50/dry T around 40 million dry T of woody residues could be procured and a small amount of dedicated feedstocks. At \$60/dry T, an additional 160 million dry T of stover could be procured and an additional 15

million dry T of dedicated feedstocks. The average price is the weighted average of the amount of biomass at \$50/dry T with the amount of biomass at \$60/dry T. Note that the biorefinery would not pay the marginal cost of feedstock but the average cost.

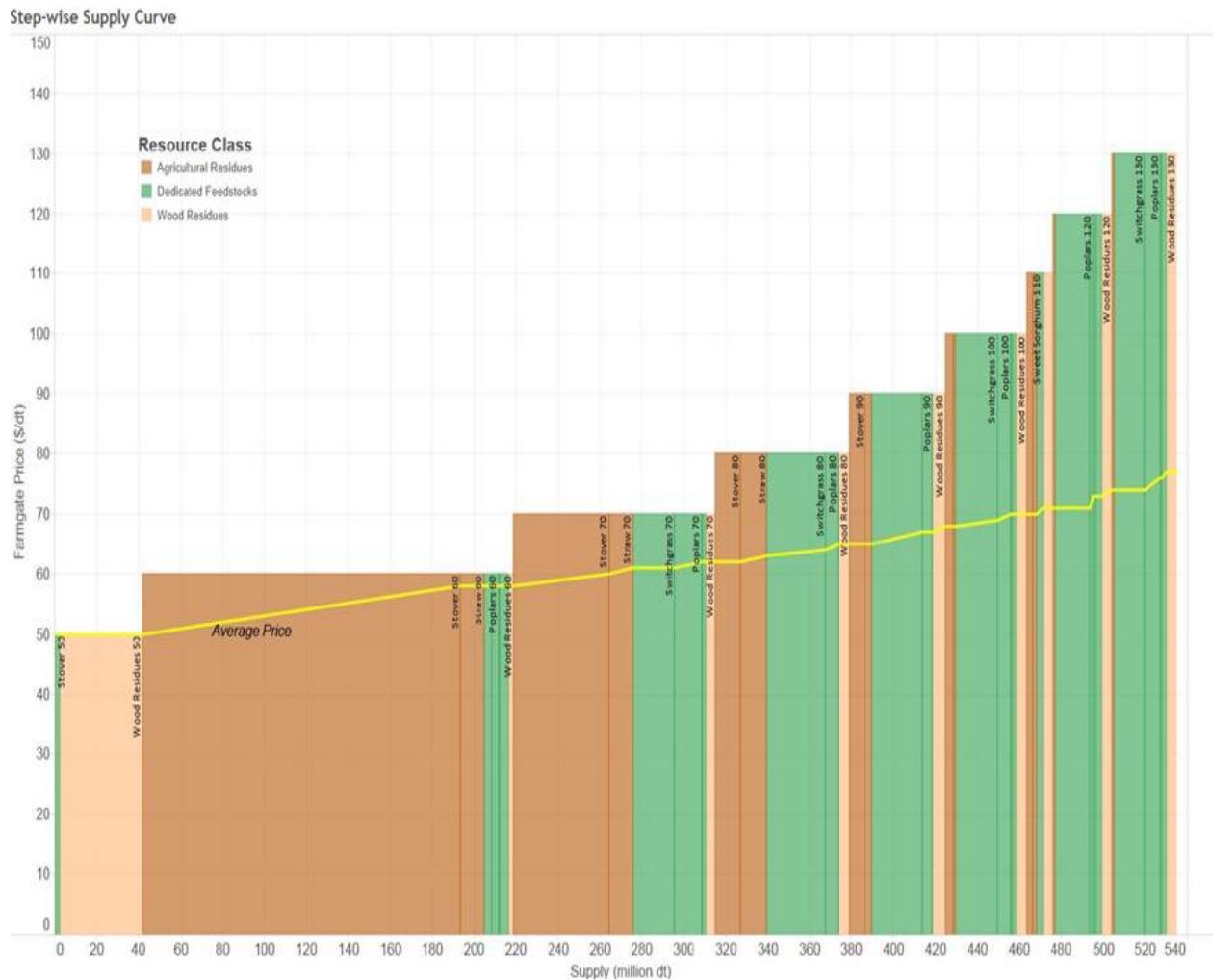


Figure 4. Marginal and average farm gate costs versus supply quantities derived from BT2 data for the U.S. predicted out to 2022¹.

Figure 5 below shows a national set of farm gate prices for the U.S. At \$55/dry T over 100 MM dry T of woody biomass can be secured, but only about 15 MM dry T of poplar. If 100 MM dry T of biomass was required to supply a biofuel industry, one path would be to pay an average of \$55/dry T for 100 MM dry T of woody biomass. A blended strategy (i.e. blended feedstocks) could select 85 MM dry T of woody biomass at \$50/dry T and supplement the rest with a combination of wheatstraw, sweet sorghum, and poplar at \$50/dry T for an average price \$50/dry T. This would decrease the overall cost of biomass by \$5/dry T. What still needs to be determined is if blended feedstocks will behave like a single feedstock in a conversion facility. The testing of blends is currently underway for several conversion technologies to determine feedstock behavior from front-end through finished blendstock.

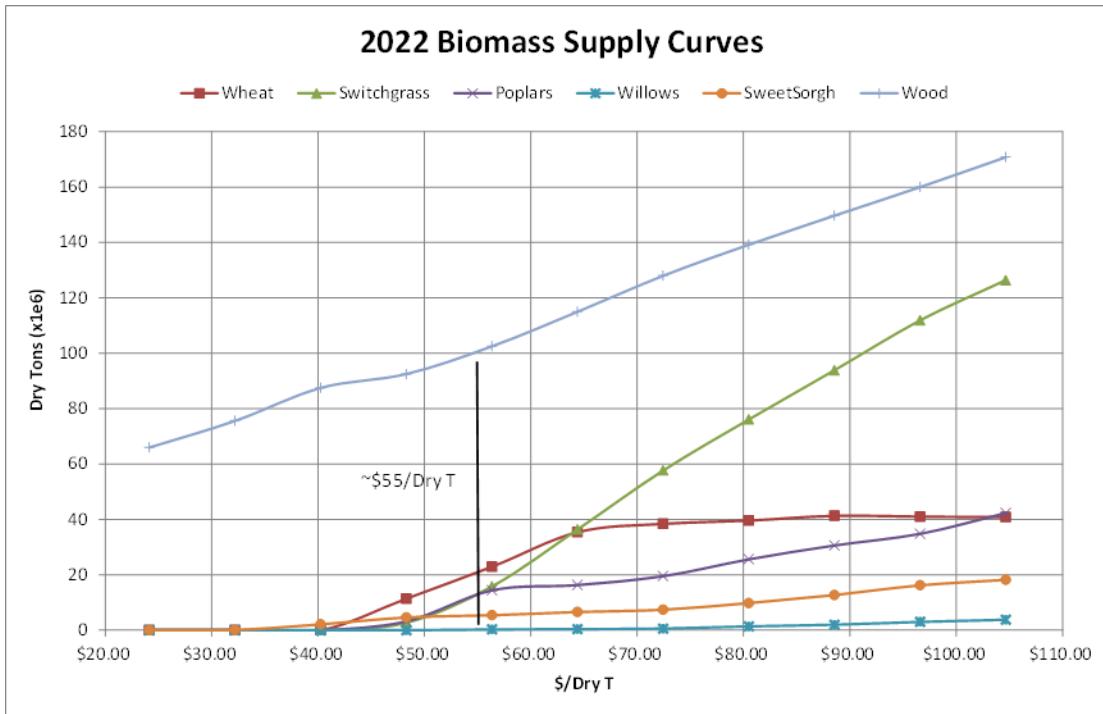


Figure 5. U.S. Marginal farm gate prices projected for 2022 by POLYSYS ¹.

Note: In this supply, Poplars is considered pulpwood, Wood is considered woody residues.

The 2017 Design Case will implement the multi-feedstock approach via a blended feedstock strategy. In this strategy, referred to at the least cost formulation (LCF), multiple feedstocks are blended together in specific ratios determined by availability, access costs (grower payment), and composition. The specific blendstocks chosen are conversion pathway specific based on in-feed specifications and are discussed in the conversion chapters later in this report. For further discussion on Least Cost Formulation see Appendix B.

4.2 Addressing the Feedstock Specification Challenge

As previously stated, compliance with biorefinery in-feed quality specification has a significant impact on bio-oil yield. Using multiple types of feedstock provides an opportunity to adjust feedstock quality; given the right blendstocks, it may be possible to blend to meet a specific biorefinery in-feed specification; thereby, reducing the need to implement a more aggressive quality control system or purchasing only the biomass that can meet the quality specifications. Blending for such purposes is a common practice in many industries. For example, blending grain to adjust quality is standard practice in the U.S. grain industry ¹³. Similarly, different grades of coal are blended to achieve compliance with regulations regarding sulfur and nitrogen emissions in the power generation industry ^{14 15}. Furthermore, the animal feed industry uses a range of feedstocks blended together to meet the specific nutrient requirements of the target animal ¹⁶. Finally, relatively high-ash content biomass sources are mixed with low-ash coal to allow their economical use in co-fired biopower generation ¹⁷. By using the blended feedstock strategy, it may be possible to develop feedstocks that conform to a desired moisture, and/or ash

specification without using expensive preprocessing technologies. More research is required to understand the behavior blended feedstocks will have on overall fuel conversion. Even though it may be possible to blend to 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 additional research and development focus to better inform blended feedstock development.

4.3 Addressing the Logistics Challenge

Moving beyond high yield areas reduces the quantity of feedstock that can be passively eliminated if not compliant with feedstock specifications. In other words, in Iowa, with high yields, only dry, low ash material can be secured while leaving the remainder of the residues for other uses. In Kansas or other lower yield areas, there may not be enough extra biomass to allow such down selection of material. The high logistics costs of the baseline case, compared to the 2012 Conventional Design Case, are mostly attributed to resource dispersion and moisture mitigation.

Additionally, the elimination of waste heat in the baseline case more realistically reflects the costs incurred by the system, since it is unreasonable to assume that the conversion facility and the depot will be co-located where they can take advantage of the waste heat. Therefore, improvements in supply systems are needed to reduce the sensitivity of grinding and transportation to biomass moisture and ash content. Additional quality specifications currently not addressed in these designs such as, high heating value (HHV) and low heating value (LHV), could also become important in future design cases. Solutions to these barriers could include fractional milling and high moisture densification with a cross flow pellet drying system. Finally, as multiple feedstocks are incorporated into the system, logistic solutions also are needed to reduce the cost that would occur due to the complexity of handling multiple types of biomass.

The blended feedstock strategy, which relies on the availability of multiple feedstock sources within an economical supply radius, adds an additional logistics challenge to the 2017 Design Case. The complex nature of this approach could bring in more business management overhead to simultaneously manage multiple feedstocks. However, this approach could increase the total amount of biomass in an area that would traditionally not have enough of a single resource to economically supply a biorefinery. Overcoming the logistics challenge of a blended feedstock design will require system-level solutions. The 2017 Design Case explores two approaches: (1) an agronomic solution based on integrated landscape management, and (2) 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 low productive 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 pulpwood stand to improve biodiversity or 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 stand 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 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 different preprocessing requirements.

5. 2017 Feedstock Supply System Design

The least-cost formulation (blending) approach to resource selection was introduced in Section 4.1 as a solution to the Farm Gate Price challenge (i.e., to reduce feedstock access costs). This section builds on the 2013 SOT thermochemical conversion scenario located in eastern South Carolina to illustrate the least-cost formulation approach to resource selection for the 2017 Design Case. Note: A similar approach is done for the biochemical conversion pathways based on herbaceous residues and energy crops. This approach challenges the single-feedstock paradigm by allowing available resources to compete based on cost, quantity, and quality considerations. It is also shown that such an approach can contribute significant cost reductions to biomass feedstock supply.

5.1 2013 State of Technology

Most cellulosic biomass supply systems are designed around a single feedstock, typically clean woodchips for thermochemical conversion processes like fast pyrolysis. Note that these supply curves represent the projected cost (i.e., farm gate) and quantity available in 2017 based on data from the BT2 analysis. Figure 7 shows the estimated supply curve for pulpwood based on the stumpage price the buyer is willing to pay. Note that if the biofuel industry starts to require large amounts of pulpwood then the price of pulpwood will respond according to an increased demand. The price of pulpwood will increase substantially for large quantities to move into the system. The 2013 SOT Design was developed around the concept of a single biorefinery and the supply system was designed accordingly. The 2017 Design Case is designed around supplying biomass to a developing industry and not for a single biorefinery.

The woody biomass scenarios/information in the BT2 database was developed using a different set of algorithms and models than the herbaceous biomass. The usage of the data needs to be adjusted accordingly. The woody scenarios were generated from estimates from the U.S. Forest Service Forest Inventory Model and represents estimates of large areas and not county level estimates as is the case for herbaceous biomass. Due to this difference, for estimates of grower payments for small demands (<1 Million dry tons), it is assumed that the current market price would be more appropriate to reflect local supply costs. Figure 6 shows the historical stumpage pulpwood prices for the southern U.S. The prices reflect approximately 57 million tons of pulpwood purchased each year. The stumpage price is for green biomass (as opposed to dry). If you assume around 50% moisture for pulpwood, the grower payment would be double the stumpage price and average around \$20/dry T. A single biorefinery would require less than a million tons of biomass each year and hence would not significantly influence the stumpage price currently being paid. A single biorefinery could expect to pay around \$20-\$25/dry T when competition for the biomass is low. For the 2017 Design Case we assumed the high end for a single refinery of \$25/dry T, assuming that they will be competing for the biomass and thus driving the prices towards the high end.

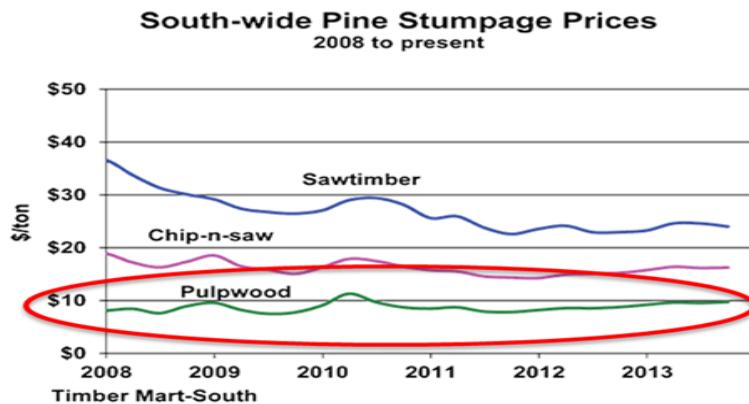


Figure 6. Historical pulpwood stumpage prices for the southern U.S. in \$/dry Ton
<http://www.timbermart-south.com/prices.html>.

There is a significant difference in the requested amount of biomass that will be required to fuel an industry versus a single biorefinery. Oak Ridge National Laboratory in their Billion Ton Update⁵ estimated that upwards of 35 million dry T of woody biomass will be required for the thermochemical biofuel conversion industry as it matures toward the 2022 Design Cases. Based on Figure 7, the farm gate price to access 35 million tons would be around \$50/dry T. It should be noted that this is based on 2022 estimates, there may in fact not be a demand as high as 35 million tons, but it is important to analyze the system based on projected industry demand and identify potential barriers that will surface when analyzing a single biorefinery supply system. What is important is to identify that as the biofuel industry grows it will begin to require large volumes of biomass that will in fact influence the supply dynamics and increase the cost to access the biomass. If the industry does grow significantly in the future then the farm gate price will increase and could be barrier that needs to be addressed.

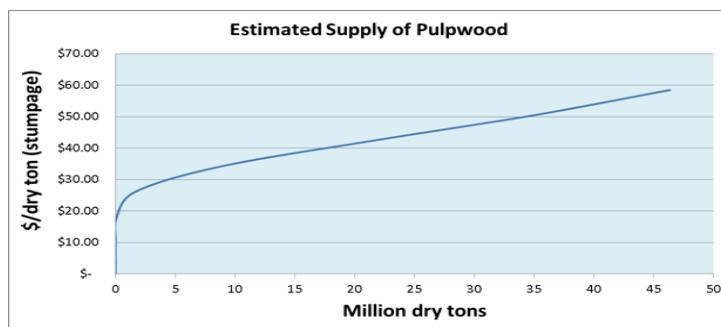


Figure 7. National estimated pulpwood stumpage prices¹.

5.2 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, often 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 grower payment cost curves shown in Figure 6, which are derived from historical prices. 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 biomass feedstock. The impact of this approach is shown in Table 5. The 2013 State of Technology assumes a 100% supply of pulpwood of 909,100 dry T at an estimated \$60/dry T farm gate or a \$25/dry T access cost. In comparison, the 2017 Design Case blend of 45% pulpwood, 32% wood residues, 20% C & D waste, and 3% switchgrass results in a weighted average feedstock cost that is nearly 15% lower than the access cost of pulpwood alone.

Table 5. Resource access cost estimate ⁵ and INL Material Solid Waste (MSW Data)

	2013 SOT		2017 Target	
	Access Cost (2011 \$/dry T)	Tons	Access Cost (2011 \$/dry T)	Tons
Pulpwood	25.00	909,100*	25.00	425,700*
Wood Residues	NA	NA	26.35	412,800**
Switchgrass	NA	NA	19.67	25,800
C&D	NA	NA	8.15	172,000
Totals	25.00	NA	21.90	1,036,300

*assumes 10% loss of material to debark/delimb ¹⁸

**assumes 40% loss of material to clean up residues ¹⁹

6. Feedstock Supply System Unit Operations

A biomass feedstock supply system also called supply chain or logistics system is a complex organization of operations necessary to transform biomass into usable feedstock that can feed into a conversion process. The feedstock supply system encompasses all operations necessary to format and move biomass from standing at the location of production (field or forest) to the conversion reactor infeed system at the biorefinery²⁰. The logistics of biomass harvest and collection, storage, preprocessing, handling, and transportation represent a large challenge to this industry. In this section we will discuss the different components (unit operations) of a feedstock supply system.

6.1 Harvest and Collection Operations

Harvest and collection operations encompass all activities required to cut and remove feedstock from the place of production to field side or landing. These operations also condition material for downstream use and can perform preliminary quality mitigation (moisture content, ash content etc.). The specific method of harvest is highly dependent on feedstock type. For example herbaceous feedstock (i.e., corn stover, switchgrass, wheatstraw, etc.) harvest systems could include a combine, rake, baler, windrower, and or forage chopper while a woody feedstock (i.e., thinnings, slash, pulpwood, etc.) harvest system could include a feller buncher, skidder, and chipper. Due to growing seasons, variations biomass harvests can occur due to environmental and crop conditions.

Collection involves moving harvested biomass to a centralized location, such as a field side stack or a landing deck. Potential collection equipment includes roadsiders, loaders, skidders, and cable systems. Like harvest, collection also only occurs during a specified window where optimal conditions can be achieved to maximize biomass quality and reduce material loss. For a herbaceous supply system, baling and collection typically occurs after some field drying. For a woody system collection typically happens at the time of harvest. However, for a woody system, there may be some cost advantages to delay collection until harvest is complete to improve collection efficiency and take advantage of field drying while an herbaceous system there may be advantages for using a single pass supply system where the biomass is baled as it is harvested.

6.1.1 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 lower stover ash content and higher removal yields. 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. States²¹. Studies comparing single-pass to multi-pass harvest systems demonstrate total ash contents in the range of 5% to 10%, respectively²², which shows that single-pass harvest systems have the potential to minimize soil contamination in production harvest operations. Table 6 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 6 feedstocks 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%²³. 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 6. 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 equipment²³. Traditional, multi-pass corn stover bales from Stevens County, Kansas, were found to range from 10 to 25% ash by mass (Figure 8), which represent increases in feedstock cost of \$4.88 to \$20.23/dry ton compared to the baseline level of 5% ash. Feedstock replacement and ash disposal costs account for the change in value, which is on the order of \$2.25/dry ton for each 1% ash above the baseline of 5%.

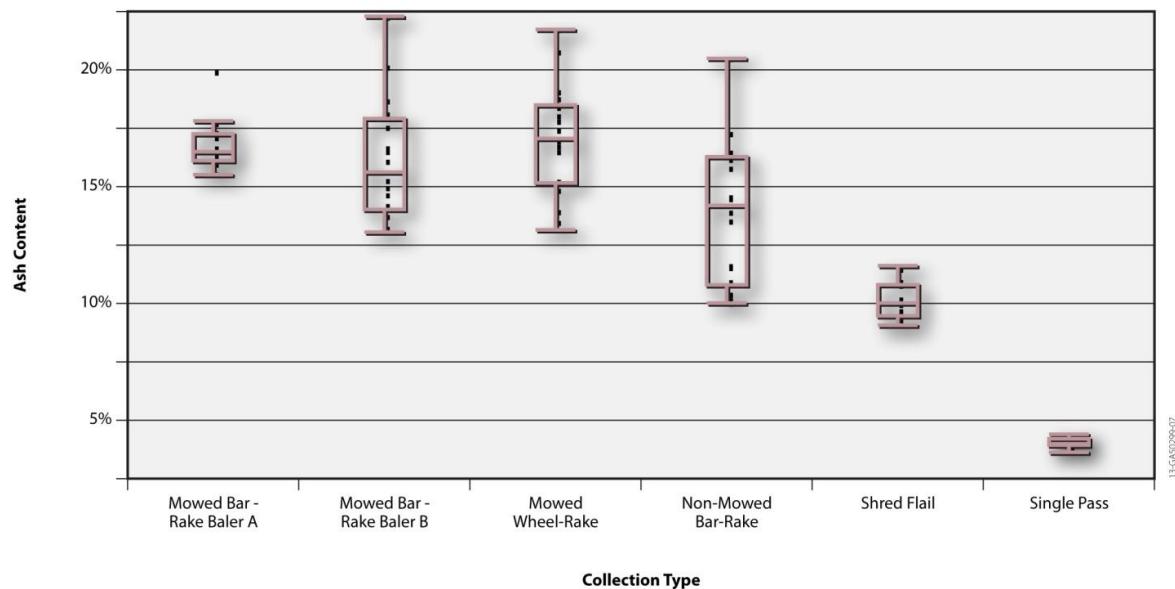


Figure 8. Ash content of corn stover bales from Stevens County, Kansas, that are collected using single pass baling and a variety of multi-pass methods, including two rakes, two balers, a mower, and a flail shredding windrower.

Single-pass bales collected from the southwest region of Kansas contained only 4% ash (Figure 8), 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 ²⁴.

In a separate study, field conditions and harvest efficiency were shown to impact corn stover bale ash content. Figure 9 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.

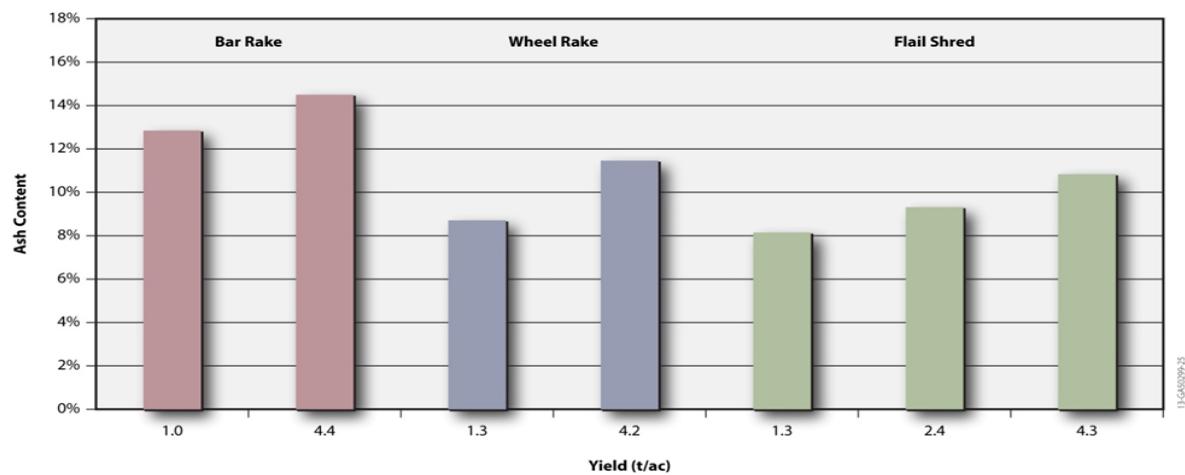


Figure 9. Ash content (bars) and yield (text) of corn stover bales from Stevens County, Kansas, show the impact of collection efficiency and windrowing equipment on yield and soil entrainment.

6.1.2 Improvement of Harvesting and Collection

Ongoing research addresses issues in harvesting. For example single pass harvesting systems are being developed to improve the harvesting and collecting operational efficiencies while improving the quality of material harvested by reducing induced ash from raking. A single pass system has fewer operations, less soil compaction, reduced cost and less soil contamination. Moreover, a single pass harvest and collection system targets harvesting the top portion of the plant leaving the lower plant material on the field, the harvested material has less nutrient value and more stable moisture content than the lower sections of the plant.

Harvest and collection improvement strategies for ash reduction 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 minimize cost, optimize yield, ash content, and sustainability. Further ash reduction may come from delaying harvest until after the first freeze, or by overwintering²⁵. However, overwintering comes with the penalty of reduced yield because of leaf loss. To reduce moisture and ash contents, one option may be to focus on the upper stalk, but at a decrease in yield^{26 27}, which will have an increase transportation and handling costs²⁸.

Harvest and collection operations typically focus on optimization of conventional equipment and processes. Optimization activities include improved fuel economy, faster harvesting, higher density balers and better collection efficiency. New research is now looking at new equipment and processes. Not all areas will reap the benefits initially from this research. For example single-pass and advanced, multi-pass harvesting systems (i.e., specialized combine operation or windrowing equipment) that reduce costs and improve ash content will likely emerge first in the highly productive regions. In less productive areas, conventional multi-pass systems will be

operated with greater focus on reducing feedstock moisture content and improving storage stability to avoid ash enrichment throughout storage⁸.

6.2 Storage

Storage involves stockpiling material to either provide an adequate lead time to more expensive processes downstream, accumulate appropriate quantities making movement more economical, or minimize the footprint and storage infrastructure at the refinery. Storage is mainly comprised of infrastructure, which can include cement, gravel or asphalt pads, silos, storage bins, and tarps.

Additionally, storage allows feedstock preservation to enable year-round biorefinery operation from seasonally available feedstocks. Harvesting of herbaceous feedstocks, specifically agricultural residues such as corn stover and cereal straws, occurs within limited operational windows that may span weeks or months, yet ideally, 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 to storage losses is to control biological degradation and to 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.

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 or loader and covered with high-quality hay tarps which are periodically tightened to prolong tarp life.

6.2.1 State of Technology Herbaceous Residues/Energy Crops

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

than 20%) 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 10). 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.

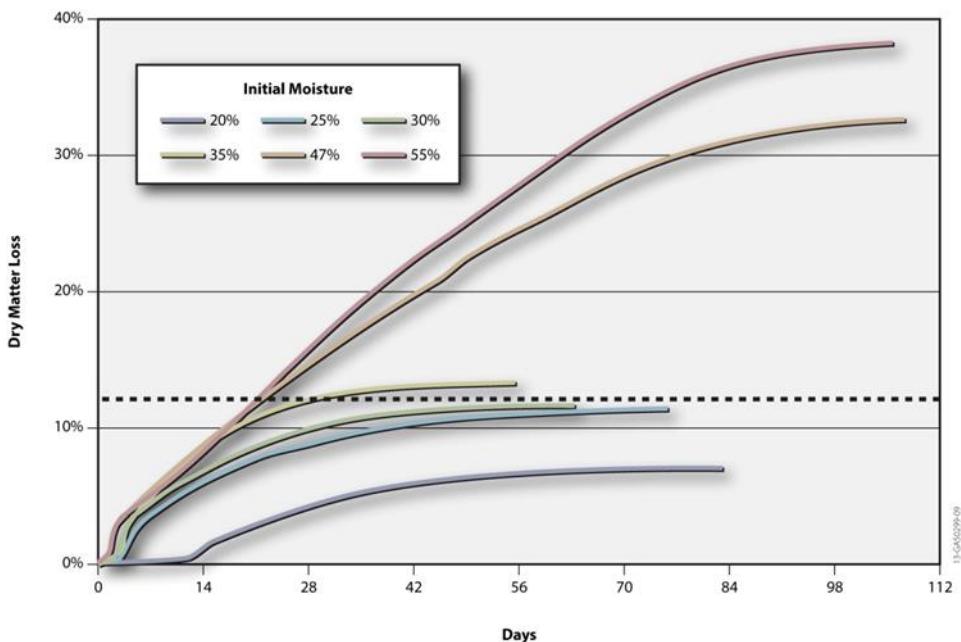


Figure 10. Dry matter loss of corn stover in laboratory storage conditions at fixed moisture contents 32.

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 10). 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 11 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 10, 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 11), 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 12 shows the change in the glucan and xylan contents of the corn stover that suffered 35% dry matter loss during storage. 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; ²⁹). 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.

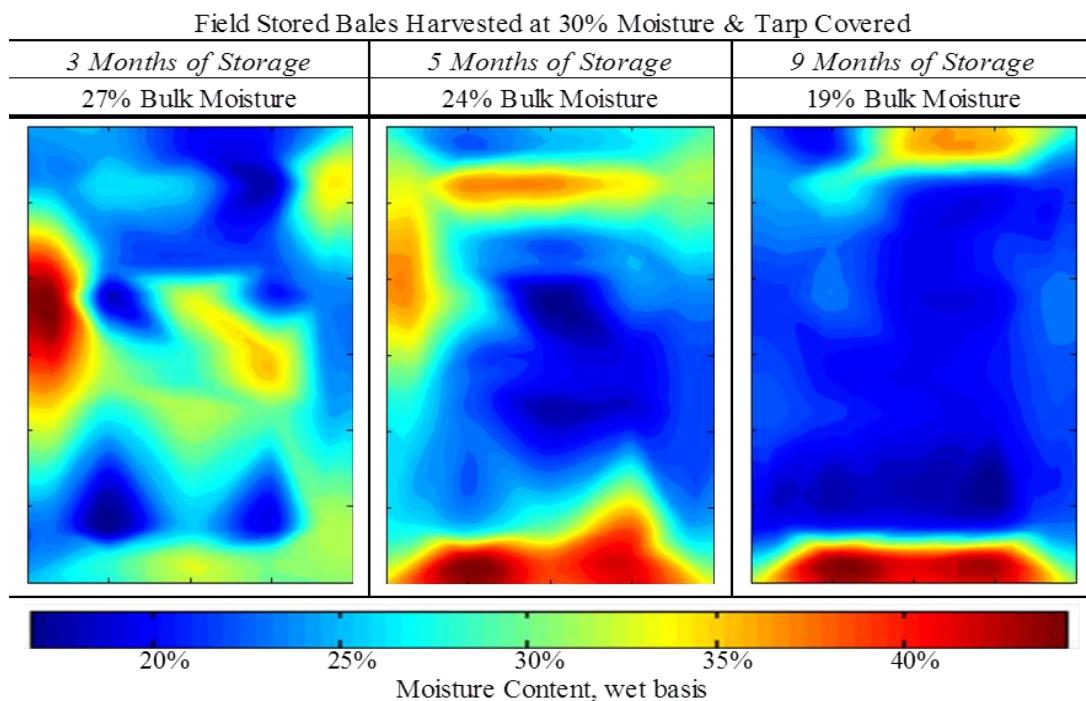


Figure 11. Change in moisture content of stacked corn stover bales in northern Iowa. Image depicts the variation in moisture content of a four-high column of bales stored outdoors for up to 9 months ³².

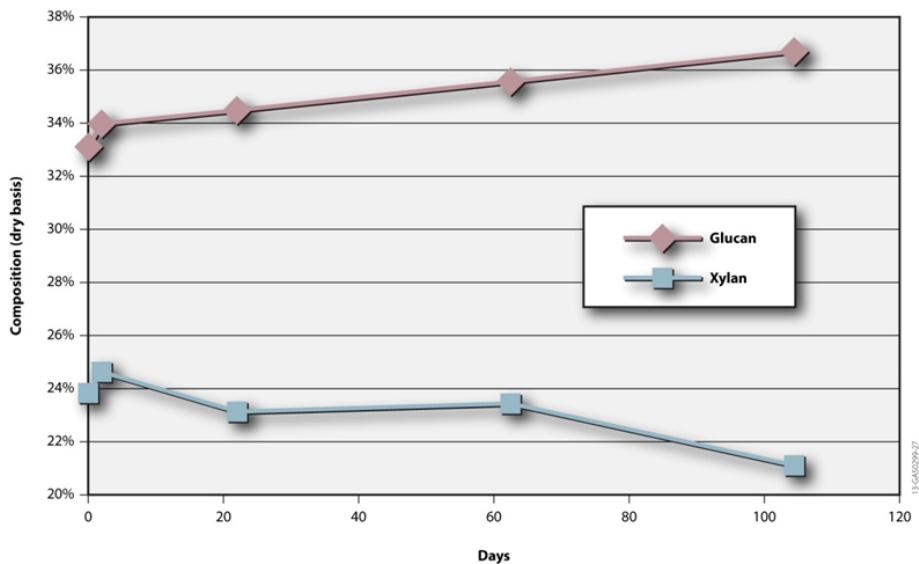


Figure 12. Change in glucan and xylan over time as corn stover is stored in laboratory reactors ³².

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 2015 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 and is explained in more detail in the next section.

6.2.2 State of Technology Woody Biomass

Unlike crop residues, woody feedstocks may be harvested as needed in most southern US regions and therefore have less need for long-term storage. However, in-field storage may be used to reduce the moisture content of whole tree or delimbed piles ³⁰ and stacks ³¹ depending upon pile configuration and local climate. The 2013 Design Case assumes 10% reduction in moisture content in pulpwood from 50% to 40% as a result of field drying prior to preprocessing at the landing. This is a very conservative assumption and therefore the 2017 Design Case assumes a 20% reduction in moisture from 50% to 30% as a result of field drying prior to landing preprocessing. Although not used in the 2013 Design Case baseline, wood residues (limbs and tops) are assumed to have a moisture content of 40% both before and 30% after storage.

Current SOT and 2017 Design Case rely upon available whitewood chips from pulpwood and residues (tops and limbs) preprocessed at the landing. Dry matter losses during in-field drying of residues is expected to be low; measured losses under laboratory controlled conditions at temperatures ranging from 15° to 35° C ranged from 1% to 2% over one month ³². Storage of logging residues in windrows and bundles was reported³³ to result in a <1% dry matter loss per month in storage; most losses were attributed to the loss of foliage. While the mechanical loss of small tops and limbs during chain flail debarking is reported to be 15% by mass ³⁴, all costs incurred to get the material into the debarked chip format will be attributed to the mass of the chipped biomass. In this design, the flail and trommel remove material that is out of specification for ash content and is thus not a part of the marketable portion of the biomass.

Following landing preprocessing the current design case relies upon limited on-site chip storage sufficient to supply three days of feedstock. Chip storage piles present favorable conditions for microbial growth, biological self-heating, and chip deterioration, which results in feedstock loss, quality changes, and risks to worker health and safety ^{35 36 37}. On-site chip quantities are limited to reduce these risks. Design assumptions call for chips to be stored outdoors and handled using a front-end loader. In the 2013 baseline short-term chip storage of 40% moisture biomass is assumed to suffer 5% dry matter loss. This assumption is considered to be conservative for the timeframe in question. INL research using intermediate scale pine chip piles shows temperature increases in the range of 60 to 65°C within three to seven days of storage depending on location within the pile ³⁸. Extended exposure to these high-temperature conditions results in acetic acid formation and changes to color and texture of the chips ³⁹. In laboratory studies conducted by INL using fresh pine chips at 50% initial moisture, dry matter loss in storage simulation reactors reached 1.5% by three days in storage during the initiation of self-heating, 2.5% by one week when a maximum temperature of 60°C was reached, and 6% by one month as shown in Figure 13. Based on these research samples, the dry matter loss assumption of 5% in the 2012 Design Case baseline does not account for longer storage lengths on-site beyond the three day window, potential pile wetting due to precipitation and/or moisture migration, and mechanical handling losses.

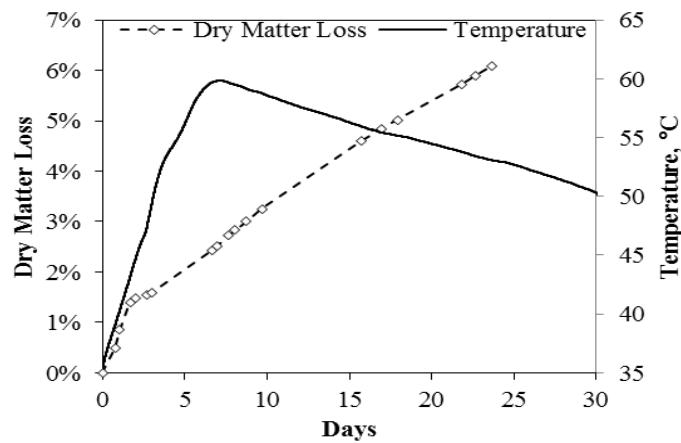


Figure 13. Dry matter loss and self-heating of 50% initial moisture pine chips stored under aerobic conditions using laboratory scale reactors at INL.

6.3 Preprocessing

Preprocessing includes any physical or chemical activity that changes the material such as: chipping, grinding, drying, and densification. Preprocessing may also 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. Different types of preprocessing operations described below:

6.3.1 Comminution

Biomass size reduction, broadly referred to as comminution takes biomass from its as received condition (i.e., baled, log, or coarse shredded) to the final particle size specification required by the end user. Energy-intensive mechanical preprocessing operations like comminution tend to be expensive; therefore optimization of this stage of preprocessing allows opportunities to reduce the amount of equipment required and costs. Several aspects of size reduction are considered in order to optimize the system to reduce cost. Design and performance considerations include the size distribution of the final milled feedstock and the energy required to process the material. Each size reduction process encounters biomass loss which has a double cost associated with the process. First, the lost material must be accounted for by accruing additional biomass to make up for the loss. Second, all cost prior to the loss are lost so any losses late in the supply chain can have substantial economic impacts. For instance, encountering a 5% loss of material at the biorefinery will mean that the harvest, collection, chipping and hauling costs will be lost for that portion of the material.

Size reduction, or comminution, is an essential component of biomass logistics as downstream conversion prefers a specific in-feed particle size. Additionally, size reduction aids in downstream handling and transportation by increased load density and flowability. Comminution can be conducted with either chippers or grinders but the cutting mechanisms are quite different. Chippers use knives to cut or shear material while grinders use hammers to smash or crush material. In general, the type of material dictates the type of comminution equipment to use. In particular, grinders are used for contaminated material like C&D waste or wood residue due to their reduced sensitivity to wear compared to chippers. Size and configuration also play a role in equipment selection as chippers tend to perform better with uniform orientation of in-feed while grinders do not have an orientation preference.

Hammer mills generally are considered the current SOT for biomass comminution due to their high throughputs and versatility in processing a wide range of materials. Grinding and separation process is described below.

6.3.1.1 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.

6.3.1.2 Pneumatic separation

Pneumatic separation has been found to be effective at increasing throughput capacities of grinders by separating out the finer particles quickly so that they do not remain in the grinder where they reduce grinding efficiency particularly with low density feedstocks like biomass. Pneumatic discharge systems can increase capacity by 3 to 4 times. Without pneumatic discharge, processed material is thrown in every direction including up the infeed. The pneumatic system helps to force the processed material quickly in the right direction – through the screen⁴⁰. Figure 14 shows the improvement in comminution capacity due to the addition of a pneumatic transfer system. Additionally, pneumatics can affect the quality of feedstock by removing moisture and potentially ash illustrated in Figure 15, Figure 16.

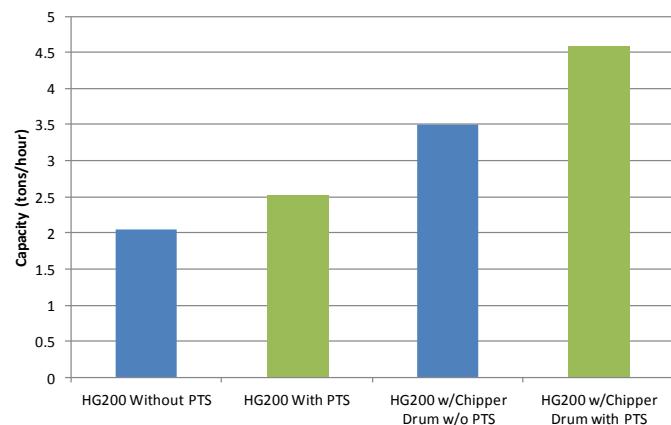


Figure 14. Comparison of comminution capacities (tons of throughput per operating hour) for woody biomass as a result of adding pneumatic transfer assist (PTS)³⁸.

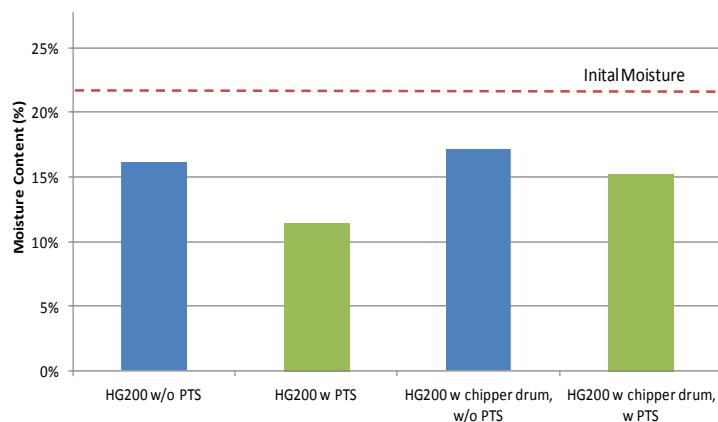


Figure 15. Change in moisture content during comminution using pneumatic transfer assist (PTS)³⁸.

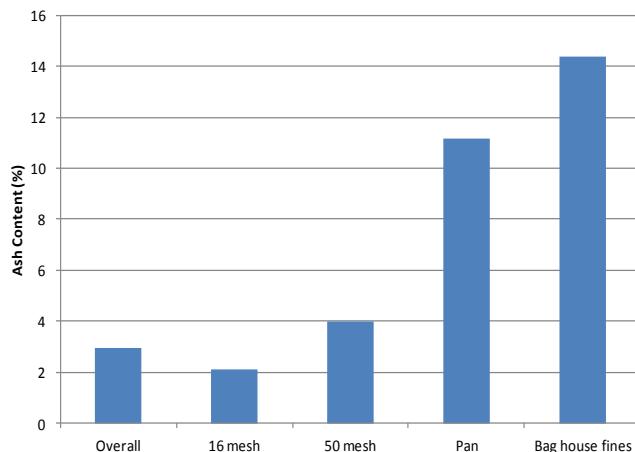


Figure 16. Ash content in various screen sizes for pinyon-juniper biomass ^{38 41}.

6.3.1.3 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, all 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.

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 17. 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.

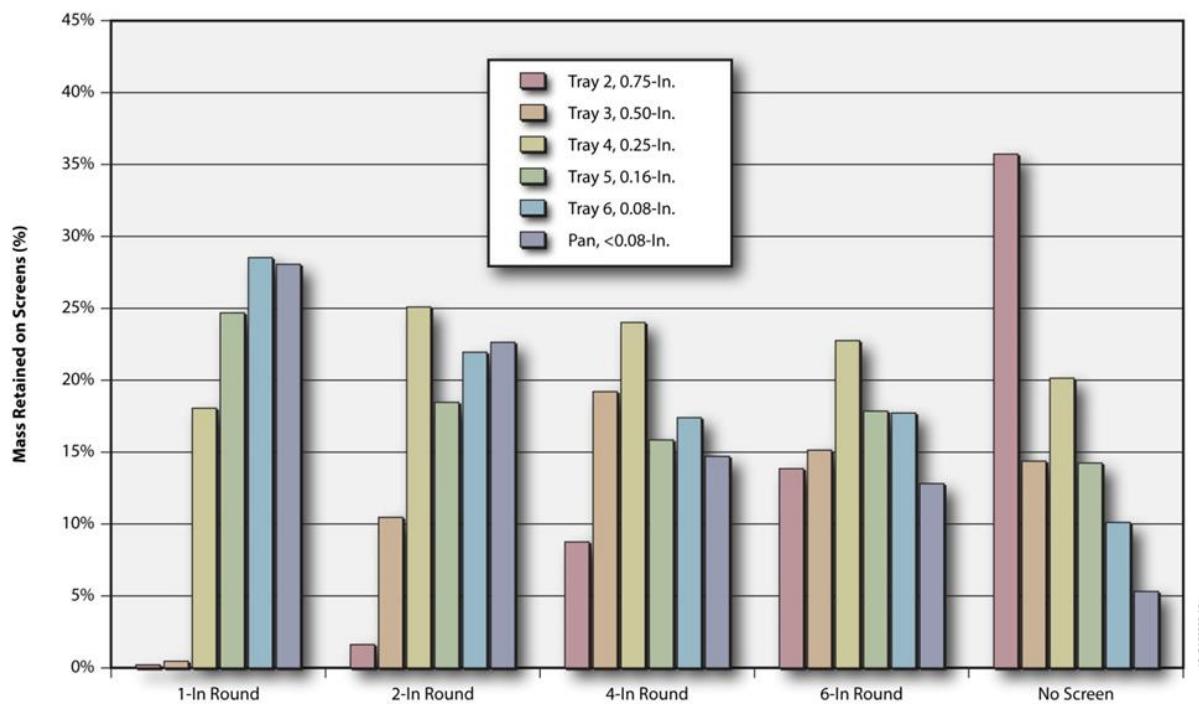


Figure 17. Particle-size distributions for five grinding scenarios ⁴¹.

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 18 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 18, 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.

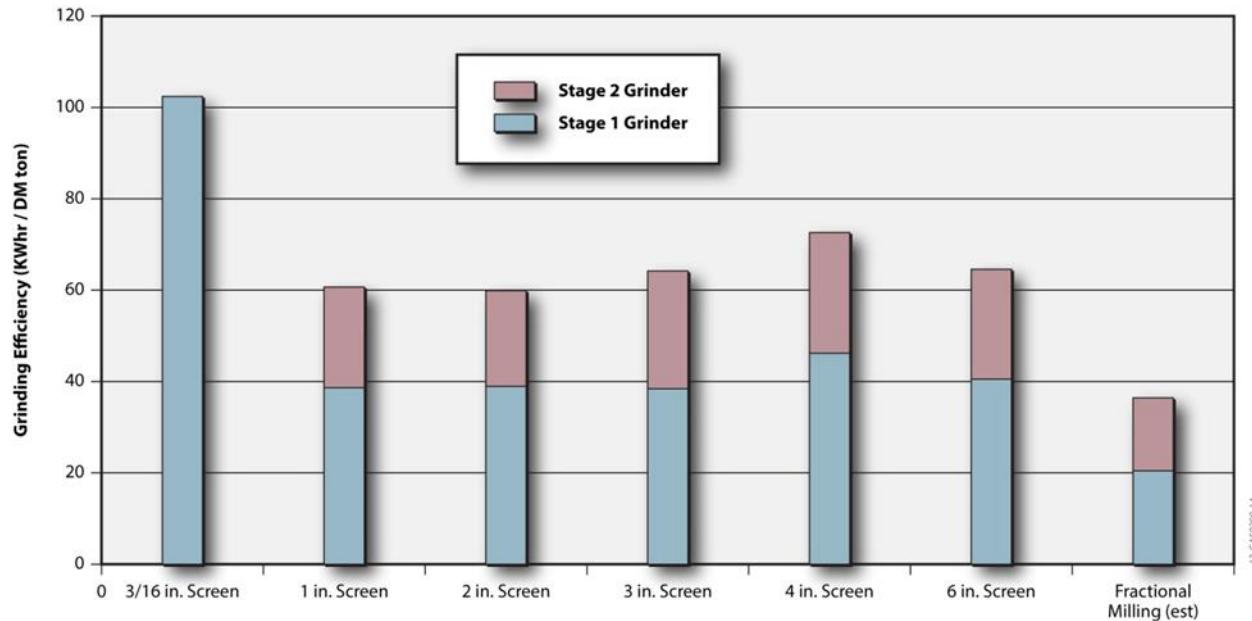


Figure 18. Comparison of conventional, two-stage grinding and fractional milling⁴¹.

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 18). 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 19 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.

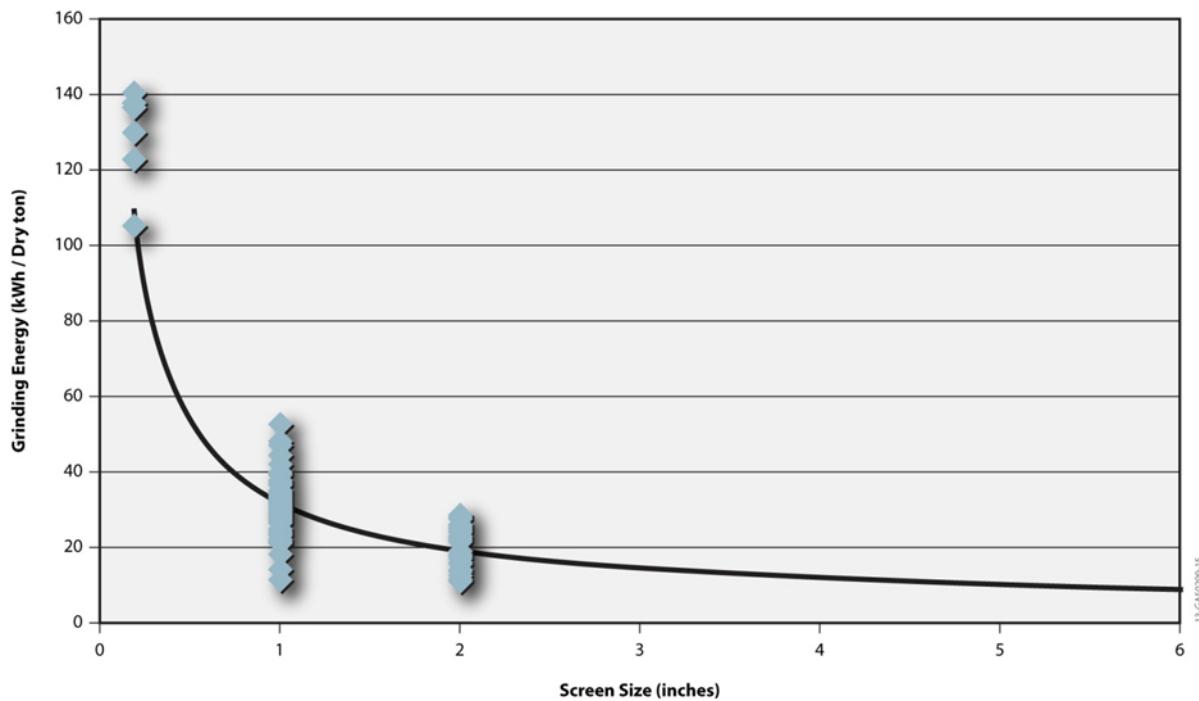


Figure 19. Grinding energy and throughput is highly dependent on screen size ⁴¹.

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 20, 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 under higher moisture scenario.

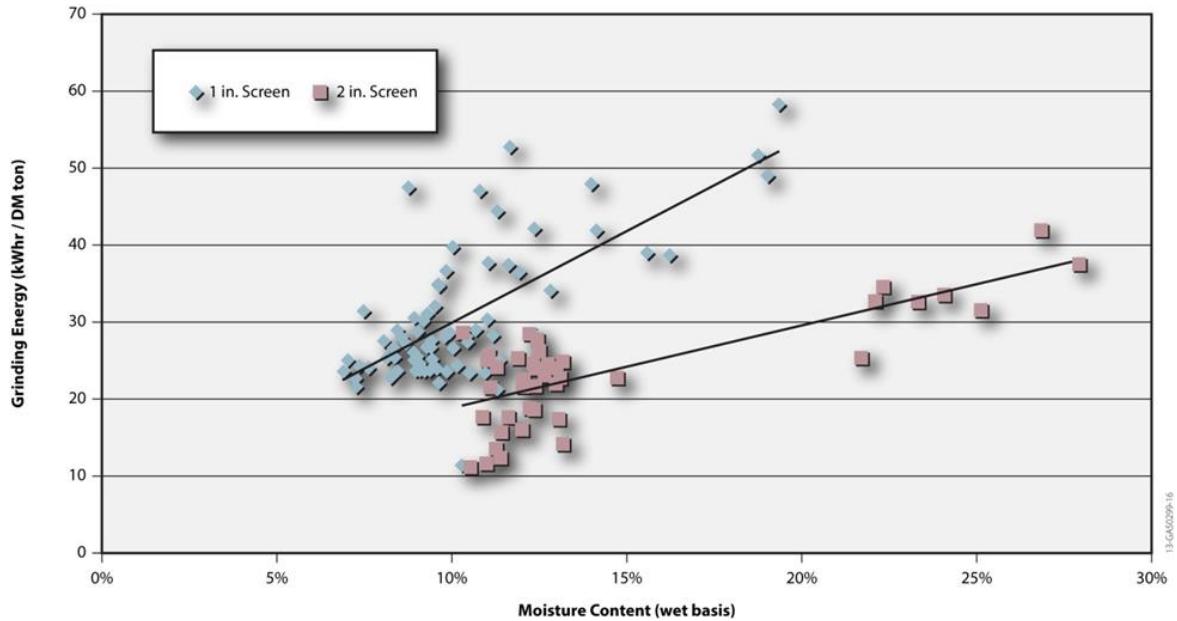


Figure 20. Hammer mill energy consumption is highly dependent on biomass moisture content (INL PDU Data).

6.3.1.4 Fractional Milling Dry Biomass

In this scenario, the data presented in Figure 18, Figure 19, and Figure 20 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 19, 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).

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 1/4-in. particle size specification, the separator will be configured with a 1/4-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 17, we assume that following the first-stage hammer milling through a 6-in. screen, approximately 45% of the material will pass through the 1/4-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).

6.3.1.5 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 20) shows that the sensitivity of energy consumption to moisture content decreases with an increasing screen size. According to Figure 20, 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 18) 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.

6.3.2 Drying

Drying is important from various standpoints. Drying permits long-term storage without deterioration and aids in the production of a better quality product. Drying could occur at the field, biorefinery, depot, or during unit operations. Agricultural materials and therefore biomass materials are dried using a variety of procedures due to differences in material properties and

desired outcomes. Factors that influence drying technologies include tolerance to temperature (i.e. materials may cook or undergo adverse physical changes), response to humidity (i.e. material undergo physiological may require specific air humidity), compression strength of material (i.e. materials may crush or deform and must be dried in thin layers) and fluidity (i.e. poor flowing material must be adjusted for proper angle of repose). Additionally quantity of materials as well as desired rate, and environmental conditions (weather) influence the technology applied.

The simplest form of drying is passive drying or field drying. This type of drying takes advantage of existing environmental conditions to reduce biomass moisture in the field or stand, but it is not consistently reliable across all spatial and temporal variations. In contrast, active drying utilizes engineering controls to stabilize material and reduce moisture. Active drying includes rotary dryers, cross flow dyers, and batch or bin dryers. Rotary dryers reduce moisture by rotating a material through a heated air in a drum at a set speed so that material is uniformly delivered at the desired moisture content. Rotary dryers work well for material that has limited fluidity. Continuous gravity flow dryers, or cross flow dryers, reduce moisture by blowing air across a column of material. Cross flow dryers work well for materials that flow easily and permit airflow between individual components (i.e. pellets). Batch or bin driers force air through a static material in a bin. Material to be bin dried must sufficiently resistant to compression to allow proper void space for air flow. Finally, biomass like algae may require unique dryers to remove water from a suspension (e.g. Like in a spray dryer) which uses the difference in air and solution moisture equilibrium.

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

6.3.3 Densification

Densification process converts the feedstock into a pellet to achieve consistent physical properties such as size and shape, bulk and unit density, and durability which significantly influence storage, transportation and handling characteristics, resulting in reduced feedstock cost and increased quality. A variety of densification systems are considered for producing a uniform format feedstock commodity for bioenergy applications, such as pellet mill, cuber, screw extruder, briquette press, roller press, tablet press, and agglomerator. Each of these systems has varying impacts on feedstock chemical composition physical properties, and energy consumption.

6.3.3.1 Conventional Pelletizing

Conventional biomass pellet production (Figure 21) includes initial size reduction to a 2- in. particle size, followed by drying to 10 to 12% moisture content (wet basis) using a rotary dryer. 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 pelletized⁴². Drying is the major energy consumption unit operation in this process, accounting for about 70% of the total pelletization energy.

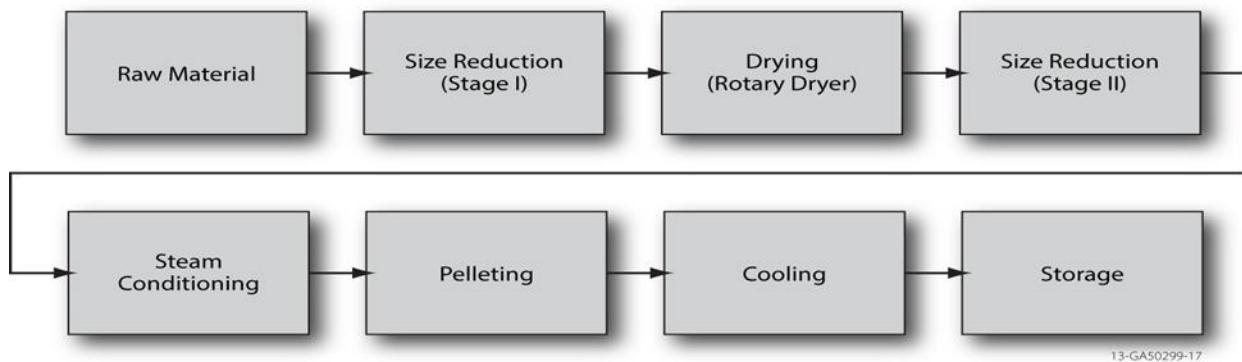


Figure 21. Conventional pelletization process.

6.3.3.2 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 (Figure 22). It should also be 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/ft³ and densities greater than 95%. The specific energy consumption was found to be in the range of 40 to 100 kWhr/ton⁴³.

The reduction in drying energy is the key advantage of this approach. 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 material. 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 7. The table shows 2017 Design Case targets to achieve a 40 to 50% reduction in the total pelletization and drying energy.

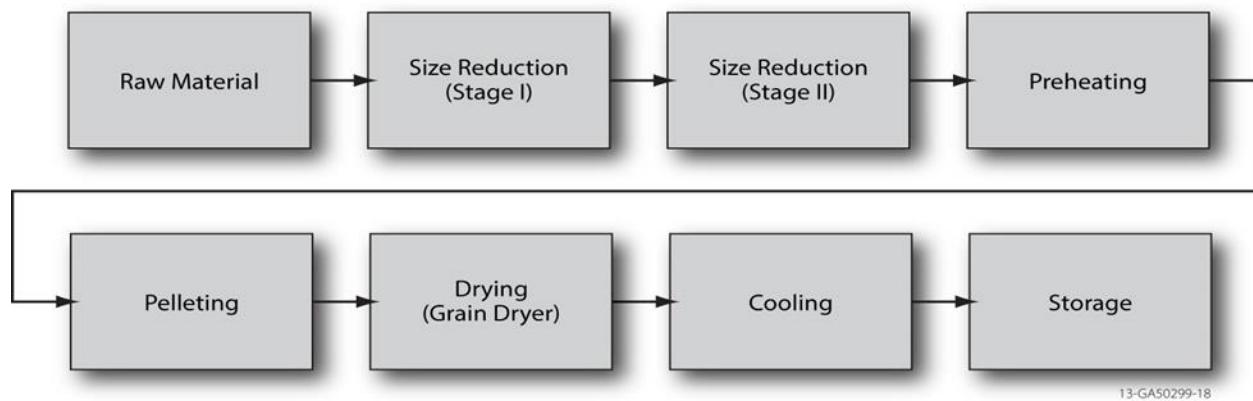


Figure 22. High-moisture pelletization process.

Table 7. Drying and densification design basis.

Moisture Properties	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.

6.4 Transportation

Transportation includes all processes involved in the movement of material from multiple locations to a centralized location (such as a preprocessing facility or depot or biorefinery). Processes include loading, trucking, rail transport, and unloading. Whereas transportation relies on existing roadways, railways, and waterways to move biomass, collection requires the use of specialized machinery to navigate off-road, gather dispersed biomass from a field or stand, and move it to the nearby staging location. In terms of biomass, the goal of transportation is to strategically utilize existing systems efficiency and cost effectively. A national scale biorefinery industry will require movement of great amounts of biomass and therefore understanding capacity and time constraints are important issues to consider. Long distance transportation like rail and barge allow biomass to be transported greater distances but this incurs additional costs. Densification of material both in particle size and energy content (i.e. torrefied material) allow for some of these costs to be offset. Unit trains or dedicated transportation of a set amount of material are additional strategies to be considered to reduce cost but the use of these options are constrained by location, timing and capacity. Differing transportation modes such as rail and barge can be cost efficient for long distance and pellet transportation. Understanding rail movement of freight rail is inherently more complex than estimating costs for trucking, as rail has to consider many factors such as distance, rail car type, car ownership, switching activities, shipment volume type, etc.

6.5 Handling and Queuing

Handling and queuing involves processes required to move biomass material to inside the gates at the biorefinery to the throat of the conversion. Handling equipment can include circular pile reclaimers, loaders, surge bins, conveyors, dust collection, pellet crumblers, and miscellaneous equipment required to move, queue and consistently deliver material. Handling operations are influenced by type of feedstock and depend on many factors, including moisture content, bulk density, particle size and shape distribution. Feedstocks, like corn stover, inherently possess characteristics that inhibit handling (such as high cohesivity, low density, high compressibility, and high variability in particle size and shape uniformity)⁸. For this reason, feedstock handling operations are typically designed at 150% of expected capacity. Handling issues can be improved by either engineering new equipment or engineering the feedstock (uniform particles or densified materials). Strategies to mix or blend multiple feedstock for cost and quality mitigation will require additional challenges handling multiple feedstock. For example, formulated feedstocks will require more complex feed operations, similar to the food industry, that are capable of consistently delivering a homogeneous and precise ratio of desired material.

7. Supply System Design: Arrangement of Unit Operations

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. Strategies can be taken in three ways to organize the earlier mentioned supply operations to reduce transportation distance, to reduce supply risk, and to increase the biomass resource. Supply chain unit operations of feedstock logistics can be configured depending on existing biomass and future commodity scale biomass markets. In this section we present conventional and advance supply system.

7.1 Conventional Feedstock Supply System

The conventional feedstock supply system design is based on practices currently developed for both the conventional forestry and agriculture industries, and is economical in high-yielding areas (for example, a corn stover production system in Iowa). The defining characteristic of the conventional feedstock system is the arrangement of the unit operations which puts preprocessing behind the biorefinery receiving gate where each biorefinery is designed to accept a specific local feedstock (Figure 23). In this organization of operations, the burden of adapting to feedstock resources is assumed primarily by the biorefinery.

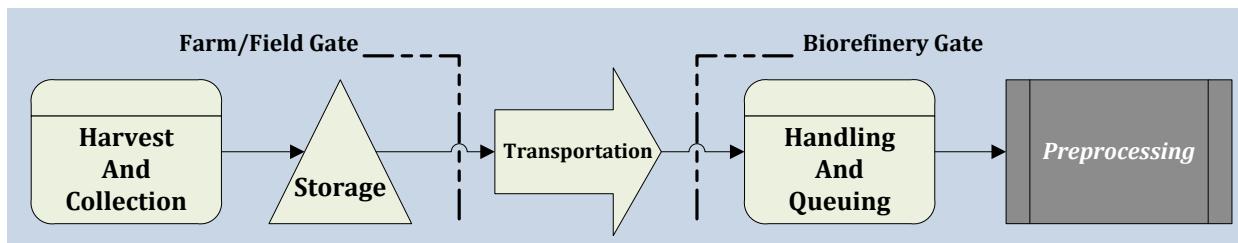


Figure 23. Conventional feedstock system for herbaceous lignocellulosic biomass.

In a conventional design, materials are stored on the field without further processing before transportation and handling operations can move material from long-term storage to shorter-term, storage at the biorefinery. Preprocessing operations are located at the biorefinery which include all milling, conveyance, dust collection, and biomass material surge systems is necessary to reduce biomass size before insertion in the conversion process (e.g., biochemical or thermochemical). With this arrangement of unit operations, biorefineries will be designed to accept a specific local feedstock or feedstocks and will need to undertake the burden of modifying the resource to a usable form.

7.2 Advanced Supply System

The advanced supply system concept arranges preprocessing technologies to mitigate the density and stability issues that prevent biomass from being handled in high-efficiency bulk dry solid or liquid distribution systems. The advanced supply system produces a feedstock supply system in which the diversity of biomass formats is minimized as early in the supply system as practically possible through a series of preprocessing steps. The organization of the unit operations in an advanced supply system allows preprocessing to occur during harvest and collection and/or at

centralized preprocessing sites (depots), which are envisioned to resemble existing systems like the grain elevator or beet dump. Advanced supply system relies on densifying biomass at local preprocessing facilities before delivering to a biorefinery and before long distance transportation. From the depot, the downstream feedstock supply systems and infrastructure will become uniform commodity-scale equipment and handling systems (Figure 24).

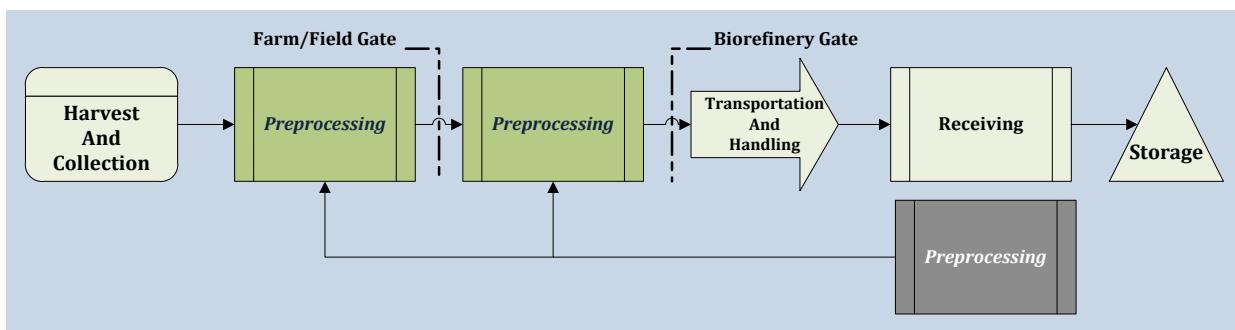


Figure 24. Advanced supply system designs (Advanced Uniform) follow the model of the current grain commodity supply system, which manages crop diversity at the point of harvest and/or depot, allowing all subsequent feedstock supply system infrastructure to be similar for all biomass resources⁴.

The purpose of the drying and densification at the advanced supply system is to achieve consistent properties, such as: size and shape, bulk and unit density, and durability. These properties significantly influence storage, transportation, and handling characteristics and, by extension, feedstock cost and quality. The drying and densification conducted under an advanced supply system converts the raw biomass into a biomass pellet.

In the advanced supply system, it is expected that biomass will be trucked from a local draw radius to a depot where preprocessing addresses quality (moisture content, ash content) and density issues to allow more efficient high capacity transportation and handling. The advanced supply system assumes that there will be insignificant material loss once preprocessing is completed, and transportation will not be intensively constrained by volume (as a result of low bulk densities). Additionally, densification increases material uniformity and flow ability, which is advantageous in transportation activities allowing for long distance transportation mode such as rail and barge. The fundamental premise of the advanced supply system design is that high-capacity, high-efficiency supply systems already exist (e.g., grain and petroleum crude) and handling low-density/aerobically unstable material is inherently inefficient, which can be mitigated through innovative organization of the unit operations within the supply system.

8. Biological Conversion of Sugars to Hydrocarbons

The following sections outline the tailored logistic designs including costs and performance specifications designed to meet the \$80 per dry ton costs for Biological Conversion of Sugars to Hydrocarbons pathway. This conversion path is coupled 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,"⁴⁴ that describes a 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.

8.1 Summary

Two requirements for the 2017 Design Case that were established early in this report are: achieving the \$80 per dry ton cost target when located outside the Midwest Corn Belt and achieving biorefinery quality specifications within the \$80 per dry ton cost target. Feedstock curves were developed for the 2017 Design Case scenario located in western Kansas (Figure 25). 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 per dry ton delivered feedstock cost target, thus satisfying the cost criterion of the 2017 Design Case (see Table 8).

Table 8. Biochemical conversion feedstock design cost analysis.

Cost Element	Single-pass Corn Stover	Multi-pass Corn Stover	Switchgrass	MSW	Blend
<i>Formulation Contribution</i>	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)	1.80	1.80	1.80	1.80	1.80
Total Delivered Feedstock Cost (\$/dry T)	78.10	86.40	79.40	62.00	~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.

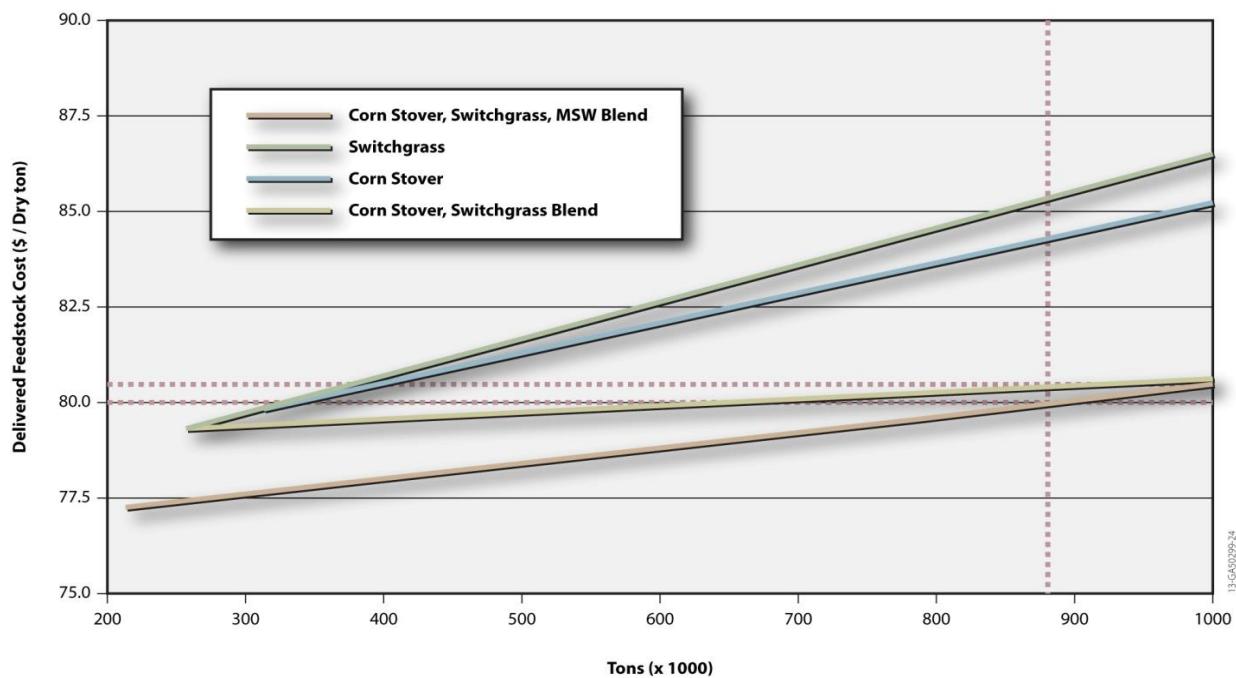


Figure 25. Comparison of individual and blended feedstock costs. A blend of 60% corn stover, 35% switchgrass, and 5% municipal solid waste is needed to hit the \$80 feedstock cost target.

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), 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 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 9). 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, 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 silica⁴⁵. 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 separation⁴⁵. 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 chemical preconversion for ash removal is included in Appendix D. 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 feedstock 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 8 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%.

8.2 Feedstock Composition (In-feed quality specifications)

The conversion target for feedstock composition remains consistent with what was assumed in the 2011 and 2013 design cases; however, the biomass *supply* composition is updated relative to the original 2011 case. Previous requirements for feedstocks assumed in the 2011-era ethanol models included cost targets only for a single biorefinery. There were no quality requirements; further analysis indicated a mismatch on biomass characteristics and conversion in-feed specifications. Furthermore, this design case focused more on supplying industry level biomass supply versus a single biorefinery. The update applied in the 2013 design case and maintained here improves on the 2011 design basis and the associated original feedstock price of \$58.50/dry ton (2007\$), which included a more uncertain grower payment, to a more reasonable target at an increased price of \$80/dry ton including grower payment (2011\$). This new price is more appropriate for a large commodity scale going beyond a “niche market” price.

As has been described in prior conversion design reports, the feedstock composition (Table 9) plays a critical role on overall process design and economics, primarily with respect to carbohydrate components (cellulose and hemicellulose), lignin, and increasingly acetate and ash, given modifications being made to the pretreatment strategy such as the use of deacetylation, as well as high sensitivity to impurity components such as ash and metals in the catalytic reactor section of this design. The blended uniform-format feedstock composition assumed here for purposes of future design case targets is shown below, with supporting details (in the context of corn stover compositional variability) described in the 2011 ethanol report⁴⁶. Also consistent with prior design cases, the moisture content for the delivered feedstock is 20% or less.

Table 9. Delivered Feedstock Composition Assumed in the Present Design ⁴⁴.

Component	Composition (dry wt %)
Glucan	35.1
Xylan	19.5
Lignin	15.8
Ash	4.9
Acetate^a	1.8
Protein	3.1
Extractives	14.7
Arabinan	2.4
Galactan	1.4
Mannan	0.6
Sucrose	0.8
Total structural carbohydrate	59.0
Total structural carbohydrate + sucrose	59.8
Moisture (bulk wt %)	20.0

^a Represents acetyl groups present in the hemicellulose polymer; converted to acetic acid in pretreatment.

The current design is assuming an ash target of 4.9%, structural carbohydrate of 59% and a moisture of <20%.

8.3 Feedstock Selection Cost Estimation

Access costs are calculated from the farm gate cost based on county level supply costs as shown in Figure 26, which are derived from The Billion Ton Update ⁵ data and are available from the Bioenergy Knowledge Discovery Framework ²⁵. Farm gate costs include nutrient replacement costs, harvest and collection costs, and an additional “profit” equal to 15% of nutrient replacement costs ⁴⁷. Access cost (grower payment) is calculated by subtracting the biomass harvest and collection costs from the farm gate costs. While the results are produced from ORNL’s analysis using POLYSYS, the harvest and collection costs are supplied by the INL’s Biomass Logistics Model.

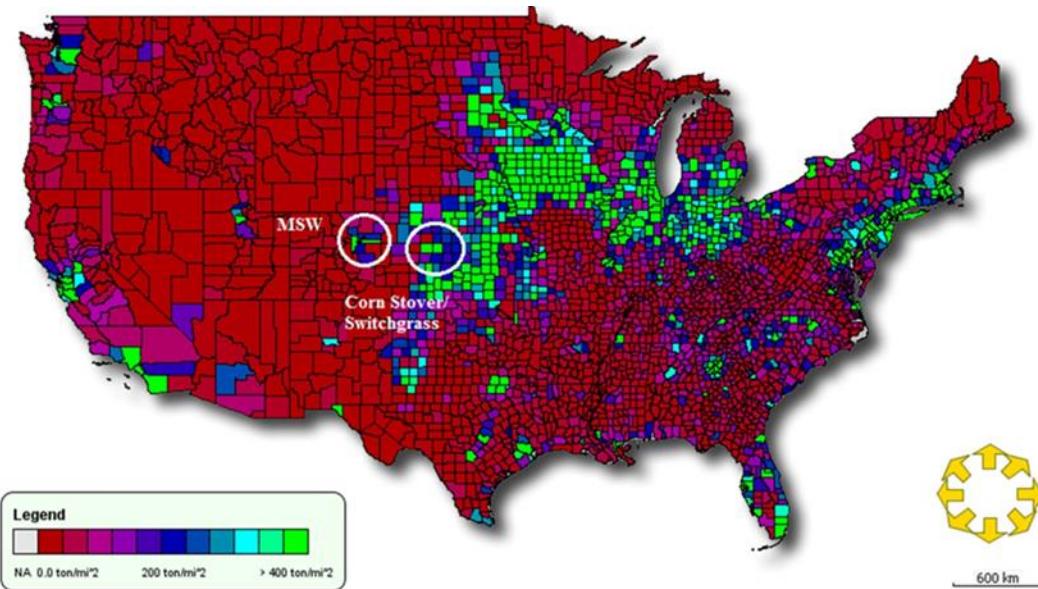


Figure 26. Resource selections for the 2017 Design Case to support biochemical conversion. Figure shows tonnages available at \$40/dry ton. Green represents higher amounts of tonnage available, red represents no available tonnage available at \$40/dry ton⁴⁷.

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 feedstock that make up the total blendstock allows us to stay lower on the supply curve than if we had to supply the entire supply demand with any single feedstock. The impact of this approach is shown in Table 10. 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 of \$27/dry ton that is nearly 30% lower than the access cost of stover alone.

Table 10. Resource farm gate price.

2013 SOT		2017 Target	
	Access Cost (2011 \$/dry T)	Tons	Access Cost (2011 \$/dry T)
Corn stover farmgate price	40.00	870,000	27.20
Switchgrass	NA	0	29.80
MSW cost to purchase and segregate	NA	0	18.00
Total	40.00	870,000	27.65 (wt avg)
			870,000

8.4 Quality Specification and Design Assumptions

The major assumptions of the 2017 Design Case, compared to the 2012 Conventional Design and the 2013 SOT are shown in Table 11. The implications of these assumptions on feedstock supply systems designs are discussed in following sections of the report.

Table 11. Summary of assumptions underpinning progressive design implementations.

	2012 Conventional Design	2013 SOT	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	Corn stover: multi-pass 7%; single-pass 3.5% Switchgrass: 4% MSW: 10% Blended ash content of 4.9%
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

8.5 Feedstock Logistics

8.5.1 Harvest and Collection

8.5.1.1 Overview

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.

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 decision⁴⁸. 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 during 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 ²².

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.

8.5.1.2 Harvest and Collection Design Basis

The 2017 Design Case uses traditional harvest and collection equipment (i.e., both multi-pass and single-pass methods); however, it depends heavily on advancing operational strategy. Maintaining the design specifications shown in

Table 12 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 merges 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 12. Technical targets for harvest and collection of herbaceous resources in the 2017 Design Case.

Process	Ash Content		Baled Moisture		Bulk Density	
	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

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. However, additional improvements are required to minimize the uncertainty of soil entrainment while maximizing biomass yield and sustainability.

8.5.1.3 Harvest and Collection Cost Estimation

Harvest and collection costs assume a sustainable 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 Billion Ton Update ⁵. Cost reductions from the 2013 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 13). These cost reductions are attributed to both a reduction in ash, 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 2.2.2. Ash dockage contributed \$14/dry T to the 2013 SOT costs. Cost of each machine consists of ownership cost and operations cost. Details are listed in Appendix E. 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 specifications, 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 13. Biomass harvest and collection cost estimates.

Machine	2013 SOT (2011 \$/dry T)	2017 Target (2011 \$/dry T)
	<i>Total</i>	<i>Total</i>
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.		

8.5.2 Storage

The 2017 Design Case assumes that storage of corn stover and switchgrass will occur field side or at a similar unimproved storage site. 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.

8.5.2.1 *Biomass Storage Design Base*

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 27, we assume that corn stover at 30% moisture 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.

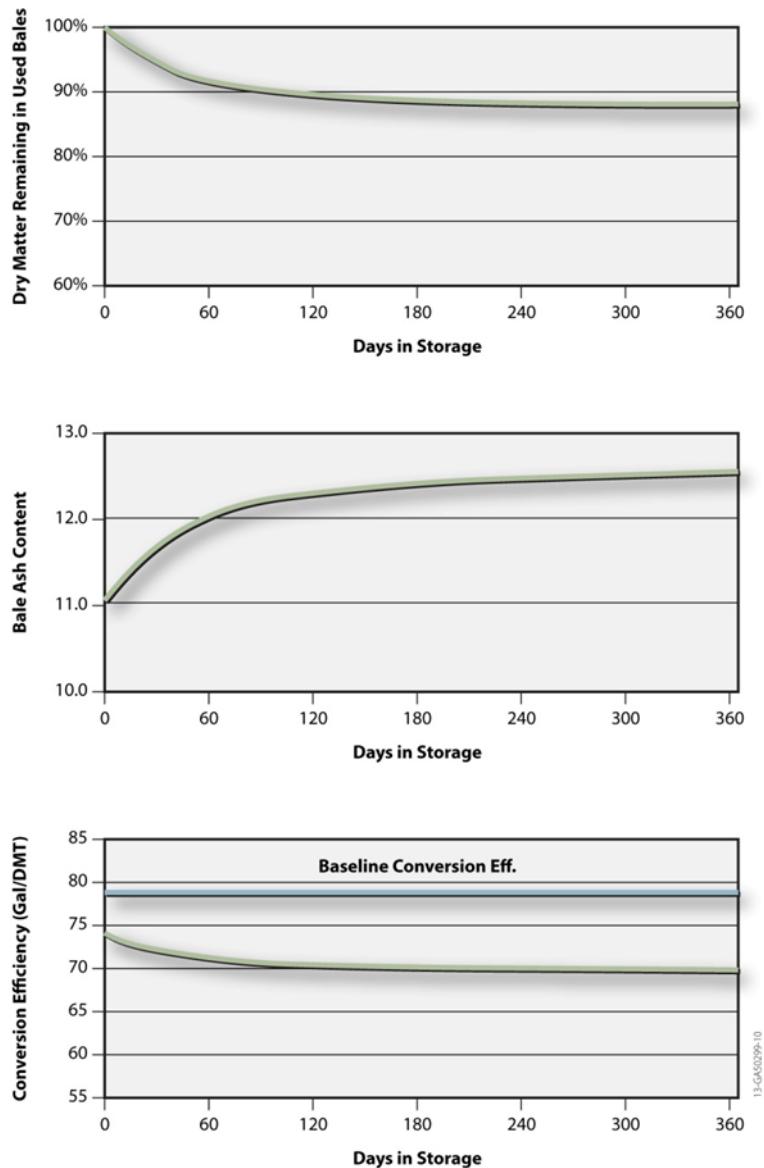


Figure 27. The impact of dry matter loss on bale ash content and final conversion efficiency (based on a 30% initial moisture and 12% ash).

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 28). 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.

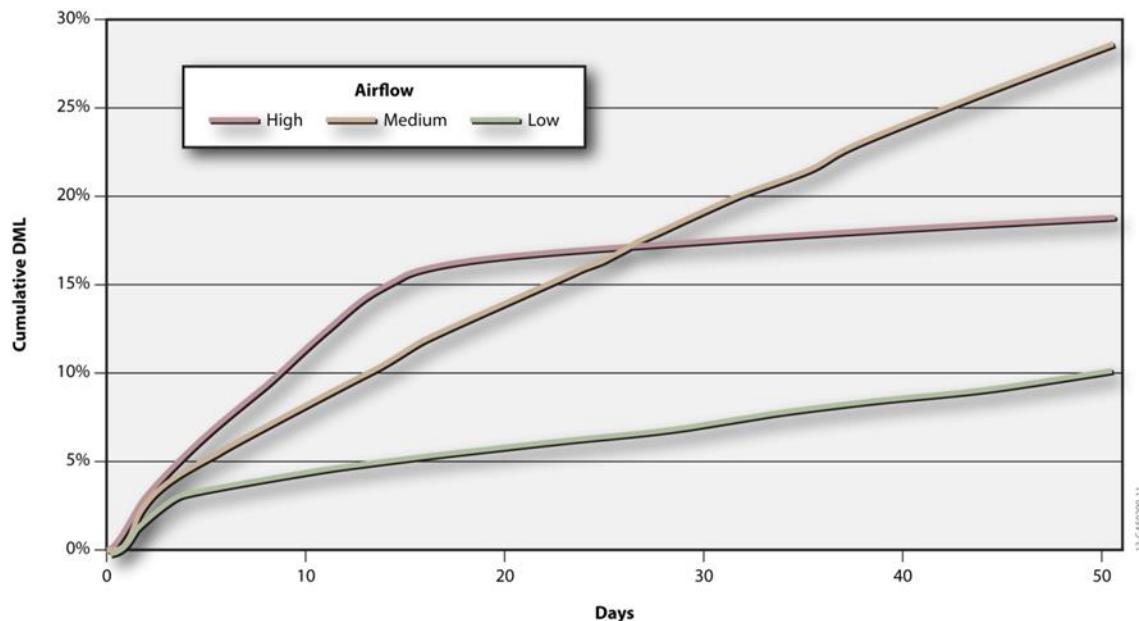


Figure 28. Dry matter loss of corn stover in the simulated storage conditions, with three air flows simulating three different oxygen availabilities.

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 12% ash) was cast in terms of the existing biochemical ethanol conversion pathway⁴⁶. 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 29). The analysis assumes that dry matter losses are confined to the non-ash biomass fraction, dry matter loss occurs proportionally across all non-ash components, and 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 27, top), several important behaviors and interactions are occurring, primarily the relative ash content of the material is becoming enriched (Figure 27, middle), causing the

carbohydrate fraction of the biomass to 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 27, bottom). These actions impact replacement costs, operational costs, and disposal costs for the refinery because more biomass must 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. 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 14). 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.

Table 14. Biomass storage design basis.

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

8.5.2.2 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 15).

Table 15. 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

8.5.3 Preprocessing

Biomass preprocessing operations of the 2017 Design Case (Figure 29) 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 next step is to separate the fractional material into two streams, one stream needing further grinding and the other stream that is at final size. 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.

The 2017 Design Case incorporates many improvements in preprocessing, including fractional milling, chemical preconversion, high-moisture densification, and formulation/blending. Figure 29 outlines the material flow given for these improvements.

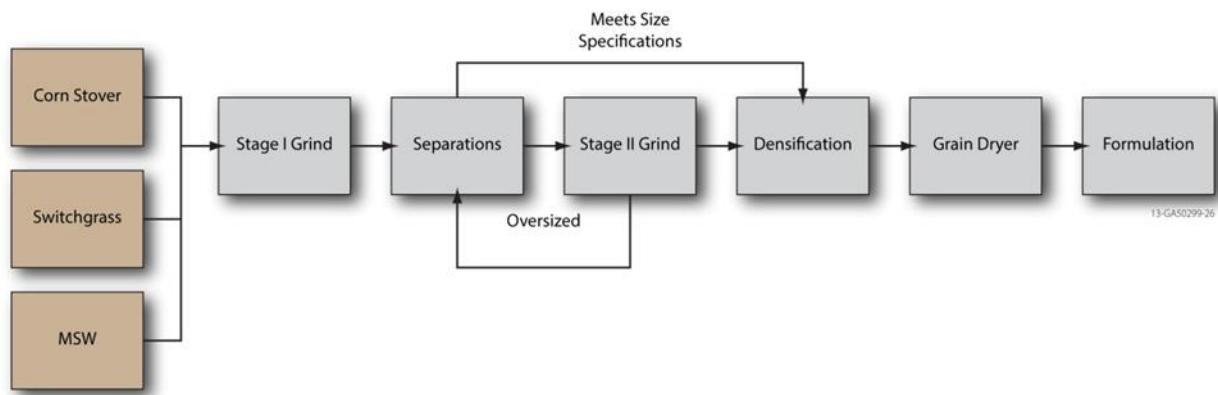


Figure 29. Material flow in the 2017 Design Case that incorporates many improvements in preprocessing, including fractional milling, chemical preconversion, high-moisture densification, and formulation/blending.

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.

8.5.3.1 Size Reduction

For the 2017 Design Case, a geometric mean particle size of $\frac{1}{4}$ - in. is the target size specification optimal for densification. Particle size after grinding 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

The fractional milling design basis is summarized in Table 16. 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 $\frac{1}{4}$ -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 16).

Table 16. 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.				

8.5.3.2 Fractional Milling Cost Estimation

Fractional milling cost estimation is based on vendor-supplied information and equipment performance from typical machine performance and process demonstration unit data (Table 17).

Table 17. Fractional milling cost estimates

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

8.5.3.3 Drying and Densification

8.5.3.4 Cost Estimation for High-Moisture Densification

The reduction in drying energy is the key advantage of this approach. First, the process uses the heat generated in the pellet die to partially dry the material. Second, drying the pellets offer 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 18. The table shows 2017 Design Case targets to achieve a 40 to 50% reduction in the total pelletization and drying energy.

Table 18. Drying and densification design basis.

Moisture Properties	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 cost of densification was estimated using vendor-supplied information and the capacity and energy assumptions shown in Table 19. 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 the source of the pellet drying cost estimate. Using a grain drying calculator found at Iowa State ⁴⁹, 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 19. Drying and densification cost estimates.

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

8.5.3.5 Formulation/Blending

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 generation¹⁴, grain is blended at elevators to adjust moisture content¹³, animal feeds are blended to balance nutrient content¹⁶, and high-ash biomass sources are mixed with low-ash coal to allow their use in biopower¹⁷. However, blending/formulation is not part of the baseline design.

8.5.3.6 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 20.

Table 20. Feedstock formulation/blending of ash and moisture contents*.

Content Delivered to Biorefinery Infeed	Single-pass cornstover(35%)	Multi-pass cornstover (25%)	Switchgrass (35%)	MSW (5%)	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

Assumptions for the formulation design basis are as follows:

- Blended feedstocks will be selected and developed to achieve conversion yield specifications. It is currently 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 study⁵⁰, 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 was examined. After

pretreatment, the feedstocks were hydrolyzed using commercial cellulose enzymes⁵¹ and sugar yields were measured. Ethanol yields also were determined using simultaneous saccharification and fermentation⁵².

- 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,⁵³ 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.
- 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.
- 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.
- The expected unit operations for formulation are shown in Table 21.

Table 21. Feedstock formulation design basis.

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

8.5.3.7 Cost Estimation for Formulation

Formulation cost estimation was based on existing technology, vendor-supplied information and equipment performance (Table 22).

Table 22. Formulation cost estimation.

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

8.5.4 Transportation and Handling

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. 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/ft³ bales at 30 and 20% moisture contents respectively. 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:

- At 30% moisture, transportation of cornstover continues to be volume limited due to low densities (12 lb/ft³)

- At 20% moisture, transportation of switchgrass continues to be volume limited due to low densities (12 lb/ft³)
- There will be insignificant material losses throughout transportation and handling.
- Densification will increase material uniformity and flowability.

8.5.4.1 Cost Estimation for Transportation

The cost estimation for transportation and handling was based on vendor-supplied information and equipment performance from typical machines (Table 23). Rail transportation costs were based on work from Searcy using a jumbo hopper car⁵⁴ adjusted for U.S. conditions.

Table 23. Transportation cost estimates.

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

*For specific feedstocks only to obtain required quantity.

8.6 Life Cycle Assessment:

This section uses a life-cycle assessment (LCA) to evaluate the energy input and GHG emissions for Biological Conversion of Sugars to Hydrocarbons. LCA considered the unit processes involved in the biomass logistics. Table 24 shows the energy consumption and Table 25 shows GHG contribution for Biochemical conversion supply chain design.

Table 24. Energy consumption for Biochemical conversion supply chain design.

Process Element	Single-pass Corn Stover	Multi-pass Corn Stover	Switchgrass	MSW	Blend
<i>Formulation Contribution</i>	35%	25%	35%	5%	—
Harvest and collection (MBTU/dry T)	108.69	204.18	122.85	—	132.08
Transportation (MBTU/ dry T)	142.08	142.08	99.35	549.43	147.49
Preprocessing (MBTU/dry T)	315.82	315.82	285.83	421.25	310.60
Storage (MBTU/dry T)	21.83	21.83	21.83	21.83	21.83
Handling (MBTU/dry T)	41.90	41.90	41.90	41.90	41.90
Total Energy Consumption Cost (MBTU/dry T)	630.32	725.81	571.76	1034.41	653.90

Table 25. GHG contribution for biochemical conversion supply chain design.

Process Element	Blend
<i>Formulation Contribution</i>	—
Harvest and collection GHGs (Kg CO₂e/ dry T)	10.90
Transportation GHGs (Kg CO₂e/ dry T)	8.62
Preprocessing GHGs (Kg CO₂e/ dry T)	27.02
Storage GHGs (Kg CO₂e/ dry T)	6.42
Handling GHGs (Kg CO₂e/ dry T)	6.41
Total GHGs (Kg CO ₂ e/ dry T)	59.40

9. Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway

This section is intended to couple with the Pacific Northwest National Laboratory's (PNNL's) hydrocarbon design report, "Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway"⁵⁵ that describes a viable route from biomass to hydrocarbon fuels. The assumptions of scale and feedstock quality requirements are consistent with the design case assumptions used by PNNL in their report and techno economic assessments. This design does not consider the different requirements and nuances of other thermochemical conversion processes or other hydrocarbon pathways.

9.1 Summary

This report establishes a plausible case for achieving the 2017 Design Case for Fast Pyrolysis conversion to bio-oils cost goals of delivering a biomass feedstock to the conversion facility at a cost of \$80/dry T (Table 26). The least-cost formulation approach (Appendix B) illustrates the importance of 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.

Table 26. Thermochemical feedstock design cost analysis for 2017.

Cost Element	Pulpwood	Wood Residues	Switchgrass	Construction and Demolition Waste (C&D)	Blend
Formulation Contribution	45%	32%	3%	20%	—
Grower payment/access cost	25.00	26.35	19.67	8.15	21.90
Harvest and collection (\$/dry T)	22.24	0	15.41	—	10.47
Landing Preprocessing/Sorting (\$/dry T)	12.17	8.73	0	9.85	10.24
Transportation (\$/dry T)	10.89	3.33	4.59	6.87	7.48
Preprocessing (\$/dry T)	23.97	23.97	19.7	28.12	24.67
Storage (\$/dry T)	3.23	3.23	5.59	3.23	3.30
Handling (\$/dry T)	1.90	1.90	1.90	1.90	1.90
Total Delivered Feedstock Cost (\$/dry T)	99.49	67.51	66.86	58.12	80.00
Delivered Feedstock Specifications					
Ash content (wt. %)	0.5	1.0	4.0	1.0	<1%
Moisture content (%, wet basis)	9	9	9	9	9
HHV (BTU/lb)	8824	9444	7557	8824	8984
LHV (BTU/lb)	7255	7616	6155	7255	7337

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*⁵ 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 gate price.

Logistics costs are based on actual field trial data but do not include the cost of various business elements, such as profit margins for transportation, depots and field agents that would be involved throughout a biomass feedstock supply chain. This would increase the overall cost of the supply system than is demonstrated in this report. This was of little consequence to the 2012 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 logistic systems become 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 (n^{th} plant costs) to

be consistent with conversion platform terminology. This was not an issue with conventional feedstock designs that were intrinsically tied to current SOT; 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 C&D 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 C&D blends) and evaluating the compatibilities and incompatibilities of blendstocks. The results of this research are critical to further development of blended feedstocks.

9.2 Feedstock Composition (In-feed quality specifications)

The dry basis elemental composition of the feedstock, shown In Table 26, is identical to previous NREL and PNNL design reports⁶. The composition was originally assumed to come from pulpwood. Recent feedstock logistics work suggests the use of blended material may be required to meet a cost target of \$80/dry US ton while still meeting these specifications. For the purpose of this report, it is assumed that any blended material provided to meet this feedstock elemental composition will not adversely affect fast pyrolysis conversion efficiencies. Ongoing studies being conducted jointly by INL, NREL and PNNL will provide experimental evidence of the impact of blended feedstocks on fast pyrolysis and gasification processes. Future TEA will be modified to reflect conversion impacts inferred from such studies. As has been described in prior conversion design reports, the feedstock composition plays a critical role on overall process design and economics, primarily with respect to high and low heating values, carbon as well as high sensitivity to impurity components such as ash and metals in this design. The blended uniform-format feedstock composition assumed here for purposes of future design case targets is shown below, with supporting details described in the 2011 ethanol report ⁴⁶. Also consistent with prior design cases, the moisture content for the delivered feedstock is 10% or less.

Table 27. Delivered woody feedstock composition and processing assumptions for the fast pyrolysis and hydrotreating design report⁶.

Component	Composition (dry wt. %)
Carbon	50.94
Hydrogen	6.04
Nitrogen	0.17
Sulfur	0.03
Oxygen	41.90
Ash	0.90-1.0
Heating Value (Btu/lb)	8,601 HHV 7,996 LHV
Moisture (Bulk Wt. %)	10.0
Particle Size (inch)	1/4

9.3 Feedstock Selection Cost Estimation

Expansion beyond highly productive resource areas has significant implications to the feedstock supply chain. Sparse areas, 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 yields increase the supply radius and biomass transportation distances. Under the 2012 Conventional Design, higher yield areas allow refinery to be selective on the resource that they access.

Consider, for example, the scenarios depicted in Figure 30. This resource map illustrates a county-level resource assessment of pulpwood farm gate at \$60/dry T prices (this includes grower payment, harvest, collection, and chipping costs). Farm gate price data were extracted from *The Billion Ton Update* (BT2)⁵ data supplied from Oak Ridge National Laboratory. It should be noted that while the data is reported at a county-level, the data should be applied at the wood shed (typically much larger area than a county) level because it was derived from the U.S. Forest Service Forest Inventory and Assessment Data (FIA)⁵⁶, and does not equate to county levels accurately. The FIA is a woodshed level assessment and therefore to use the data correctly it is necessary to combine multiple counties.

The cost competitiveness of the 2012 Conventional Design was demonstrated in the scenario located in southern Alabama, a high biomass yielding area³. We further suggest, based on the consistency of farm gate (i.e., landing) prices shown in this map, that the 2012 Conventional Design can be deployed cost effectively in South Carolina. Commercial readiness of conventional supply systems ultimately will be demonstrated by commercial-scale cellulosic ethanol plants opening in these areas in the near future.

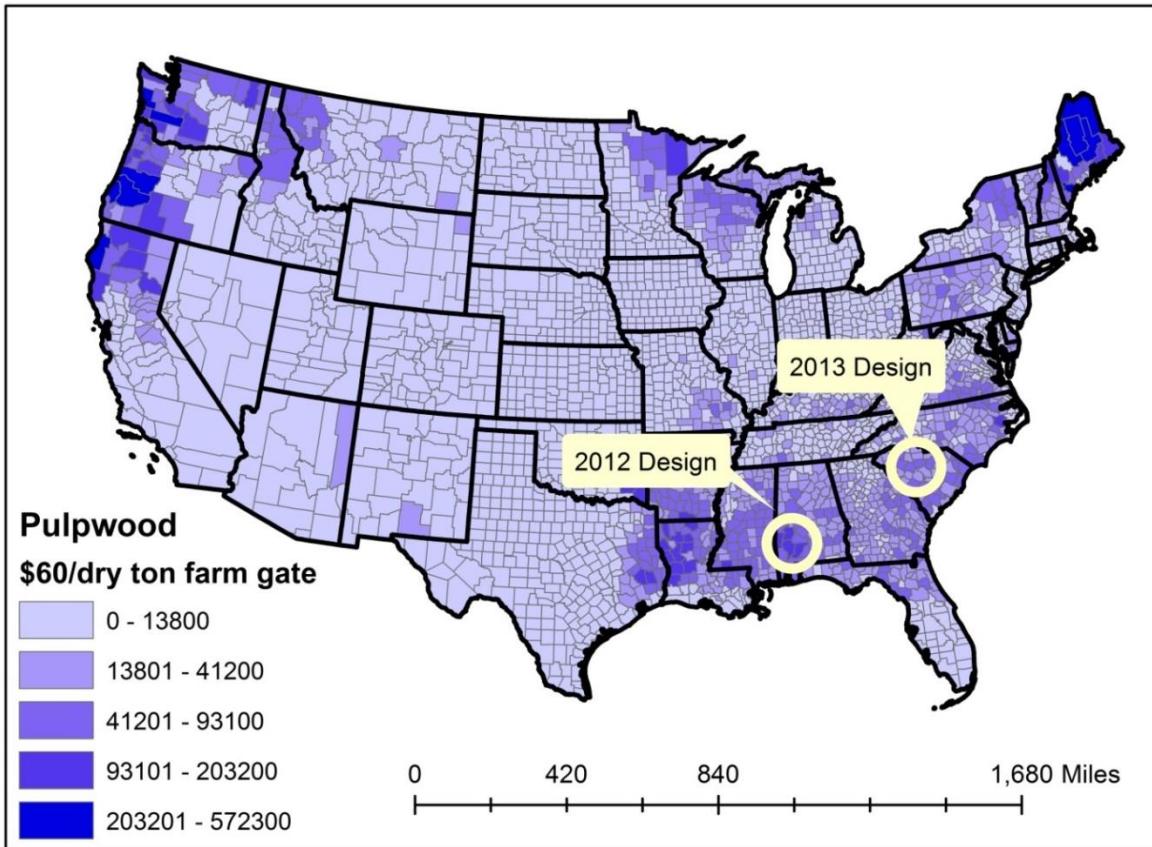


Figure 30. Total tons per county of available pulpwood at \$60/dry T farm gate price. Yellow circles show areas represented in the 2012 Conventional Design and the Relocated (2013) Design Case⁵.

Access costs are calculated from the grower payment cost curves shown in Figure 6, which are derived from historical prices. 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 feedstock allows us to stay lower on the supply curve than if we had to supply the entire refinery with any single feedstock. The impact of this approach is shown in Table 28. The 2013 State of Technology assumes a 100% supply of pulpwood of 909,100 dry T at an estimated \$60/dry T farm gate or a \$25/dry T access cost. In comparison, the 2017 Design Case blend of 45% pulpwood, 32% wood residues, 20% C & D waste, and 3% switchgrass results in a weighted average feedstock cost that is nearly 15% lower than the access cost of pulpwood alone.

Table 28. Resource access cost estimate (U.S. DOE 2011⁵ and INL MSW Data).

	2013 SOT		2017 Target	
	Access Cost (2011 \$/dry T)	Tons	Access Cost (2011 \$/dry T)	Tons
Pulpwood	25.00	909,100*	25.00	425,700*
Wood Residues	NA	NA	26.35	412,800**
Switchgrass	NA	NA	19.67	25,800
C&D	NA	NA	8.15	172,000
Totals	25.00	NA	21.90	1,036,300

*assumes 10% loss of material to debark/delimb¹⁸.

**assumes 40% loss of material to clean up residues¹⁹.

9.4 Quality Specification and Design Assumptions

The 2012 Conventional Design focused on conventional woody harvest operations (i.e., felling and/or skidding operations are separate from landing preprocessing operations). In addition to including switchgrass into the feedstock blend, the 2017 Design Case assumes that the immaturity of the biomass market will limit the forest and farm owner's investment in advanced equipment options for both woody and herbaceous feedstocks. Therefore, with the exception of a few proactive, early adopters, conventional forestry and farming operations will dominate the market in the regions defined by the 2017 Design Case. Table 29 below summarizes the assumptions and differences between the 2012 and 2017 logistic designs.

Table 29. Summary of assumptions underpinning progressive design implementations⁵⁷.

	2012 Conventional Design	Baseline	2017 Design Case
Feedstock(s)	Pulpwood		Blended feedstock: pulpwood, wood residues, switchgrass, and select construction and demolition wastes (C &D)
Grower payment	Breakeven cost of production	Pulpwood	Calculated and modeled according to specific location and resource blend/formulation
Moisture	Field dried to 40%	Field dried to 40%	Arrives: Pulpwood chips 30% wood residue chips 30%, switchgrass 20%, and C & D ground 20%; All dried to 9% pellets
Ash	Debark/delimb	Debark/delimb	Debark/delimb pulpwood Trommel screen residues Wash and sort C & D waste Blended ash content of <1% Debarked pulpwood <1%, screened wood residues 1.4%; washed and sorted C&D 1.0 %
Logistics	Uses existing systems	Uses existing systems	Pneumatics attached to hammermill High-moisture densification
Quality controls (passive)	Field drying to reduce moisture Ample available resource; quality spec manually selected	Field drying to meet moisture spec	Harvest/collection and storage best management practices for pulpwood and switchgrass More rigorous field drying of pulpwood and residues
Quality controls (active)	Waste heat dryer	Rotary drying	Multiple resource blending/formulation High-moisture densification High-efficiency pellet drying
Meets quality target	Yes	Yes	Yes
Meets cost target	Yes	No	Yes
Accesses dispersed resources	No	No	Yes

Relative to the woody feedstocks used in the Thermochemical Design Case, the 2013 baseline and 2017 Design Case are similar in many ways for harvest and collection, but the latter has two key changes to improve quality and production of woody materials. While each system is discussed later, the key differences of the 2017 Design Case are first inclusion of woody residues

sourced from pulpwood operations, and second in-forest drying of whole tree piles at the landing to achieve a more aggressive moisture content of 30%. In this design debarking and dellimbing are conducted to improve biomass quality. Construction and demolition wastes are considered to enter the feedstock logistics system at the preprocessing stage and are therefore not discussed here.

9.5 Feedstock Logistics

9.5.1 Harvest and Collection

Conventional wood harvest and collection relies on existing forestry technologies designed for timber and pulp and paper production. Collection systems for woody material involve cutting the feedstock with a tracked feller buncher and transporting the material to the landing with a grapple skidder immediately after felling. Felling and skidding operations increase the overall ash content of harvested whole-trees by introducing soil as it is moved in contact with the ground from one location to the next⁵⁸. Thermochemical conversion processes via fast pyrolysis are highly sensitive to silica, alkali, and transition metals found in most soils, impacting process performance^{59 60 61}. In both the 2013 and 2017 Design Cases active management strategies are employed during the landing preprocessing to reduce biomass ash content. Current forestry production of pine pulpwood is reported to yield roundwood with a moisture content of 45-55% and a whole-tree ash content ranging from 1% to 3%^{62 63 64}. The 2013 baseline assumes the moisture content of pulpwood to be 50% for whole-trees entering storage.

Woody residues are generated through typical commercial forestry operations on southern pine plantations where trees are harvested for pulpwood, chip-and-saw, and saw timber. Similar to the above described collection of pulpwood, these operations bring whole trees to the landing where they are delimbed and topped using a pull-through delimer. The roundwood is then loaded onto trucks for delivery to the mill while the residues are piled at the landing. While not collected in the 2013 baseline, the 2017 Design Case utilizes these materials as a fraction of the feedstock blend. The baseline for residue moisture content is reported at 40%, while ash content has been reported to range from 2% to 4%^{47, 62, 65 66}. Switchgrass, which is part of the blend, harvest and collection systems use a conventional windrowing harvester and rectangular baler (3x4x8-ft).

9.5.1.1 Harvest and Collection Design Basis

The 2017 Design Case incorporates a chain flail debarker during preprocessing at the landing to increase the quality of the final chipped pulpwood product. Therefore moisture and ash contents of material entering storage are not different between the 2013 and 2017 Designs. However, there is still impetus to increase the operational efficiency of roundwood collection for reducing costs^{67 68}. This can be achieved through forest management shifts to short-rotation pine plantations aimed at supplying bioenergy production, increased efficiency of harvesting machinery, and increased efficiency of grapple skidder transportation. Research conducted by Auburn University for the DOE High Tonnage Forest Biomass Project has demonstrated high capacity grapplers to increase productivity by 80 tons per productive machine hour compared to traditional systems⁵⁸. Figure 31 depicts a conventional skidder and a high capacity skidder. Further development of such operational improvements will play a key role in reducing costs of clean pulp chips for thermochemical conversion. In addition, transition of forest management to

short rotation pine plantations focused on energy use is a promising option for increasing yields; should the economics of establishment be overcome⁶⁹.



Figure 31. Conventional (left) and high-capacity grapple skidder (right) for transporting small diameter pulpwood from the forest to the landing. Photo credit: Auburn University High Tonnage Forest Biomass Project⁵⁸.

Wood residues (tree tops and limbs) originate from other commercial logging operations and are located in piles at the landing, eliminating the costs for harvest and collection (e.g., felling and skidding). Similar to pulpwood, the 2017 Design Case incorporates active quality controls to reduce the ash content during preprocessing at the landing. These active controls applied after storage may contain ash contents in excess of the desired specification of 0.9% for wood residues and less for pulpwood.

Switchgrass harvest in the 2017 Design Case follows conventional practices for feed and forage in terms of the equipment used, but incorporates more rigorous passive quality controls to reduce ash content. Delayed harvest of switchgrass provides the benefits of reducing moisture and ash content, but even with the practice of delayed-harvest, it is clear that the raw feedstock will not meet the final quality specification for ash. Blending of switchgrass with a low-ash feedstock is necessary to achieve ash specification of <1%. Nevertheless, it is important that best management practices for switchgrass harvest are used to reduce soil contamination during the processes of cutting and baling while respecting the relationship between delayed harvest date and collection efficiency. Research conducted by Oklahoma State University in collaboration with INL shows that switchgrass can achieve moisture contents at or below the 2017 Design Case specification (10% to 5%), though climatic variance can still introduce moisture variability in delayed harvests (Figure 32). In this same research the ash content of switchgrass was found to be low even at an early harvest (5% in August), though a decreasing trend was observed as harvest was delayed (4% by December). This work stands as an example of the effectiveness of proper harvesting techniques, and stresses the importance of establishing best management practices to cope with variability in weather conditions. Goals for the 2017 Design Case include reducing ash content to 4% through harvest timing and advanced harvesting techniques.

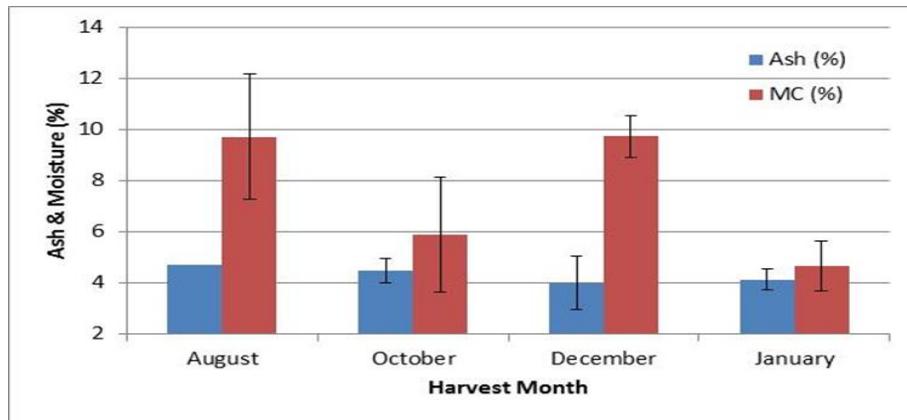


Figure 32. Ash and moisture content of switchgrass harvested in Oklahoma, 2010 by Oklahoma State University. Error bars represent one standard deviation. Ash samples for October, December, and January are three samples comprised of six individual core samples composited.

9.5.1.2 *Harvest and Collection Cost Estimation*

Harvest and collection costs assume a removal rate of 15 dry T./acre for pulpwood⁷⁰, 4 dry T./acre for residues⁶⁶, and 5-dry T./acre for switchgrass⁷¹. These assumptions are consistent with those used in the Billion Ton Update⁵. Cost of harvest and collection is shown in Table 30. The cost of ash at this point within the feedstock logistics system described in section 2.2 is not yet applicable to pulpwood or wood residue, as the material will undergo active quality controls during landing preprocessing. Switchgrass may be subjected to an ash dockage at this point in the process if ash contents are greater than those needed by the feedstock blending process.

Table 30. Biomass harvest and collection cost estimates derived from INL analysis.

Machine	2013 SOT (2011 \$/dry T)	2017 Target (2011 \$/dry T)
	<i>Total</i>	<i>Total</i>
Pulpwood		
Felling	15.00	15.00
Yarding	7.24	7.24
Totals	22.24	22.24
Wood Residues*		
Felling	0.00	0.00
Yarding	0.00	0.00
Totals	0.00	0.00
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 harvest and collection of other process.

9.5.2 Storage

9.5.2.1 2013 State of Technology

Because the 2017 Design Case utilizes a blended feedstock, switchgrass storage must be addressed. The storage of switchgrass occurs field side or at a similar on-farm unimproved storage site. As for any baled feedstock, 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 stack to be positioned in a North-South orientation to reduce moisture accumulation on the north side of the stack⁷². Tarped stacks are chosen as a balance between bale protection against moisture infiltration, which leads to dry matter loss, and storage configuration costs^{73 22}. Stacks are constructed with a self-propelled stacking bale wagon and are six bales high and covered with a high-quality hay tarp. In order to prolong tarp life, it is also important that adequate year-round maintenance be provided to periodically tighten the tarps⁷⁴. Biomass storage systems in the current Design Case seek to provide a low-cost, low-maintenance, moisture-tolerant solution that focus on maintaining moisture content <20%, minimizing dry matter loss and preserving feedstock composition. Table 31 shows the assumed changes in moisture content between the 2013 SOT and the 217 Design Case.

Table 31. Technical targets for biomass field storage of resources in the 2017 Design Case.

Process	After Field Drying Moisture Content	
	2013 SOT	2017 Target
Pulpwood	40 %	30%
Wood Residues	40%	30%
Switchgrass	20%	20%

9.5.2.2 Storage Design Basis

The 2017 Design Case is based on field drying for pulpwood and forest residues, both to 30% moisture at the time the material enters landing preprocessing. Field studies on field drying of short rotation southern pine pulpwood and residues have shown final moisture contents of 30% to be achievable given adequate time^{65 58 64}.

Since chips are expected to enter storage at 30% moisture in the 2017 Design Case, it is reasonable to assume that dry matter losses will be much less (nearly negligible) within the three day holding window. The concerns of unplanned storage extensions, moisture addition, or mechanical losses could increase this number, and therefore the 2017 Design Case assumes a target chip-storage dry matter loss of 5%. Protection of chip piles with tarps could help to prevent these losses, if the additional material and labor costs are merited, and their presence does not interfere with regular loading and unloading of the piles. Storage of switchgrass is not expected to deviate from the 2013 Design Case baseline. Due to the low moisture content entering storage, the use of a tarp to protect from moisture addition through precipitation has been shown to be sufficient and cost effective when properly applied.

9.5.2.3 Biomass Storage Cost Estimation

Cost estimations for biomass storage were calculated based on literature values from recent reviews⁷⁴, the storage cover vendor's information, and laboratory and field level experiments⁷² (Table 32).

Table 32. Field-side storage cost estimation.

	SOT (2011 \$/dry T)			Design Target (2011 \$/dry T)		
	Storage	Dockage	Total	Storage	Dockage	Total
Switchgrass	N/A	N/A	N/A	5.50	0.00	5.50

9.5.3 Preprocessing

The 2017 Design Case that incorporates many improvements in preprocessing, including pneumatics, high-moisture densification, and formulation/blending. Figure 33 outlines the material flow given for these improvements. In the 2017 Design Case, substantial cost savings in size reduction are realized by tailoring the preprocessing stages to the individual feedstock and not applying a one size fits all approach. For example, pulpwood is debarked and delimbed and then processed through a chipper to optimize retention of usable material; wood residues are processed through a first stage grinder then separated by passing through a trommel screen;

switchgrass is processed through a grinder while Construction and Demolition (C&D) waste undergoes sorting and a wash step.

Separation/sorting of C&D waste 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, C&D is sorted to supply usable material for thermochemical conversion. Prior to any preprocessing the ash content of untreated C&D waste fractions is estimated to be about 6%. The application of a wash stage further reduces the ash content down to pure wood levels of about 1 %. (Reference Appendix A).

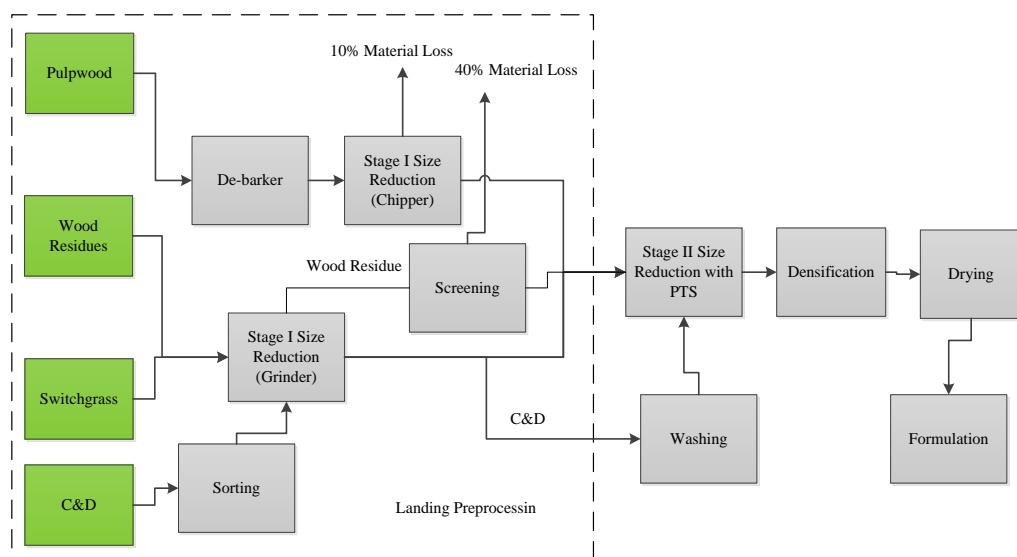


Figure 33. Material flow in the 2017 Design Case that incorporates many improvements in preprocessing, including pneumatics, high-moisture densification, and formulation/blending.

The logistics of a blended feedstock scenario are certainly more complex than a single-feedstock scenario. The 2017 Design Case assumes that preprocessing of C&D will occur at a preprocessing depot located at the source landfill or refuse transfer station, and C&D pellets will be shipped from the depot to the blending depot located within proximity of the biorefinery. Switchgrass that is formatted in large square bales will be delivered to the blending depot, where they will be processed into pellets. Pulpwood and wood residues will be initially processed at the landing for initial size reduction and ash mitigation then transported to a processing facility for pelletization. The pulpwood, wood residues, switchgrass, and C&D pellets will be queued up in blending bunkers or silos and blended to specification prior to being fed into the conversion process. The pellets of the four blendstocks (i.e., pulpwood, wood residues, switchgrass, and C&D) 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.

9.5.3.1 *State of Technology:*

For the 2017 Design Case, a geometric mean particle size of $\frac{1}{4}$ - in. is the target size specification for the thermochemical conversion process design under development by PNNL. As the target size specification is the same as biochemical conversion, size reduction system to the final particle size specification required by the end user will be the same as biochemical conversion. 2013 state of technology follows sequential two stage size reduction described in section 8.5.3.1(Table 33).

Table 33. Size-reduction design basis.

			2013 SOT	2017 Target
	Equipment Used	Screen Size	Capacity Ton/hr	Capacity Ton/hr
First Stage Size Reduction				
Pulpwood	Chipper	2 in.	17	17
Wood Residue	Grinder	2in.		
Second Stage Size Reduction				
Pulpwood	Hammer mill	$\frac{1}{4}$ in.	5	6.5
Wood Residue	Hammer mill	$\frac{1}{4}$ in.	5	6.5

9.5.3.2 *Size Reduction Cost Estimation*

Milling cost estimation is based on vendor-supplied information and equipment performance from typical machine performance and process demonstration unit data and is shown in Table 34.

Table 34. Size reduction cost estimates.

	2013 SOT (2011 \$/dry T)	2017 Target (2011 \$/dry T)
	Total	Total
Pulpwood		
Chipper	6.10	6.10
Debark/delimb	6.10	6.10
Hammer Mill	17.09	13.97
Total	29.29	26.17
Wood Residue		
Grinder	5.39	5.39
Trommel Screen	3.32	3.32
Hammer Mill	17.09	13.97
Total	25.08	22.70

9.5.3.3 Drying and Densification

Conversion of lignocellulosic biomass to hydrocarbon fuels: Fast Pyrolysis and Hydrotreating Bio-Oil Pathway use the same technology as Biological Conversion of Sugars to Hydrocarbons described in section 8.5.3.3. Therefore, state of technology and design basis for high moisture technology are the same as Biological Conversion of Sugars to Hydrocarbons described in section 8.5.3.3.

A comparison of pellet properties and energy balances for conventional and high-moisture pelletization processes is given in Table 35. The table shows 2017 Design Case targets to achieve a 40 to 50% reduction in the total pelletization and drying energy.

Table 35. Drying and densification design basis.

	2013 SOT	2017 Target
Infeed Moisture	40%	30%
Dryer Moisture Reduction	28%	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	65 lb/ft ³	70 lb/ft ³
Bulk Density	35 lb/ft ³	40 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 from woody material; 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.

9.5.3.4 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 36.

Table 36. Drying and densification cost estimates.

	2013 SOT (2011 \$/dry T)	2017 Target (2011 \$/dry T)
	<i>Total</i>	<i>Total</i>
Drying	17.20	5.60
Densification	7.70	4.40
Totals	24.90	10.00

9.5.3.5 Formulation/Blending

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 37.

Table 37. Feedstock formulation/blending of ash and moisture contents*.

Content Delivered to Biorefinery Infeed	Pulpwood	Wood Residues	Switchgrass	C&D waste	Final Blend
Ash content (wt. %)	0.5	1.0	4.0	1.0	<1%
Moisture content (%) (%, wet basis)	9	9	9	9	9
HHV (lb/BTU)	8824	9444	7557	8824	8984
LHV (lb/BTU)	7255	7616	6155	7255	7337

10. Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Thermochemical Pathways with In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors

This section is intended to couple with the National Renewable Energy Laboratory's (NREL's) hydrocarbon design report, "Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Thermochemical Pathways with In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors"⁶ that describes a viable route from biomass to hydrocarbon fuels. 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. This design does not consider the different requirements and nuances of other thermochemical conversion processes or other hydrocarbon pathways.

10.1 Summary

This report establishes a plausible case for achieving the 2017 Design Case for Fast Pyrolysis conversion to bio-oils cost goals of delivering a biomass feedstock to the conversion facility at a cost of \$80/dry T (Table 38). The least-cost formulation approach (Appendix B) illustrates the importance of 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.

Table 38. Thermochemical feedstock design cost analysis for 2017.

Cost Element	Pulpwood	Wood Residues	Switchgrass	Construction and Demolition Waste (C&D)	Blend
<i>Formulation Contribution</i>	45%	32%	3%	20%	—
Grower payment/ access cost	25.00	26.35	19.67	8.15	21.90
Harvest and Collection (\$/dry T)	22.24	0	15.41	—	10.47
Landing Preprocessing/ Sorting (\$/dry T)	12.17	8.73	0	9.85	10.24
Transportation (\$/dry T)	10.89	3.33	4.5	6.87	7.48
Preprocessing (\$/dry T)	23.97	23.97	19.7	28.12	24.67
Storage (\$/dry T)	3.23	3.23	5.5	3.23	3.30
Handling (\$/dry T)	1.90	1.90	1.90	1.90	1.90
Total Delivered Feedstock Cost (\$/dry T)	99.49	67.51	66.68	58.12	80.00
Delivered Feedstock Specifications					
Ash content (wt. %)	0.5	1.0	4.0	1.0	<1%
Moisture content (%, wet basis)	9	9	9	9	9
HHV (BTU/lb)	8824	9444	7557	8824	8984
LHV (BTU/lb)	7255	7616	6155	7255	7337

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*⁵ 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 gate price.

Logistics costs are based on actual field trial data but do not include the cost of various business elements, such as profit margins for transportation, depots and field agents that would be involved throughout a biomass feedstock supply chain. This would increase the overall cost of the supply system than is demonstrated in this report. This was of little consequence to the 2012 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 logistic systems become 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 (n^{th} plant costs) to be consistent with conversion platform terminology. This was not an issue with conventional feedstock designs that were intrinsically tied to current SOT; 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 C&D 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 C&D blends) and evaluating the compatibilities and incompatibilities of blendstocks. The results of this research are critical to further development of blended feedstocks.

10.2 Feedstock Composition (In-feed quality specifications)

The dry basis elemental composition of the feedstock, shown in Table 39, is similar to previous NREL and PNNL design reports⁶. The composition was originally assumed to come from pulpwood. Recent feedstock logistics work suggests the use of blended material may be required to meet a cost target of \$80/dry US ton while still meeting these specifications. For the purpose of this report, it is assumed that any blended material provided to meet this feedstock elemental composition will not adversely affect fast pyrolysis conversion efficiencies. Ongoing studies being conducted jointly by INL, NREL and PNNL will provide experimental evidence of the impact of blended feedstocks on fast pyrolysis and gasification processes. Future TEA will be modified to reflect conversion impacts inferred from such studies. As has been described in prior conversion design reports, the feedstock composition plays a critical role on overall process design and economics, primarily with respect to high and low heating values, carbon as well as high sensitivity to impurity components such as ash and metals in this design. The blended uniform-format feedstock composition assumed here for purposes of future design case targets is shown below, with supporting details described in the 2011 ethanol report⁴⁶. Also consistent with prior design cases, the moisture content for the delivered feedstock is 10% or less.

Table 39. Delivered woody feedstock composition and processing assumptions for the In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors⁶.

Component	Composition (dry wt. %)
Carbon	50.94
Hydrogen	6.04
Nitrogen	0.17
Sulfur	0.03
Oxygen	41.90
Ash	0.90-1.0
Heating Value (Btu/lb)	8,601 HHV 7,996 LHV
Moisture (Bulk Wt. %)	10.0
Particle Size (inch)	¼

10.3 Feedstock Selection Cost Estimation

Expansion beyond highly productive resource areas has significant implications to the feedstock supply chain. Sparse areas, 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 yields increase the supply radius and biomass transportation distances. Under the 2012 Conventional Design, higher yield areas allow refinery to be selective on the resource that they access.

Consider, for example, the scenarios depicted in Figure 34. This resource map illustrates a county-level resource assessment of pulpwood farm gate at \$60/dry T prices (this includes grower payment, harvest, collection, and chipping costs). Farm gate price data were extracted from *The Billion Ton Update* (BT2)⁵ data supplied from Oak Ridge National Laboratory. It should be noted that while the data is reported at a county-level, the data should be applied at the wood shed (typically much larger area than a county) level because it was derived from the U.S. Forest Service Forest Inventory and Assessment Data (FIA)⁵⁶ and does not equate to county levels accurately. The FIA is a woodshed level assessment and therefore to use the data correctly it is necessary to combine multiple counties.

The cost competitiveness of the 2012 Conventional Design was demonstrated in the scenario located in southern Alabama, a high biomass yielding area. We further suggest, based on the consistency of farm gate (i.e., landing) prices shown in this map, that the 2012 Conventional Design can be deployed cost effectively in South Carolina. Commercial readiness of conventional supply systems ultimately will be demonstrated by commercial-scale cellulosic ethanol plants opening in these areas in the near future.

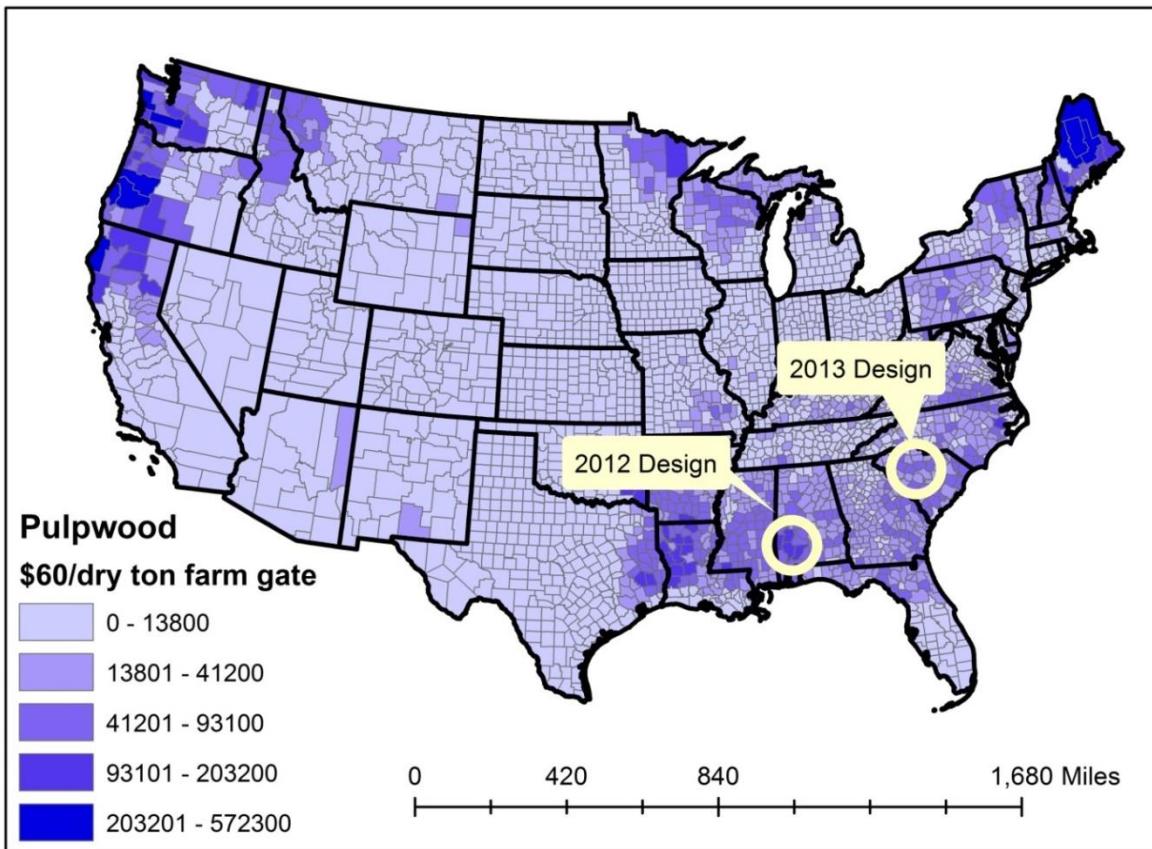


Figure 34. Total tons per county of available pulpwood at \$60/dry T farm gate price. Yellow circles show areas represented in the 2012 Conventional Design and the Relocated (2013) Design Case⁵.

Access costs are calculated from the grower payment cost curves shown in Figure 6, which are derived from historical prices. 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 feedstock allows us to stay lower on the supply curve than if we had to supply the entire refinery with any single feedstock. The impact of this approach is shown in Table 40. The 2013 State of Technology assumes a 100% supply of pulpwood of 909,100 dry T at an estimated \$60/dry T farm gate or a \$25/dry T access cost. In comparison, the 2017 Design Case blend of 45% pulpwood, 32% wood residues, 20% C & D waste, and 3% switchgrass results in a weighted average feedstock cost that is nearly 15% lower than the access cost of pulpwood alone.

Table 40. Resource access cost estimate (U.S. DOE 2011⁵, and INL MSW Data).

	2013 SOT		2017 Target	
	Access Cost (2011 \$/dry T)	Tons	Access Cost (2011 \$/dry T)	Tons
Pulpwood	25.00	909,100*	25.00	425,700*
Wood Residues	NA	NA	26.35	412,800**
Switchgrass	NA	NA	19.67	25,800
C&D	NA	NA	8.15	172,000
Totals	25.00	NA	21.90	1,036,300

*assumes 10% loss of material to debark/delimb¹⁸.

** assumes 40% loss of material to clean up residues¹⁹.

10.4 Quality Specification and Design Assumptions

The 2012 Conventional Design focused on conventional woody harvest operations (i.e., felling and/or skidding operations are separate from landing preprocessing operations). In addition to including switchgrass into the feedstock blend, the 2017 Design Case assumes that the immaturity of the biomass market will limit the forest and farm owner's investment in advanced equipment options for both woody and herbaceous feedstocks. Therefore, with the exception of a few proactive, early adopters, conventional forestry and farming operations will dominate the market in the regions defined by the 2017 Design Case. Table 41 below summarizes the assumptions and differences between the 2012 and 2017 logistic designs.

Table 41. Summary of assumptions underpinning progressive design implementations⁵⁷.

	2012 Conventional Design	Baseline	2017 Design Case
Feedstock(s)	Pulpwood	Pulpwood	Blended feedstock: pulpwood (45%), wood residues (32%), switchgrass (3%), and select construction and demolition wastes (C & D)(20%)
Grower payment	Breakeven cost of production	Increases based on marginal cost differential	Calculated and modeled according to specific location and resource blend/formulation
Moisture	Field dried to 40%	Field dried to 40%	Arrives: Pulpwood chips 30% wood residue chips 30%, switchgrass 20%, and C& D ground 20%; All dried to 9% pellets
Ash	Debark/delimb	Debark/delimb	Debark/delimb pulpwood Trommel screen residues Wash and sort C& D waste Blended ash content of <1% Debarked pulpwood <1%, screened wood residues 1.4%; washed and sorted C&D 1.0 %
Logistics	Uses existing systems	Uses existing systems	Pneumatics attached to hammer mill High-moisture densification
Quality controls (passive)	Field drying to reduce moisture Ample available resource; quality spec manually selected	Field drying to meet moisture spec	Harvest/collection and storage best management practices for pulpwood and switchgrass More rigorous field drying of pulpwood and residues
Quality controls (active)	Waste heat dryer	Rotary drying	Multiple resource blending/formulation High-moisture densification High-efficiency pellet drying
Meets quality target	Yes	Yes	Yes
Meets cost target	Yes	No	Yes
Accesses dispersed resources	No	No	Yes

Relative to the woody feedstocks used in the Thermochemical Design Case, the 2013 baseline and 2017 Design Case are similar in many ways for harvest and collection, but the latter has two key changes to improve quality and production of woody materials. While each system is discussed later, the key differences of the 2017 Design Case are first inclusion of woody residues sourced from pulpwood operations, and second in-forest drying of whole tree piles at the landing to achieve a more aggressive moisture content of 30%. In this design debarking and delimiting are conducted to improve biomass quality. Construction and demolition wastes are considered to enter the feedstock logistics system at the preprocessing stage and are therefore not discussed here.

10.5 Feedstock Logistics

10.5.1 Harvest and Collection

Conventional wood harvest and collection relies on existing forestry technologies designed for timber and pulp and paper production. Collection systems for woody material involve cutting the feedstock with a tracked feller buncher and transporting the material to the landing with a grapple skidder immediately after felling. Felling and skidding operations increase the overall ash content of harvested whole-trees by introducing soil as it is moved in contact with the ground from one location to the next⁵⁸. In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors are highly sensitive to silica, alkali, and transition metals found in most soils, impacting process performance^{59 60 61}. In both the 2013 and 2017 Design Cases active management strategies are employed during the landing preprocessing to improve biomass ash content. Current forestry production of pine pulpwood is reported to yield roundwood with a moisture content of 45-55% and a whole-tree ash content ranging from 1% to 3%^{62 63 64}. The 2013 baseline assumes the moisture content of pulpwood to be 50% for whole-trees entering storage.

Woody residues are generated through typical commercial forestry operations on southern pine plantations where trees are harvested for pulpwood, chip-and-saw, and saw timber. Similar to the above described collection of pulpwood, these operations bring whole trees to the landing where they are delimated and topped using a pull-through delimiter. The roundwood is then loaded onto trucks for delivery to the mill while the residues are piled at the landing. While not collected in the 2013 baseline, the 2017 Design Case utilizes these materials as a fraction of the feedstock blend. The baseline for residue moisture content is reported at 40%, while ash content has been reported to range from 2% to 4%^{47, 62, 65 66}. Switchgrass, which is part of the blend, harvest and collection systems use a conventional windrowing harvester and rectangular baler (3x4x8-ft).

10.5.1.1 Harvest and Collection Design Basis

The 2017 Design Case incorporates a chain flail debarker during preprocessing at the landing to increase the quality of the final chipped pulpwood product. Therefore, moisture and ash contents of material entering storage are not different between the 2013 and 2017 Designs. However, there is still impetus to increase the operational efficiency of roundwood collection for reducing costs^{67 68}. This can be achieved through forest management shifts to short-rotation pine plantations aimed at supplying bioenergy production, increased efficiency of harvesting machinery, and increased efficiency of grapple skidder transportation. Research conducted by Auburn University for the DOE High Tonnage Forest Biomass Project has demonstrated high capacity grapplers to increase productivity by 80 tons per productive machine hour compared to

traditional systems⁵⁸. Figure 35 depicts a conventional skidder and a high capacity skidder. Further development of such operational improvements will play a key role in reducing costs of clean pulp chips for thermochemical conversion. In addition, transition of forest management to short rotation pine plantations focused on energy use is a promising option for increasing yields; should the economics of establishment be overcome⁶⁹.



Figure 35. Conventional (left) and high-capacity grapple skidder (right) for transporting small diameter pulpwood from the forest to the landing. Photo credit: Auburn University High Tonnage Forest Biomass Project⁵⁸.

Wood residues (tree tops and limbs) originate from other commercial logging operations and are located in piles at the landing, eliminating the costs for harvest and collection (e.g., felling and skidding). Similar to pulpwood, the 2017 Design Case incorporates active quality controls to reduce the ash content during preprocessing at the landing. These active controls applied after storage may contain ash contents in excess of the desired specification of 0.9% for wood residues and less for pulpwood.

Switchgrass harvest in the 2017 Design Case follows conventional practices for feed and forage in terms of the equipment used, but incorporates more rigorous passive quality controls to reduce ash content. Delayed harvest of switchgrass provides the benefits of reducing moisture and ash content, but even with the practice of delayed-harvest, it is clear that the raw feedstock will not meet the final quality specification for ash. Blending of switchgrass with a low-ash feedstock is necessary to achieve ash specification of <1%. Nevertheless, it is important that best management practices for switchgrass harvest are used to reduce soil contamination during the processes of cutting and baling while respecting the relationship between delayed harvest date and collection efficiency. Research conducted by Oklahoma State University in collaboration with INL shows that switchgrass can achieve moisture contents at or below the 2017 Design Case specification (10% to 5%), though climatic variance can still introduce moisture variability in delayed harvests (Figure 36). In this same research the ash content of switchgrass was found to be low even at an early harvest (5% in August), though a decreasing trend was observed as harvest was delayed (4% by December). This work stands as an example of the effectiveness of proper harvesting techniques, and stresses the importance of establishing best management

practices to cope with variability in weather conditions. Goals for the 2017 Design Case include reducing ash content to 4% through harvest timing and advanced harvesting techniques.

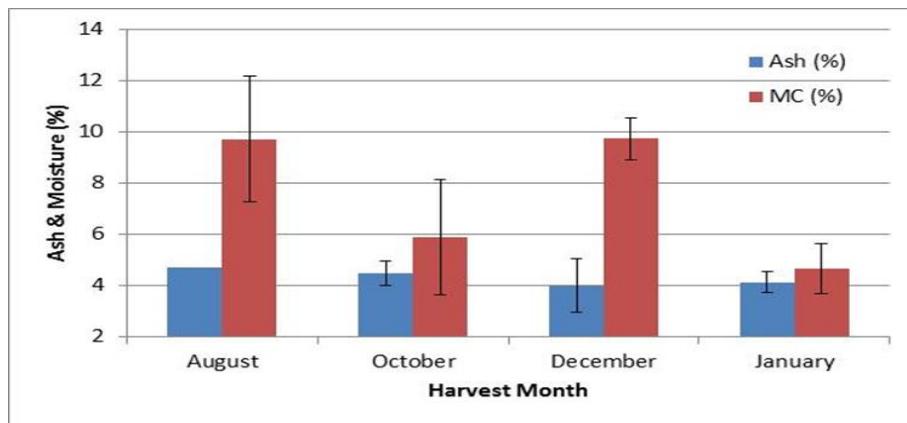


Figure 36. Ash and moisture content of switchgrass harvested in Oklahoma, 2010 by Oklahoma State University. Error bars represent one standard deviation. Ash samples for October, December, and January are three samples comprised of six individual core samples composited.

10.5.1.2 Harvest and Collection Cost Estimation

Harvest and collection costs assume a removal rate of 15 dry T/acre for pulpwood⁷⁰, 4 dry T/acre for residues⁶⁶, and 5-dry T/acre for switchgrass⁷¹. These assumptions are consistent with those used in the Billion Ton Update⁵. Cost of harvest and collection is shown in Table 42. The cost of ash at this point within the feedstock logistics system described in section 4 is not yet applicable to pulpwood or wood residue, as the material will undergo active quality controls during landing preprocessing. Switchgrass may be subjected to an ash dockage at this point in the process if ash contents are greater than those needed by the feedstock blending process.

Table 42. Biomass harvest and collection cost estimates derived from INL analysis.

Machine	2013 SOT (2011 \$/dry T)	2017 Target (2011 \$/dry T)
	Total	Total
Pulpwood		
Felling	15.00	15.00
Yarding	7.24	7.24
Totals	22.24	22.24
Wood Residues*		
Felling	0.00	0.00
Yarding	0.00	0.00
Totals	0.00	0.00
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 harvest and collection of other process.

10.5.2 Storage

10.5.2.1 2013 State of Technology

Because the 2017 Design Case utilizes a blended feedstock, switchgrass storage must be addressed. The storage of switchgrass occurs field side or at a similar on-farm unimproved storage site. As for any baled feedstock, 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 stack to be positioned in a North-South orientation to reduce moisture accumulation on the north side of the stack⁷². Tarped stacks are chosen as a balance between bale protection against moisture infiltration, which leads to dry matter loss, and storage configuration costs^{73 22}. Stacks are constructed with a self-propelled stacking bale wagon and are six bales high and covered with a high-quality hay tarp. In order to prolong tarp life, it is also important that adequate year-round maintenance be provided to periodically tighten the tarps⁷⁴. Biomass storage systems in the current Design Case seek to provide a low-cost, low-maintenance, moisture-tolerant solution that focus on maintaining moisture content <20%, minimizing dry matter loss and preserving feedstock composition. Table 43 shows the assumed changes in moisture content between the 2013 SOT and the 2017 Design Case.

Table 43. Technical targets for biomass field storage of resources in the 2017 Design Case.

Process	After Field Drying Moisture Content	
	2013 SOT	2017 Target
Pulpwood	40 %	30%
Wood Residues	40%	30%
Switchgrass	20%	20%

10.5.2.2 Storage Design Basis

The 2017 Design Case is based on field drying for pulpwood and forest residues, both to 30% moisture at the time the material enters landing preprocessing. Field studies on field drying of short rotation southern pine pulpwood and residues have shown final moisture contents of 30% to be achievable given adequate time^{65 58 64}.

Since chips are expected to enter storage at 30% moisture in the 2017 Design Case, it is reasonable to assume that dry matter losses will be much less (nearly negligible) within the three day holding window. The concerns of unplanned storage extensions, moisture addition, or mechanical losses could increase this number, and therefore the 2017 Design Case assumes a target chip-storage dry matter loss of 5%. Protection of chip piles with tarps could help to prevent these losses, if the additional material and labor costs are merited, and their presence does not interfere with regular loading and unloading of the piles. Storage of switchgrass is not expected to deviate from the 2013 Design Case baseline. Due to the low moisture content entering storage, the use of a tarp to protect from moisture addition through precipitation has been shown to be sufficient and cost effective when properly applied.

10.5.2.3 Biomass Storage Cost Estimation

Cost estimations for biomass storage were calculated based on literature values from recent reviews⁷⁴, the storage cover vendor's information, and laboratory and field level experiments⁷² (Table 44).

Table 44. Field-side storage cost estimation.

SOT (2011 \$/dry T)			Design Target (2011 \$/dry T)			
	Storage	Dockage	Total	Storage	Dockage	Total
Switchgrass	N/A	N/A	N/A	5.50	0.00	5.50

10.5.3 Preprocessing

2017 Design Case that incorporates many improvements in preprocessing, including pneumatics, high-moisture densification, and formulation/blending. Figure 37 outlines the material flow given for these improvements. In the 2017 Design Case, substantial cost savings in size reduction are realized by tailoring the preprocessing stages to the individual feedstock and not applying a one size fits all approach. For example, pulpwood is debarked and delimbed and then processed through a chipper to optimize retention of usable material; wood residues are processed through

a first stage grinder then separated by passing through a trommel screen; switchgrass is processed through a grinder while Construction and Demolition (C&D) waste undergoes sorting and a wash step.

Separation/sorting of C&D waste 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, C&D is sorted to supply usable material for thermochemical conversion. Prior to any preprocessing the ash content of untreated C&D waste fractions is estimated to be about 6%. The application of a wash stage further reduces the ash content down to pure wood levels of about 1%.

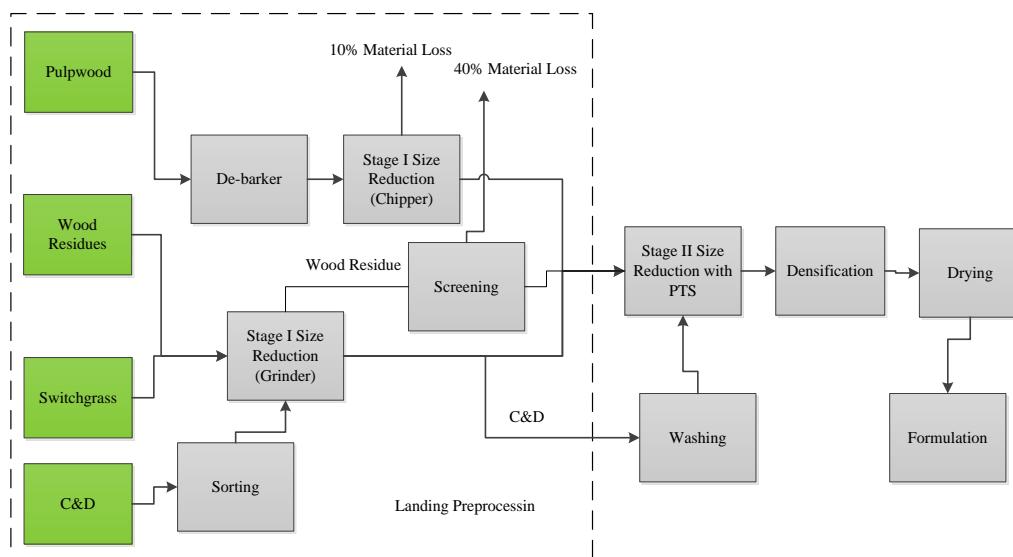


Figure 37. Material flow in the 2017 Design Case that incorporates many improvements in preprocessing, including pneumatics, high-moisture densification, and formulation/blending.

The logistics of a blended feedstock scenario are certainly more complex than a single-feedstock scenario. The 2017 Design Case assumes that preprocessing of C&D will occur at a preprocessing depot located at the source landfill or refuse transfer station, and C&D pellets will be shipped from the depot to the blending depot located within proximity of the biorefinery. Switchgrass that is formatted in large square bales will be delivered to the blending depot, where they will be processed into pellets. Pulpwood and wood residues will be initially processed at the landing for initial size reduction and ash mitigation then transported to a processing facility for pelletization. The pulpwood, wood residues, switchgrass, and C&D pellets will be queued up in blending bunkers or silos and blended to specification prior to being fed into the conversion process. The pellets of the four blendstocks (i.e., pulpwood, wood residues, switchgrass, and C&D) 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.

10.5.3.1 State of Technology:

For the 2017 Design Case, a geometric mean particle size of 1/4- in. is the target size specification for the thermochemical conversion process design under development by PNNL (Table 45). As the target size specification is the same as biochemical conversion, size reduction system used to meet the final particle size specification required by the end user will be the same for fast pyrolysis conversion. The 2013 state of technology follows sequential two stage size reduction described in section 6

Table 45. Size-reduction design basis.

			2013 SOT	2017 Target
	Equipment Used	Screen Size	Capacity Ton/hr	Capacity Ton/hr
First Stage Size Reduction				
Pulpwood	Chipper	2 in.	17	17
Wood Residue	Grinder	2in.		
Second Stage Size Reduction				
Pulpwood	Hammer mill	1/4 in.	5	6.5
Wood Residue	Hammer mill	1/4 in.	5	6.5

10.5.3.2 Size Reduction Cost Estimation

Milling cost estimation is based on vendor-supplied information and equipment performance from typical machine performance and process demonstration unit data and is shown in Table 46.

Table 46. Size reduction cost estimates.

	2013 SOT (2011 \$/dry T)	2017 Target (2011 \$/dry T)
	<i>Total</i>	<i>Total</i>
Pulpwood		
Chipper	6.10	6.10
Debark/delimb	6.10	6.10
Hammer Mill	17.09	13.97
Total	29.29	26.17
Wood Residue		
Grinder	5.39	5.39
Trommel Screen	3.32	3.32
Hammer Mill	17.09	13.97
Total	25.80	22.68

10.5.3.3 Drying and Densification

A comparison of pellet properties and energy balances for conventional and high-moisture pelletization processes is given in Table 47. The table shows 2017 Design Case targets to achieve a 40 to 50% reduction in the total pelletization and drying energy.

Table 47. Drying and densification design basis.

	2013 SOT	2017 Target
Infeed Moisture	40%	30%
Dryer Moisture Reduction	28%	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	65 lb/ft ³	70 lb/ft ³
Bulk Density	35 lb/ft ³	40 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 from woody material; 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.

10.5.3.4 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 48.

Table 48. Drying and densification cost estimates.

	2013 SOT (2011 \$/dry T)	2017 Target (2011 \$/dry T)
	<i>Total</i>	<i>Total</i>
Drying	17.20	5.60
Densification	7.70	4.40
Totals	24.90	10.00

10.5.3.5 Formulation/Blending

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 49.

Table 49. Feedstock formulation/blending of ash and moisture contents*.

Content Delivered to Biorefinery Infeed	Pulpwood(45%)	Wood Residues(32%)	Switchgrass(3%)	C&D Waste(20%)	Final Blend
Ash content (wt. %)	0.5	1.0	4.0	1.0	<1%
Moisture content (%, wet basis)	9	9	9	9	9
HHV (lb/BTU)	8824	9444	7557	8824	8984
LHV (lb/BTU)	7255	7616	6155	7255	7337

*Pulpwood, wood residues, and switchgrass composition data were obtained from the INL Biomass Library⁷⁵.

Assumptions for the formulation design basis are as follows:

- Blended feedstocks are selected and developed to achieve conversion yield specifications. It currently unknown how blended feedstocks will perform in the conversion pathways. The simplest assumption is that the blended feedstocks would be the sum of performances of each individual component. There are on-going trials to test various blended feedstocks and to compare the conversion efficiencies against a single feedstocks.
- Individual feedstocks will be pelleted at depots for shipment to biorefineries. At the biorefinery, these 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 mixed prior to insertion for the conversion process.
- Material will be metered from individual bunkers onto a conveyer and then thoroughly homogenized through 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.
- The expected unit operations for formulation are shown in Table 50.

Table 50. Feedstock formulation design basis.

2013 SOT (2011 \$/dry T)	Operating Parameters	
	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 is currently ongoing at INL to examine the compatibility of various feedstocks blends, with an initial focus on the blends reactivity 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 including bio-oil conversion via fast pyrolysis.

While the costs for preprocessing of feedstocks (e.g., grinding, chemical preconversion, pelleting, and drying) are addressed in other parts of the 2017 Design Case, formulation itself will require a different set of preprocessing options in order to match up with the bio-oil conversion pathway. These processes include bulk storage, conveying systems and a pellet pulverizer to insure that the appropriate recipe of material enters the throat of the conversion reactor in the appropriate blends and sizing requirements.

10.5.3.6 Cost Estimation for Formulation.

Cost estimation for formulation was based on existing technology, vendor-supplied information, and equipment performance (Table 51). These costs are cursory and require more extensive research, especially in their specific application to the bioenergy industry.

Table 51. Formulation cost estimation.

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

10.5.4 Transportation and Handling Design Basis

The 2017 Design Case includes formulation and densification that meets feedstock specifications and costs targets. Both processes of formulation and densification will improve feedstock handling operations through active controls. Given formulation and the specific quantities of individual feedstocks required, the average transportation distance will change based on feedstock type. In the 2017 Design Case, pulpwood will be trucked from a local draw radius of 50 miles while switchgrass will be trucked fewer than 15 miles. In Appendix A sufficient C&D waste resources in the selected counties in western South Carolina; therefore, C&D will be transported by truck from transfer stations after processing. This is not a new concept, transfer stations are already used for sorting and transporting valuable material such as cardboard and scrap metal in densified forms (e.g. baled cardboard, crushed and baled scrap metal).

Switchgrass will be loaded and unloaded at each location using a loader (telehandler) capable of moving 12 lb/ft³ bales at 20% respective moisture content. A 53-ft. trailer and 800,000-GVW limits were assumed in all trucking operations. Transportation for switchgrass will occur from a field side stack to a densification facility completely separate from the conversion facility, but within a minimal conveyor distance (typically <50 miles). C&D waste transportation will occur from the waste transfer station as pellets to the preprocessing facility for storage and transfer to the biorefinery. Further transportation and handling assumptions are given as follows:

- At 20% moisture, transportation continues to be volume limited at densities of 12 lb/ft³.
- At 30% moisture, transportation of chips continues to be volume limited.
- At 9% moisture, transportation of pellets is weight limited at 40 lb/ft³.
- There will be insignificant material losses throughout transportation and handling.
- Densification will increase material uniformity and flowability

10.5.4.1 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 52). Rail transportation costs were estimated using a jumbo hopper car⁵⁴ adjusted for U.S. conditions.

Table 52. Transportation cost estimates.

	2013 SOT (2011 \$/dry T)	2017 Target (2011 \$/dry T)
	<i>Total</i>	<i>Total</i>
Truck	14.84*	7.52**
*Individual feedstock therefore one transportation pathway		
**Multiple feedstocks therefore multiple transportation pathways and draw radiiuses.		

10.6 Life Cycle Analysis

This section uses a life-cycle assessment (LCA) to evaluate the energy input and GHG emissions for conversion In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors. LCA considered the unit processes involved in the biomass logistics. Table 53 shows the energy consumption and Table 54 show GHG contribution for In Situ and Ex Situ Upgrading of Fast Pyrolysis Vapors Pathway conversion supply chain design.

Table 53. Energy Consumption for Thermochemical conversion supply chain design.

Process Element	Pulpwood	Wood Residues	Switchgrass	Construction and Demolition Waste (C&D)	Blend
<i>Formulation Contribution</i>	45%	32%	3%	20%	–
Harvest and Collection (MBTU/dry T)	182.78	–	122.85	–	85.94
Landing Preprocessing/Sorting (MBTU/dry T)	231.52	110.25	–	410.25	221.51
Transportation (MBTU/dry T)	136.87	101.38	99.35	273.73	151.76
Preprocessing (MBTU/dry T)	408.01	408.01	285.83	408.01	404.34
Storage (MBTU/dry T)	8.46	8.46	21.83	8.46	8.86
Handling (MBTU/dry T)	42.69	42.69	41.90	42.69	42.67
Total Energy Consumption (MBTU/dry T)	1001.33	670.79	571.76	1143.14	915.08

Table 54. GHG contribution for thermochemical conversion supply chain design.

Process Element	Blend
<i>Formulation Contribution</i>	–
Harvest and collection GHGs (Kg CO₂e/ dry T)	8.65
Landing Preprocessing GHGs (Kg CO₂e/ dry T)	18.95
Transportation GHGs (Kg CO₂e/ dry T)	8.62
Preprocessing GHGs (Kg CO₂e/ dry T)	34.60
Storage GHGs (Kg CO₂e/ dry T)	0.89
Handling GHGs (Kg CO₂e/ dry T)	4.2
Total GHGs (Kg CO₂e/ dry T)	75.91

11. Dilute-Acid Conversion of Lignocellulosic Biomass to High Octane Gasoline via Indirect Gasification and Methanol Intermediate

This section is intended to couple with the National Renewable Energy Laboratory's (NREL's) hydrocarbon design report, "Process Design and Economics for the Conversion of Lignocellulosic Biomass to High Octane Gasoline via Indirect Gasification and Methanol Intermediate"⁶ that describes a viable route from biomass to hydrocarbon fuels. 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. This design does not consider the different requirements and nuances of other thermochemical conversion processes or other hydrocarbon pathways.

11.1 Summary

This report establishes a plausible case for achieving the 2017 Design Case for Lignocellulosic Biomass to High Octane Gasoline via Indirect Gasification and Methanol Intermediate conversion cost goals of delivering a biomass feedstock to the conversion facility at a cost of \$80/dry T (Table 55). The least-cost formulation approach (Appendix B) illustrates the importance of 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.

Table 55. Thermochemical feedstock design cost analysis for 2017.

Cost Element	Pulpwood	Wood Residues	Switchgrass	Construction and Demolition Waste (C&D)	Blend
<i>Formulation Contribution</i>	45%	32%	3%	20%	—
Grower payment/ access cost	25.00	26.35	19.67	8.15	21.90
Harvest and collection (\$/dry T)	22.24	0	15.41	—	10.47
Landing Preprocessing/ Sorting (\$/dry T)	12.17	8.73	0	9.85	10.24
Transportation (\$/dry T)	10.89	3.33	4.5	6.87	7.47
Preprocessing (\$/dry T)	23.97	23.97	19.7	28.12	24.67
Storage (\$/dry T)	3.23	3.23	5.5	3.23	3.30
Handling (\$/dry T)	1.90	1.90	1.90	1.90	1.90
Total Delivered Feedstock Cost (\$/dry T)	99.49	67.51	66.68	58.12	80.00
Delivered Feedstock Specifications					
Ash content (wt. %)	0.5	1.0	4.0	1.0	<1%
Moisture content (%, wet basis)	9	9	9	9	9
HHV (BTU/lb)	8824	9444	7557	8824	8984
LHV (BTU/lb)	7255	7616	6155	7255	7337

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*⁵ 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 gate price.

Logistics costs are based on actual field trial data but do not include the cost of various business elements, such as profit margins for transportation, depots and field agents that would be involved throughout a biomass feedstock supply chain. This would increase the overall cost of the supply system than is demonstrated in this report. This was of little consequence to the 2012 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 logistic systems become 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 (n^{th} plant costs) to be consistent with conversion platform terminology. This was not an issue with conventional feedstock designs that were intrinsically tied to current SOT; 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 C&D 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 C&D blends) and evaluating the compatibilities and incompatibilities of blendstocks. The results of this research are critical to further development of blended feedstocks.

11.2 Feedstock Composition (In-feed quality specifications)

The dry basis elemental composition of the feedstock, shown in Table 79 is similar to previous NREL and PNNL design reports⁶. The composition was originally assumed to come from pulpwood. Recent feedstock logistics work suggests the use of blended material may be required to meet a cost target of \$80/dry US ton while still meeting these specifications. For the purpose of this report, it is assumed that any blended material provided to meet this feedstock elemental composition will not adversely affect fast pyrolysis conversion efficiencies. Ongoing studies being conducted jointly by INL, NREL and PNNL will provide experimental evidence of the impact of blended feedstocks on fast pyrolysis and gasification processes. Future TEA will be modified to reflect conversion impacts inferred from such studies. As has been described in prior conversion design reports, the feedstock composition plays a critical role on overall process design and economics, primarily with respect to high and low heating values, carbon as well as high sensitivity to impurity components such as ash and metals in this design. The blended uniform-format feedstock composition assumed here for purposes of future design case targets is shown below, with supporting details described in the 2011 ethanol report⁴⁶. Also consistent with prior design cases, the moisture content for the delivered feedstock is 10% or less.

Table 56. Delivered woody feedstock composition and processing assumptions for the fast pyrolysis and hydrotreating design report⁶.

Component	Composition (dry wt. %)
Carbon	50.94
Hydrogen	6.04
Nitrogen	0.17
Sulfur	0.03
Oxygen	41.90
Ash	0.90-1.0
Heating Value (Btu/lb)	8,601 HHV 7,996 LHV
Moisture (Bulk Wt. %)	10.0
Particle Size (inch)	1/4

11.3 Feedstock Selection Cost Estimation

Expansion beyond highly productive resource areas has significant implications to the feedstock supply chain. Sparse areas, 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 yields increase the supply radius and biomass transportation distances. Under the 2012 Conventional Design, higher yield areas allow refinery to be selective on the resource that they access.

Consider, for example, the scenarios depicted in Figure 38. This resource map illustrates a county-level resource assessment of pulpwood farm gate at \$60/dry T prices (this includes grower payment, harvest, collection, and chipping costs). Farm gate price data were extracted from *The Billion Ton Update* (BT2)⁵ data supplied from Oak Ridge National Laboratory. It should be noted that while the data is reported at a county-level, the data should be applied at the wood shed (typically much larger area than a county) level because it was derived from the U.S. Forest Service Forest Inventory and Assessment Data (FIA)⁵⁶ and does not equate to county levels accurately. The FIA is a woodshed level assessment and therefore to use the data correctly it is necessary to combine multiple counties.

The cost competitiveness of the 2012 Conventional Design was demonstrated by in the scenario located in southern Alabama, a high biomass yielding area³. We further suggest, based on the consistency of farm gate (i.e., landing) prices shown in this map, that the 2012 Conventional Design can be deployed cost effectively in South Carolina. Commercial readiness of conventional supply systems ultimately will be demonstrated by commercial-scale cellulosic ethanol plants opening in these areas in the near future.

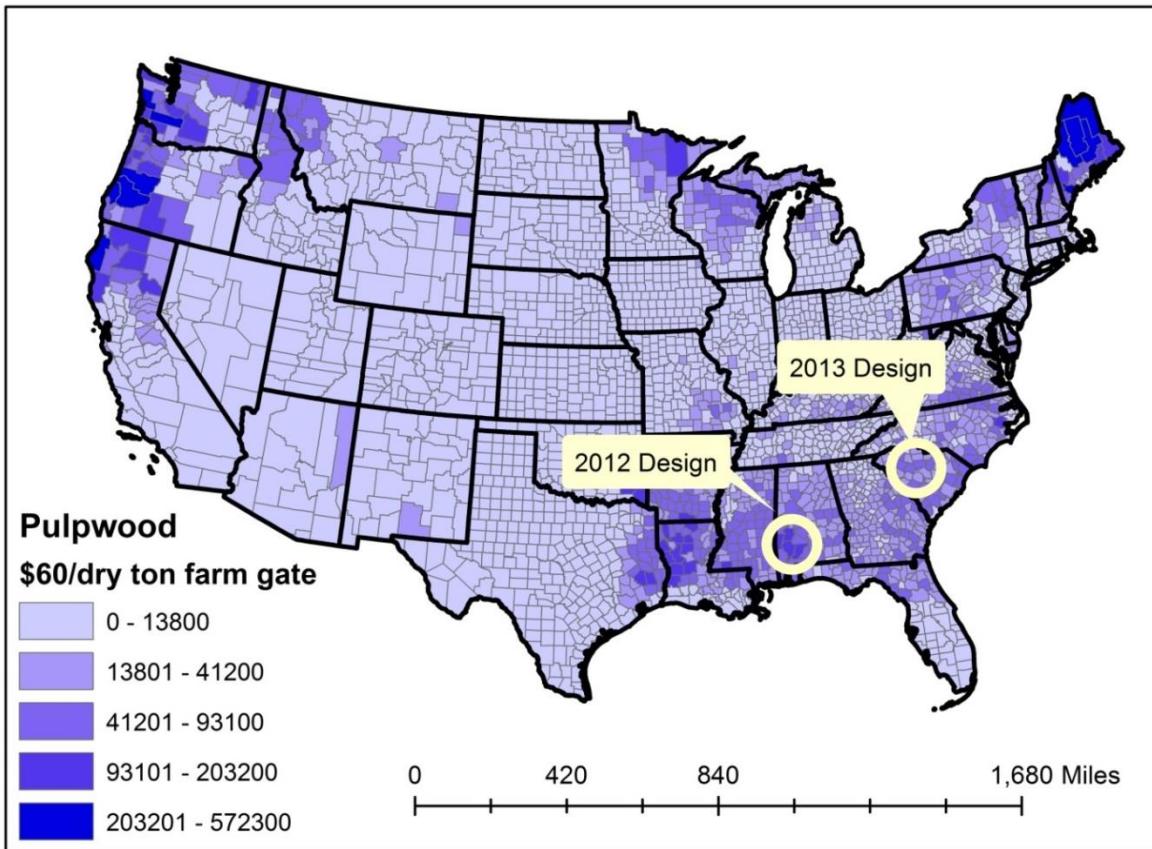


Figure 38. Total tons per county of available pulpwood at \$60/dry T farm gate price. Yellow circles show areas represented in the 2012 Conventional Design and the Relocated (2013) Design Case⁵.

Access costs are calculated from the grower payment cost curves shown in Figure 6, which are derived from historical prices. 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 feedstock allows us to stay lower on the supply curve than if we had to supply the entire refinery with any single feedstock. The impact of this approach is shown in Table 57. The 2013 State of Technology assumes a 100% supply of pulpwood of 909,100 dry T at an estimated \$60/dry T farm gate or a \$25/dry T access cost. In comparison, the 2017 Design Case blend of 45% pulpwood, 32% wood residues, 20% C & D waste, and 3% switchgrass results in a weighted average feedstock cost that is nearly 15% lower than the access cost of pulpwood alone.

Table 57. Resource access cost estimate (U.S. DOE 2011⁵, and INL MSW Data).

	2013 SOT		2017 Target	
	<i>Access Cost (2011 \$/dry T)</i>	<i>Tons</i>	<i>Access Cost (2011 \$/dry T)</i>	<i>Tons</i>
Pulpwood	25.00	909,100*	25.00	425,700*
Wood Residues	NA	NA	26.35	412,800**
Switchgrass	NA	NA	19.67	25,800
C&D	NA	NA	8.15	172,000
Totals	25.00	NA	21.90	1,036,300

*assumes 10% loss of material to debark/delimb (Walker, 2006)

11.4 Quality Specification and Design Assumptions

The 2012 Conventional Design focused on conventional woody harvest operations (i.e., felling and/or skidding operations are separate from landing preprocessing operations). In addition to including switchgrass into the feedstock blend, the 2017 Design Case assumes that the immaturity of the biomass market will limit the forest and farm owner's investment in advanced equipment options for both woody and herbaceous feedstocks. Therefore, with the exception of a few proactive, early adopters, conventional forestry and farming operations will dominate the market in the regions defined by the 2017 Design Case. Table 58 below summarizes the assumptions and differences between the 2012 and 2017 logistic designs.

Table 58. Summary of assumptions underpinning progressive design implementations⁵⁷.

	2012 Conventional Design	Baseline	2017 Design Case
Feedstock(s)	Pulpwood	Pulpwood	Blended feedstock: pulpwood (45%), wood residues (32%), switchgrass (3%), and select construction and demolition wastes (C & D)(20%)
Grower payment	Breakeven cost of production	Increases based on marginal cost differential	Calculated and modeled according to specific location and resource blend/formulation
Moisture	Field dried to 40%	Field dried to 40%	Arrives: Pulpwood chips 30% wood residue chips 30%, switchgrass 20%, and C& D ground 20%; All dried to 9% pellets
Ash	Debark/delimb	Debark/delimb	Debark/delimb pulpwood Trommel screen residues Wash and sort C& D waste Blended ash content of <1% Debarked pulpwood <1%, screened wood residues 1.4%; washed and sorted C&D 1.0 %
Logistics	Uses existing systems	Uses existing systems	Pneumatics attached to hammermill High-moisture densification
Quality controls (passive)	Field drying to reduce moisture Ample available resource; quality spec manually selected	Field drying to meet moisture spec	Harvest/collection and storage best management practices for pulpwood and switchgrass More rigorous field drying of pulpwood and residues
Quality controls (active)	Waste heat dryer	Rotary drying	Multiple resource blending/formulation High-moisture densification High-efficiency pellet drying
Meets quality target	Yes	Yes	Yes
Meets cost target	Yes	No	Yes
Accesses dispersed resources	No	No	Yes

Relative to the woody feedstocks used in the Thermochemical Design Case, the 2013 baseline and 2017 Design Case are similar in many ways for harvest and collection, but the latter has two key changes to improve quality and production of woody materials. While each system is discussed later, the key differences of the 2017 Design Case are first inclusion of woody residues sourced from pulpwood operations, and second in-forest drying of whole tree piles at the landing to achieve a more aggressive moisture content of 30%. In this design debarking and delimiting are conducted to improve biomass quality. Construction and demolition wastes are considered to enter the feedstock logistics system at the preprocessing stage and are therefore not discussed here.

11.5 Feedstock Logistics

11.5.1 Harvest and Collection

Conventional wood harvest and collection relies on existing forestry technologies designed for timber and pulp and paper production. Collection systems for woody material involve cutting the feedstock with a tracked feller buncher and transporting the material to the landing with a grapple skidder immediately after felling. Felling and skidding operations increase the overall ash content of harvested whole-trees by introducing soil as it is moved in contact with the ground from one location to the next⁵⁸. Thermochemical conversion processes via fast pyrolysis are highly sensitive to silica, alkali, and transition metals found in most soils, impacting process performance^{59 60 61}. In both the 2013 and 2017 Design Cases active management strategies are employed during the landing preprocessing to improve biomass ash content. Current forestry production of pine pulpwood is reported to yield roundwood with a moisture content of 45-55% and a whole-tree ash content ranging from 1% to 3%^{62 63 64}. The 2013 baseline assumes the moisture content of pulpwood to be 50% for whole-trees entering storage.

Woody residues are generated through typical commercial forestry operations on southern pine plantations where trees are harvested for pulpwood, chip-and-saw, and saw timber. Similar to the above described collection of pulpwood, these operations bring whole trees to the landing where they are delimbed and topped using a pull-through delimeter. The roundwood is then loaded onto trucks for delivery to the mill while the residues are piled at the landing. While not collected in the 2013 baseline, the 2017 Design Case utilizes these materials as a fraction of the feedstock blend. The baseline for residue moisture content is reported at 40%, while ash content has been reported to range from 2% to 4%^{47, 62, 65 66}. Switchgrass, which is part of the blend, harvest and collection systems use conventional windrowing harvester and rectangular baler (3x4x8-ft).

11.5.1.1 Harvest and Collection Design Basis

The 2017 Design Case incorporates a chain flail debarker during preprocessing at the landing to increase the quality of the final chipped pulpwood product. Therefore, moisture and ash contents of material entering storage are not different between the 2013 and 2017 Designs. However, there is still impetus to increase the operational efficiency of roundwood collection for reducing costs^{67 68}. This can be achieved through forest management shifts to short-rotation pine plantations aimed at supplying bioenergy production, increased efficiency of harvesting machinery, and increased efficiency of grapple skidder transportation. Research conducted by Auburn University for the DOE High Tonnage Forest Biomass Project has demonstrated high capacity grapplers to increase productivity by 80 tons per productive machine hour compared to

traditional systems⁵⁸. Figure 39 depicts a conventional skidder and a high capacity skidder. Further development of such operational improvements will play a key role in reducing costs of clean pulp chips for thermochemical conversion. In addition, transition of forest management to short rotation pine plantations focused on energy use is a promising option for increasing yields; should the economics of establishment be overcome⁶⁹.



Figure 39. Conventional (left) and high-capacity grapple skidder (right) for transporting small diameter pulpwood from the forest to the landing. Photo credit: Auburn University High Tonnage Forest Biomass Project⁵⁸.

Wood residues (tree tops and limbs) originate from other commercial logging operations and are located in piles at the landing, eliminating the costs for harvest and collection (e.g., felling and skidding). Similar to pulpwood, the 2017 Design Case incorporates active quality controls to reduce the ash content during preprocessing at the landing. These active controls applied after storage may contain ash contents in excess of the desired specification of 0.9% for wood residues and less for pulpwood.

Switchgrass harvest in the 2017 Design Case follows conventional practices for feed and forage in terms of the equipment used, but incorporates more rigorous passive quality controls to reduce ash content. Delayed harvest of switchgrass provides the benefits of reducing moisture and ash content, but even with the practice of delayed-harvest, it is clear the raw feedstock will not meet the final quality specification for ash. Blending of switchgrass with a low-ash feedstock is necessary to achieve ash specification of <1%. Nevertheless, it is important that best management practices for switchgrass harvest are used to reduce soil contamination during the processes of cutting and baling while respecting the relationship between delayed harvest date and collection efficiency. Research conducted by Oklahoma State University in collaboration with INL shows that switchgrass can achieve moisture contents at or below the 2017 Design Case specification (10% to 5%), though climatic variance can still introduce moisture variability in delayed harvests (Figure 40). In this same research the ash content of switchgrass was found to be low even at an early harvest (5% in August), though a decreasing trend was observed as harvest was delayed (4% by December). This work stands as an example of the effectiveness of proper harvesting techniques, and stresses the importance of establishing best management

practices to cope with variability in weather conditions. Goals for the 2017 Design Case include reducing ash content to 4% through harvest timing and advanced harvesting techniques.

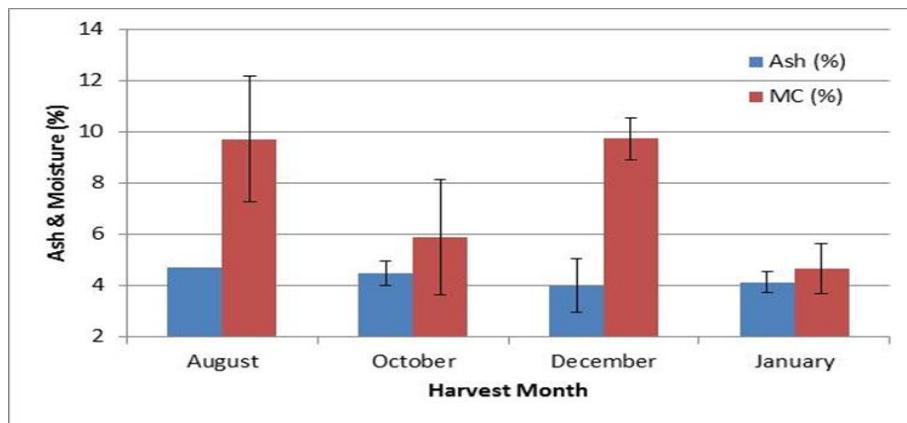


Figure 40. Ash and moisture content of switchgrass harvested in Oklahoma, 2010 by Oklahoma State University. Error bars represent one standard deviation. Ash samples for October, December, and January are three samples comprised of six individual core samples composited.

11.5.1.2 Harvest and Collection Cost Estimation

Harvest and collection costs assume a removal rate of 15 dry T/acre for pulpwood⁷⁰, 4 dry T/acre for residues⁶⁶, and 5-dry T/acre for switchgrass⁷¹. These assumptions are consistent with those used in the Billion Ton Update⁵. Cost of harvest and collection is shown in Table 59. The cost of ash at this point within the feedstock logistics system described in section 4 is not yet applicable to pulpwood or wood residue, as the material will undergo active quality controls during landing preprocessing. Switchgrass may be subjected to an ash dockage at this point in the process if ash contents are greater than those needed by the feedstock blending process.

Table 59. Biomass harvest and collection cost estimates derived from INL analysis.

Machine	2013 SOT	2017 Target (2011
	(2011 \$/dry T)	\$/dry T)
	<i>Total</i>	<i>Total</i>
Pulpwood		
Felling	15.00	15.00
Yarding	7.24	7.24
Totals	22.24	22.24
Wood Residues*		
Felling	0.00	0.00
Yarding	0.00	0.00
Totals	0.00	0.00
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 harvest and collection of other process.

11.5.2 Storage

11.5.2.1 2013 State of Technology

Because the 2017 Design Case utilizes a blended feedstock, switchgrass storage must be addressed. The storage of switchgrass occurs field side or at a similar on-farm unimproved storage site. As for any baled feedstock, 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 stack to be positioned in a North-South orientation to reduce moisture accumulation on the north side of the stack⁷². Tarped stacks are chosen as a balance between bale protection against moisture infiltration, which leads to dry matter loss, and storage configuration costs^{73 22}. Stacks are constructed with a self-propelled stacking bale wagon and are six bales high and covered with a high-quality hay tarp. To prolong tarp life, it is also important that adequate year-round maintenance be provided to periodically tighten the tarps⁷⁴. Biomass storage systems in the current Design Case seek to provide a low-cost, low-maintenance, moisture-tolerant solution that focus on maintaining moisture content <20%, minimizing dry matter loss and preserving feedstock composition. Table 60 shows the assumed changes in moisture content between the 2013 SOT and the 2017 Design Case.

Table 60. Technical targets for biomass field storage of resources in the 2017 Design Case.

Process	After Field Drying Moisture Content	
	2013 SOT	2017 Target
Pulpwood	40 %	30%
Wood Residues	40%	30%
Switchgrass	20%	20%

11.5.2.2 Storage Design Basis

The 2017 Design Case is based on field drying for pulpwood and forest residues, both to 30% moisture at the time the material enters landing preprocessing. Field studies on field drying of short rotation southern pine pulpwood and residues have shown final moisture contents of 30% to be achievable given adequate time^{65 58 64}.

Since chips are expected to enter storage at 30% moisture in the 2017 Design Case, it is reasonable to assume that dry matter losses will be much less (nearly negligible) within the three day holding window. The concerns of unplanned storage extensions, moisture addition, or mechanical losses could increase this number, and therefore the 2017 Design Case assumes a target chip-storage dry matter loss of 5%. Protection of chip piles with tarps could help to prevent these losses, if the additional material and labor costs are merited, and their presence does not interfere with regular loading and unloading of the piles. Storage of switchgrass is not expected to deviate from the 2013 Design Case baseline. Due to the low moisture content entering storage, the use of a tarp to protect from moisture addition through precipitation has been shown to be sufficient and cost effective when properly applied.

11.5.2.3 Biomass Storage Cost Estimation

Cost estimations for biomass storage were calculated based on literature values from recent reviews⁷⁴, the storage cover vendor's information, and laboratory and field level experiments⁷² (Table 61).

Table 61. Field-side storage cost estimation.

	SOT (2011 \$/dry T)			Design Target (2011 \$/dry T)		
	Storage	Dockage	Total	Storage	Dockage	Total
Switchgrass	N/A	N/A	N/A	5.50	0.00	5.50

11.5.3 Preprocessing

The 2017 Design Case that incorporates many improvements in preprocessing, including pneumatics, high-moisture densification, and formulation/blending. Figure 41 outlines the material flow given for these improvements. In the 2017 Design Case, substantial cost savings in size reduction are realized by tailoring the preprocessing stages to the individual feedstock and not applying a one size fits all approach. For example, pulpwood is debarked and delimbed and then processed through a chipper to optimize retention of usable material; wood residues are

processed through a first stage grinder then separated by passing through a trommel screen; switchgrass is processed through a grinder while Construction and Demolition (C&D) waste undergoes sorting and a wash step.

Separation/sorting of C&D waste 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, C&D is sorted to supply usable material for thermochemical conversion. Prior to any preprocessing the ash content of untreated C&D waste fractions is estimated to be about 6%. The application of a wash stage further reduces the ash content down to pure wood levels of about 1%.

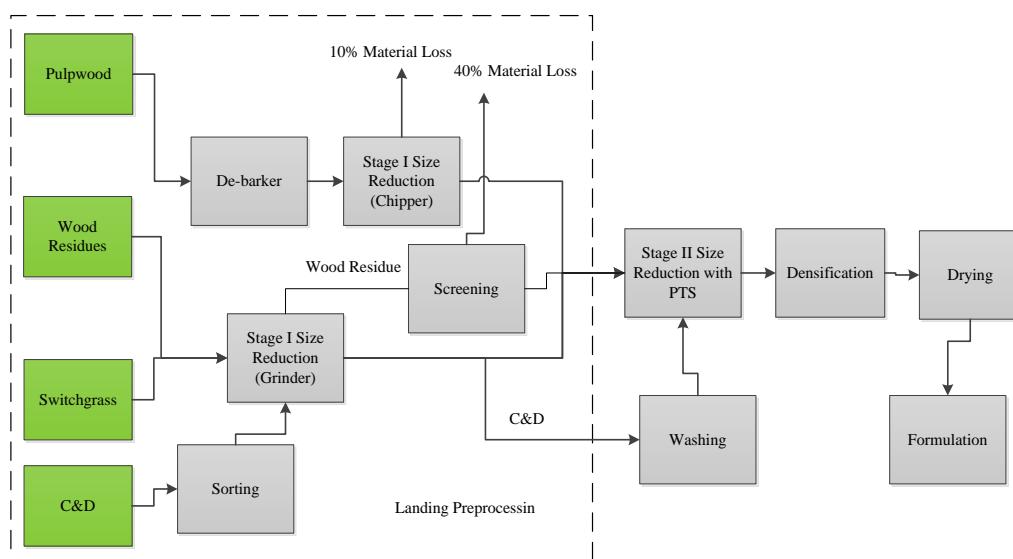


Figure 41. Material flow in the 2017 Design Case that incorporates many improvements in preprocessing, including pneumatics, high-moisture densification, and formulation/blending.

The logistics of a blended feedstock scenario are certainly more complex than a single-feedstock scenario. The 2017 Design Case assumes that preprocessing of C&D will occur at a preprocessing depot located at the source landfill or refuse transfer station, and C&D pellets will be shipped from the depot to the blending depot located within proximity of the biorefinery. Switchgrass that is formatted in large square bales will be delivered to the blending depot, where they will be processed into pellets. Pulpwood and wood residues will be initially processed at the landing for initial size reduction and ash mitigation then transported to a processing facility for pelletization. The pulpwood, wood residues, switchgrass, and C&D pellets will be queued up in blending bunkers or silos and blended to specification prior to being fed into the conversion process. The pellets of the four blendstocks (i.e., pulpwood, wood residues, switchgrass, and C&D) 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.

11.5.3.1 State of Technology:

For the 2017 Design Case, a geometric mean particle size of 1/4- in. is the target size specification for the thermochemical conversion process design under development by PNNL (Table 62). As the target size specification is the same as biochemical conversion, size reduction system to meet the final particle size specification required by the end user will be the same for fast pyrolysis conversion. The 2013 state of technology follows sequential two stage size reduction described in section 9.

Table 62. Size-reduction design basis.

			2013 SOT	2017 Target
	Equipment Used	Screen Size	Capacity Ton/hr	Capacity Ton/hr
First stage Size Reduction				
Pulpwood	Chipper	2 in.	17	17
Wood Residue	Grinder	2in.		
Second Stage Size Reduction				
Pulpwood	Hammer mill	1/4 in.	5	6.5
Wood Residue	Hammer mill	1/4 in.	5	6.5

11.5.3.2 Size Reduction Cost Estimation

Milling cost estimation is based on vendor-supplied information and equipment performance from typical machine performance and process demonstration unit data and is shown in Table 63.

Table 63. Size reduction cost estimates.

	2013 SOT (2011 \$/dry T)	2017 Target (2011 \$/dry T)
	Total	Total
Pulpwood		
Chipper	6.10	6.10
Debark/delimb	6.10	6.10
Hammer Mill	17.09	13.97
Total	29.29	26.17
Wood Residue		
Grinder	5.39	5.39
Trommel Screen	3.32	3.32
Hammer Mill	17.09	13.97
Total	25.08	22.70

11.5.3.3 Drying and Densification

Conversion of lignocellulosic biomass to hydrocarbon fuels: Lignocellulosic Biomass to High Octane Gasoline via Indirect Gasification and Methanol Intermediate use the same technology as fast pyrolysis case described in section 9. Therefore, state of technology and design basis for high moisture technology are the same as fast pyrolysis case described in section 9

A comparison of pellet properties and energy balances for conventional and high-moisture pelletization processes is given in Table 64. The table shows 2017 Design Case targets to achieve a 40 to 50% reduction in the total pelletization and drying energy.

Table 64. Drying and densification design basis.

	2013 SOT	2017 Target
Infeed Moisture	40%	30%
Dryer Moisture Reduction	28%	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	65 lb/ft ³	70 lb/ft ³
Bulk Density	35 lb/ft ³	40 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 from woody material; 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.

11.5.3.4 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 65.

Table 65. Drying and densification cost estimates.

	2013 SOT (2011 \$/dry T)	2017Target (2011 \$/dry T)
	<i>Total</i>	<i>Total</i>
Drying	17.20	5.60
Densification	7.70	4.40
Totals	24.90	10.00

11.5.3.5 Formulation/Blending

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 66.

Table 66. Feedstock formulation/blending of ash and moisture contents*.

Content Delivered to Biorefinery Infeed	Pulpwood(45%)	Wood Residues(32%)	Switchgrass (3%)	C&D waste(20%)	Final Blend
Ash content (wt. %)	0.5	1.0	4.0	1.0	<1%
Moisture content (%, wet basis)	9	9	9	9	9
HHV (lb/BTU)	8824	9444	7557	8824	8984
LHV (lb/BTU)	7255	7616	6155	7255	7337

*Pulpwood, wood residues, and switchgrass composition data were obtained from the INL Biomass Library ⁷⁵.

Assumptions for the formulation design basis are as follows:

- Blended feedstocks will be selected and developed to achieve conversion yield specifications. It is currently unknown how blended feedstocks will perform in the conversion pathways. The simplest assumption is the blended feedstocks would be the sum of performances of each individual component. There are on-going trials to test various blended feedstocks and to compare the conversion efficiencies against a single feedstocks.
- Individual feedstocks will be pelleted at depots for shipment to biorefineries. At the biorefinery, these 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 mixed prior to insertion for the conversion process.

- Material will be metered from individual bunkers onto a conveyer and then thoroughly homogenized through 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.
- The expected unit operations for formulation are shown in Table 67.

Table 67. Feedstock formulation design basis.

2013 SOT (2011 \$/dry T)	Operating Parameters	
	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 is currently ongoing at INL to examine the compatibility of various feedstocks blends, with an initial focus on the blends reactivity 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 including bio-oil conversion via fast pyrolysis.

While the costs for preprocessing of feedstocks (e.g., grinding, chemical preconversion, pelleting, and drying) are addressed in other parts of the 2017 Design Case, formulation itself will require a different set of preprocessing options in order to match up with the bio-oil conversion pathway. These processes include bulk storage, conveying systems and a pellet pulverizer to insure that the appropriate recipe of material enters the throat of the conversion reactor in the appropriate blends and sizing requirements.

11.5.3.6 Cost Estimation for Formulation.

Cost estimation for formulation was estimated based on existing technology, vendor-supplied information, and equipment performance (Table 68). These costs are cursory and require more extensive research, especially in their specific application to the bioenergy industry.

Table 68. Formulation cost estimation.

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

11.5.4 Transportation and Handling Design Basis

The 2017 Design Case includes formulation and densification meeting feedstock specifications and costs targets. Both processes of formulation and densification will improve feedstock handling operations through active controls. Given formulation and the specific quantities of individual feedstocks required, the average transportation distance will change based on feedstock type. In the 2017 Design Case, pulpwood will be trucked from a local draw radius of 50 miles while switchgrass will be trucked fewer than 15 miles. In Appendix A shows sufficient C&D waste resources in the selected counties in western South Carolina therefore C&D will be transported by truck from transfer stations after processing. This is not a new concept, transfer stations are already used for sorting and transporting valuable material such as cardboard and scrap metal in densified forms (e.g. baled cardboard, crushed and baled scrap metal).

Switchgrass will be loaded and unloaded at each location using a loader (telehandler) capable of moving 12 lb/ft³ bales at 20% respective moisture content. A 53ft. trailer and 800,000-GVW limits were assumed in all trucking operations. Transportation for switchgrass will occur from a field side stack to a densification facility completely separate from the conversion facility, but within a minimal conveyor distance (typically <50 miles). C&D waste transportation will occur from the waste transfer station as pellets to the preprocessing facility for storage and transfer to the biorefinery. Further transportation and handling assumptions are given as follows:

- At 20% moisture, transportation continues to be volume limited at densities of 12 lb/ft³.
- At 30% moisture, transportation of chips continues to be volume limited.
- At 9% moisture, transportation of pellets is weight limited at 40 lb/ft³.
- There will be insignificant material losses throughout transportation and handling.
- Densification will increase material uniformity and flowability

11.5.4.1 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 69). Rail transportation costs were based on work from Searcy using a jumbo hopper car⁵⁴ adjusted for U.S. conditions.

Table 69. Transportation cost estimates.

	2013 SOT (2011 \$/dry T)	2017 Target (2011 \$/dry T)
	<i>Total</i>	<i>Total</i>
Truck	14.84*	7.52**
*Individual feedstock therefore one transportation pathway		
**Multiple feedstocks therefore multiple transportation pathways and draw radiiuses.		

11.6 Life Cycle Analysis

This section uses a life-cycle assessment (LCA) to evaluate the energy input and GHG emissions for conversion of Lignocellulosic Biomass to High Octane Gasoline via Indirect Gasification and Methanol Intermediate Pathway. LCA considered the unit processes involved in the biomass logistics. Table 70 shows the energy consumption and Table 71 shows GHG contribution for Lignocellulosic Biomass to High Octane Gasoline via Indirect Gasification and Methanol Intermediate conversion supply chain design.

Table 70. Energy Consumption for Thermochemical conversion supply chain design.

Process Element	Pulpwood	Wood Residues	Switchgrass	Construction and Demolition Waste (C&D)	Blend
<i>Formulation Contribution</i>	45%	32%	3%	20%	—
Harvest and collection (MBTU/dry T)	182.78	—	122.85	—	85.94
Landing Preprocessing/Sorting (MBTU/dry T)	231.52	110.25	—	410.25	221.51
Transportation (MBTU/dry T)	136.87	101.38	99.35	273.73	151.76
Preprocessing (MBTU/dry T)	408.01	408.01	285.83	408.01	404.34
Storage (MBTU/dry T)	8.46	8.46	21.83	8.46	8.86
Handling (MBTU/dry T)	42.69	42.69	41.90	42.69	42.67
Total Energy Consumption (MBTU/dry T)	1001.33	670.79	571.76	1143.14	915.08

Table 71. GHG contribution for thermochemical conversion supply chain design.

Process Element	Blend
<i>Formulation Contribution</i>	—
Harvest and collection GHGs (Kg CO₂e/ dry T)	8.65
Landing Preprocessing GHGs (Kg CO₂e/ dry T)	18.95
Transportation GHGs (Kg CO₂e/ dry T)	8.62
Preprocessing GHGs (Kg CO₂e/ dry T)	34.60
Storage GHGs (Kg CO₂e/ dry T)	0.89
Handling GHGs (Kg CO₂e/ dry T)	4.2
Total GHGs (Kg CO₂e/ dry T)	75.91

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Appendix A

Construction & Demolition Waste and Municipal Solid Waste

Construction & Demolition Waste

Construction and Demolition (C&D) waste is a potential feedstock for the thermochemical pathways. 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. It is currently unknown whether the treated material would affect downstream processing of these materials in a thermochemical process.

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 non-woody materials would be required. In the given study area potential C&D waste availability was determined by the South Carolina Solid Waste Management Annual Report 2012. (Table A 1).

Table A 1. Potential C&D available in select counties in western South Carolina.

County	Potential C&D Waste (tons)
Aiken	32553.2
Edegfield	2406
Greenwood	3688.4
Kershaw	13766.8
Laurens	7504.4
Lexington	52146.4
Newberry	3335.6
Richland	79640.8
Saluda	150.4
Total	195192

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 landfilling⁷⁶. 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 2.

Table A 2. 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 3 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 3. 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 – Phoenix¹	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

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

Other considerations for these MSW fractions include moisture content, ash content, carbohydrate content, compatibility with other biorefinery operations, and obtaining a clean feed stream of these fractions from mixed MSW (Table A 4).

Table A 4. Physical parameters of solid waste

Fraction	Moisture (%)	Ash (%)	Carbohydrate (%) (glucan+xylan)	Pretreatment Severity	Sorting Required?
Yard waste	43 ⁷⁷	28 ⁷⁸	46	More severe pretreatment may be needed ⁷⁹	No, if curbside recycling is in place
Food waste	37 ⁷⁷	NA	64	No pretreatment needed ⁸⁰	Yes
Non-recyclable paper	5	19.5 ⁷⁹	56	Lower severity pretreatment needed ⁸¹	Yes
Untreated C&D wood	13 ⁷⁷	6.5 ⁷⁸	62	Higher severity pretreatment required ⁸²	Yes, unless onsite sorting occurs

¹Valkenburg et al. 2008⁷⁷
⁷⁸
³Gustafson et al. 2009⁷⁹
⁴Yan et al. 2012⁸⁰
⁵Unpublished data generated at INL⁸¹
⁶Cho et al. 2011 (includes mannan content)⁸²

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 <1% for the blended feedstock, only the C&D waste that has been treated by a wash stage could be used if blended with lower ash materials. It is estimated that the wash stage would reduce ash content down to about 1% and cost about \$4.15/dry T making its application still cost effective.

Appendix B

Least Cost Formulation

The biofuel conversion quality in-feed specifications have a large impact on whether or not a particular feedstock is cost effective. Raw biomass standing in the field is aerobically unstable, high in moisture and does not qualify as a feedstock; certain upgrades to the raw biomass are needed to make it compatible with conversion requirements. In addition, raw biomass is highly variable even within a single field.

In response to the variability in biomass quality, a variety of more robust biofuel conversion technologies are being developed, even though it is unlikely a single best conversion technology will be capable of handling all the variability experienced within raw biomass. Other approaches to addressing the variability include blending/formulation, leaching, densification, and other preprocessing options.

By combining analyses using farm gate price assumptions with quality specifications obtained from the Biomass R&D Library, gains in the projected volumes available at cost and biorefinery specifications are being realized by transitioning to a blended feedstock approach. Feedstock blending allows a conversion facility to collect less of any one feedstock and thus pay a lower average price for each feedstock by moving down the cost vs. supply curve.

In addition, with blended feedstocks biomass quality is a key aspect to consider when analyzing cost and volume availability. Formulating a designed feedstock through blending and other preprocessing logistical methods allows low cost and typically low quality biomass to be blended with biomass of higher cost and typically higher quality to achieve the specifications at the in-feed of a conversion facility. The use of low cost biomass allows the supply chain to implement additional preprocessing technologies that actively control feedstock quality, while also bringing more biomass into the system. This analysis and design approach is being called the “least-cost formulation” (LCF) strategy.

The LCF concept is best explained through an example of how it is calculated. This analysis focuses 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 multiple 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. Note that it is assumed that a blended feedstock will perform “like” the single feedstock. There are a number of collaboration projects between the INL and NREL and PNNL to test these blended feedstocks and evaluate their performance compared to single feedstocks.

At present most cellulosic biomass feedstock supply systems are designed around a single feedstock, typically corn stover. Figure B1 illustrates the available corn stover and switchgrass at varying farm gate prices for the western Kansas scenario. 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 Update⁵. 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 B 1. The farm gate cost curves suggest that corn stover is the preferred feedstock because it is less expensive than switchgrass, 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.

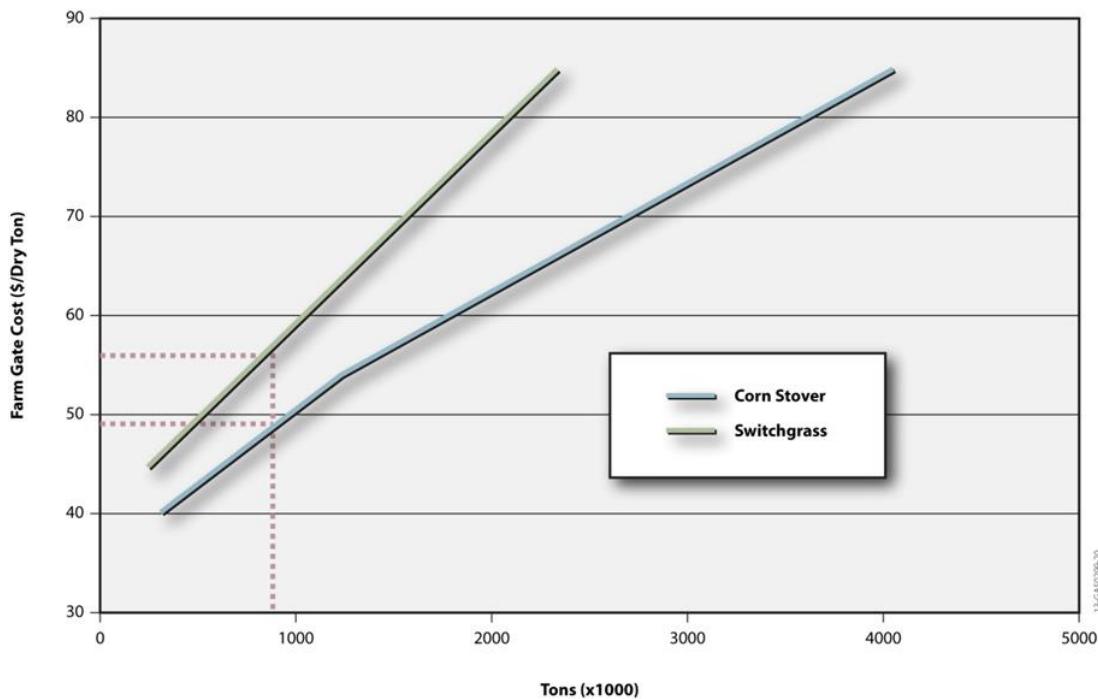


Figure B 1. The farm gate cost curves suggest that corn stover is the preferred feedstock because it is less expensive than switchgrass.

However, when we consider the total delivered feedstock costs, which includes farm gate price plus logistics costs plus quality dockage costs then the dynamics of the biomass supply curve begin to change. These additional costs shift the aggregated supply curves to the left; the addition of a dockage cost differs for corn stover and switchgrass because corn stover on average has a higher ash content, so the curves do not shift by the same amount (Figure B 2). 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 B2). 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.

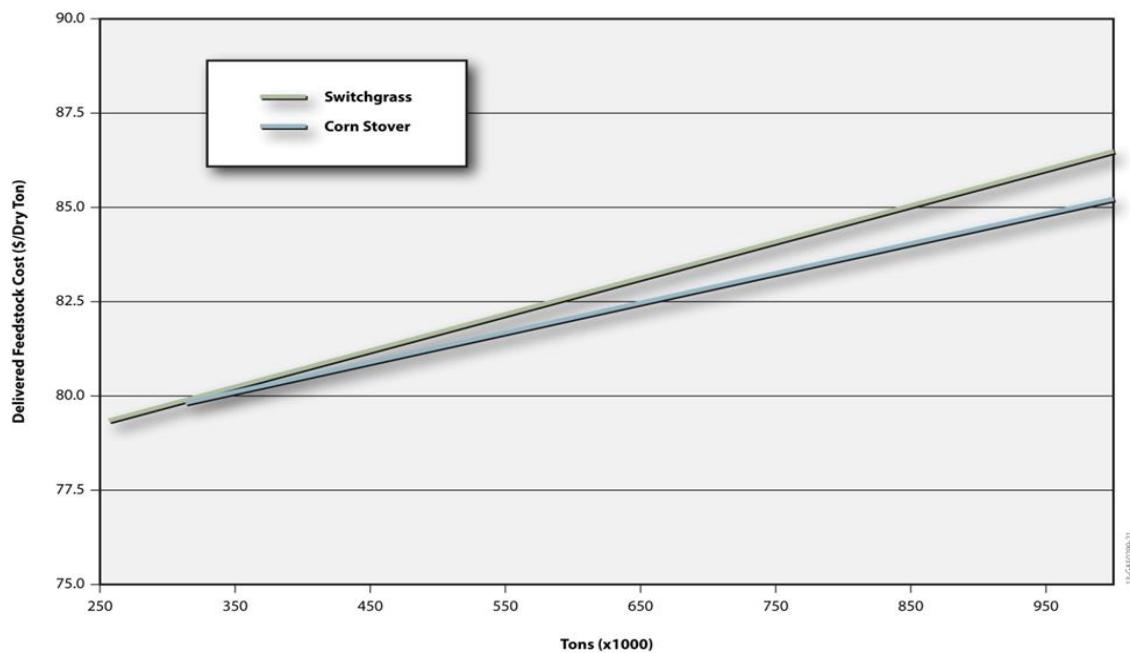


Figure B 2. Accounting for quality (dockage)—shows that about 300,000 tons of switchgrass can be supplied at a lower cost than corn stover.

The feedstock supply curves in Figure B 3 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 stover 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 B3)

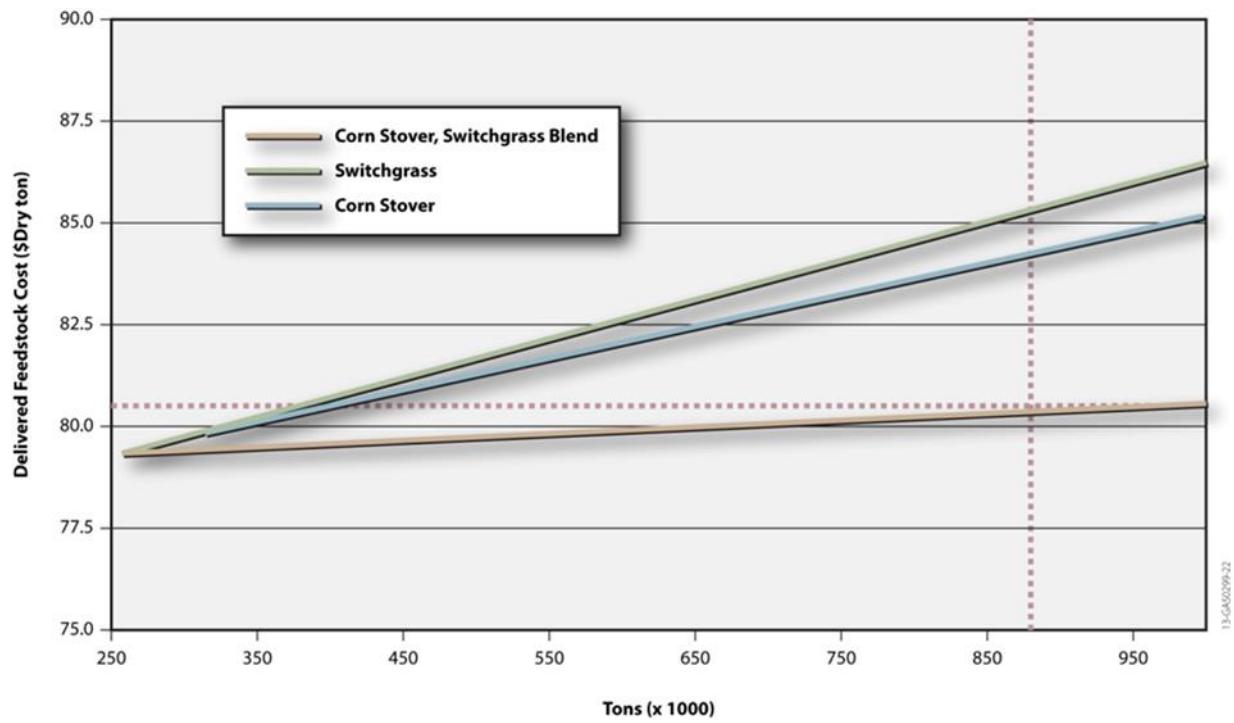


Figure B 3. A corn stover/switchgrass blend that will deliver at about \$81/dry T.

The least-cost formulation strategy suggests 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 T⁷⁸ and logistics costs of about \$44/ton, 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 B4). 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

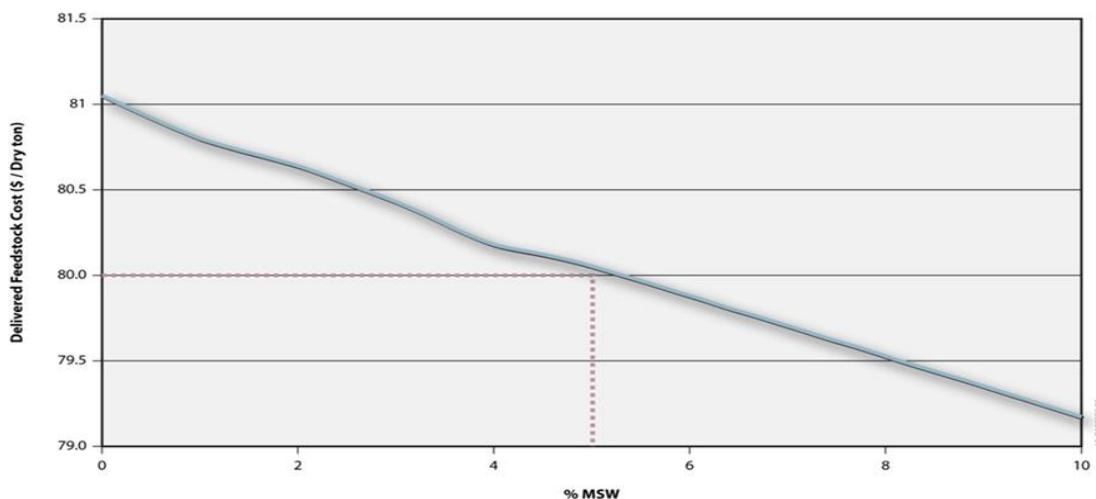


Figure B 4. A minimum of 5% MSW (at \$1/dry T) is needed to achieve the \$80/dry T cost target with a corn stover, switchgrass, and municipal solid waste blend.

The supply curves in Figure B 5 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.

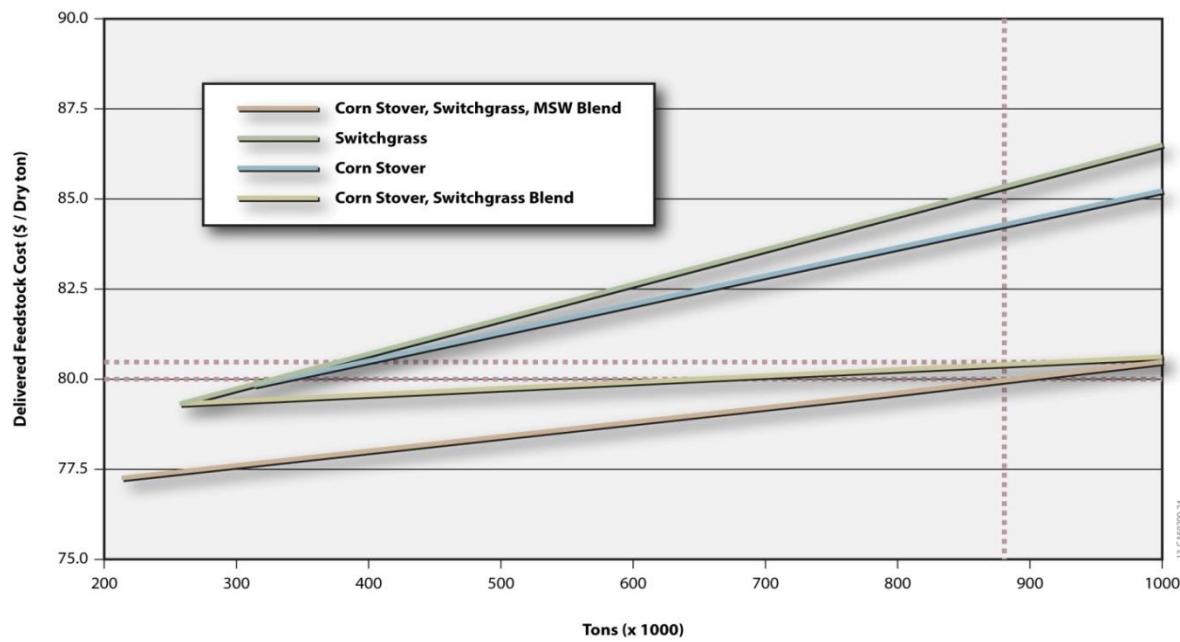


Figure B 5. Comparison of individual and blended feedstock costs. A blend of 60% corn stover, 35% switchgrass, and 5% municipal solid waste is needed to hit the \$80 feedstock cost target.

The availability of these resources for the western Kansas scenario that was chosen to demonstrate the 2017 Design Case is illustrated in Figure 18. 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.

Appendix C

Off-Specifications Feedstock Dockage Approach

Ash serves no purpose in a conversion process, and in fact will result in additional costs for disposal, machine wear, and potential negative implications on the process itself. In order to mitigate these costs, they must be subtracted from the purchase payment of biomass that contains unacceptable levels of ash contamination. This milestone report demonstrates the potential impact of off-specification ash content in a traditional, well vetted liquid fuel conversion system.

The analysis below was based on the costs⁸³ where feedstock procurement is priced at 58.50 \$/DMT. Disposal of ash was applied at 28.86 \$/dry T of ash. The ethanol conversion yield of 79 gal/dry T was used to estimate non-enzymatic manufacturing costs and capital costs at 23.94 \$/dry T and 13.83 \$/dry T, respectively. The analysis assumes that ash content is measured at the point of sale between a feedstock supplier and refinery (exchange-point), and payout is based on the delivered material's quality compared to a baseline feedstock containing 5% ash. It was assumed that production quality and quantity must be maintained, such that the decreased yield resulting from off-specification (high ash) feedstock will require additional biomass to be purchased and processed to match the yield anticipated from baseline feedstocks. Five individually calculated dockages encompass the reduced value of off-specification materials: (1) the decrease value of above-baseline feedstocks due to mass displacement by ash; 'off-specification doc', (2) the cost of additional ash disposal; 'disposal doc', (3) the cost associated with sourcing additional feedstock; 'replacement doc', (4) the added cost of processing more material on manufacturing expenses; 'manufacturing doc', and (5) the cost of capital expansion from handling addition quantities of material; 'capital dock'.

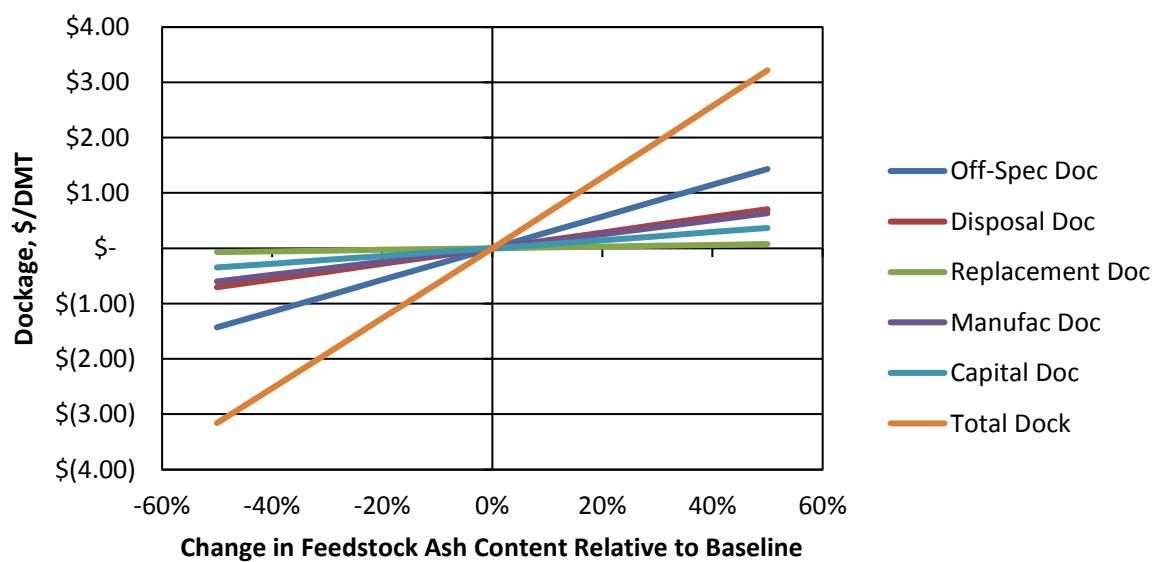


Figure C 1. Sensitivity of dockage by altering feedstock ash content relative to the baseline ash content of 4.9%⁸³.

The off-specification dockage was found to be the greatest contributor to the total dockage (45% of the total dockage), and the most sensitive to increases in delivered feedstock ash content followed by additional disposal (22% of the total cost; Figure C 2, where a 50% relative increase in ash equates to 7.4% ash). This is important as the dockage associated with delivering off-specification material, accounting for additional disposal, and the cost of replacement are largely process independent and likely to be accounted for in the biomass supply and logistics cost basis. On the other hand, the estimates of manufacturing and capital are highly process dependent and thus subject to criticism for their inclusion in a feedstock delivery dockage. Furthermore, the argument can be made from this data that if a dockage is to be applied to material arriving above the baseline specification due to its decreased value, materials of value greater (i.e., ash content lower than the baseline) would in theory warrant a positive purchase price incentive. In the case of this data, a feedstock delivered at -50% relative ash content to the baseline (2.5% ash) would in essence qualify for a 3.16 \$/dry T bonus on top of the baseline feedstock purchase price of 58.50 \$/dry T. While this type of system has not yet been proposed for a commercial system, this type of financial motivation may provide further incentive for farmers to invest in single-pass technology as the material generated is truly of higher value to a conversion facility.

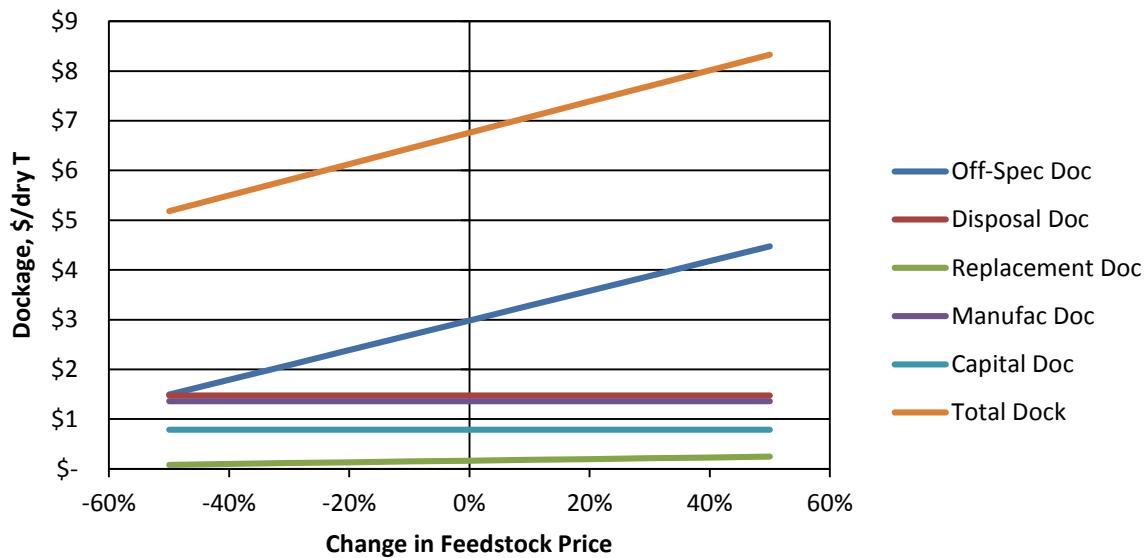


Figure C 2. Sensitivity of the costs impacts to altering feedstock price relative to the base case of 58.50 \$/dry T for a delivered feedstock with 10% ash⁸³.

To demonstrate the importance of a proper feedstock procurement cost, the analysis was conducted over a range of feedstock prices, from 29.25 \$/dry T to 87.75 \$/dry T (-50% to 50% change, respectively) for a delivered feedstock with 10% ash (Figure C 3). The results clearly show the impact of feedstock price on off-specification cost impacts and ultimately total costs, increasing the total costs by 0.03 %/ relative change. When considering the 2017 Design Case target feedstock price of 80\$/dry T (a 37%), the total costs impact rises to 7.91 \$/dry T for a 10% ash delivered material, where the off-specification costs now accounts for 52% of the total cost impacts. This case exemplifies the ability of feedstock price to inflate off-specification cost

impacts and potentially lead to a poor estimation of total cost impacts if the other costs associated with high ash are not appropriately modified as well.

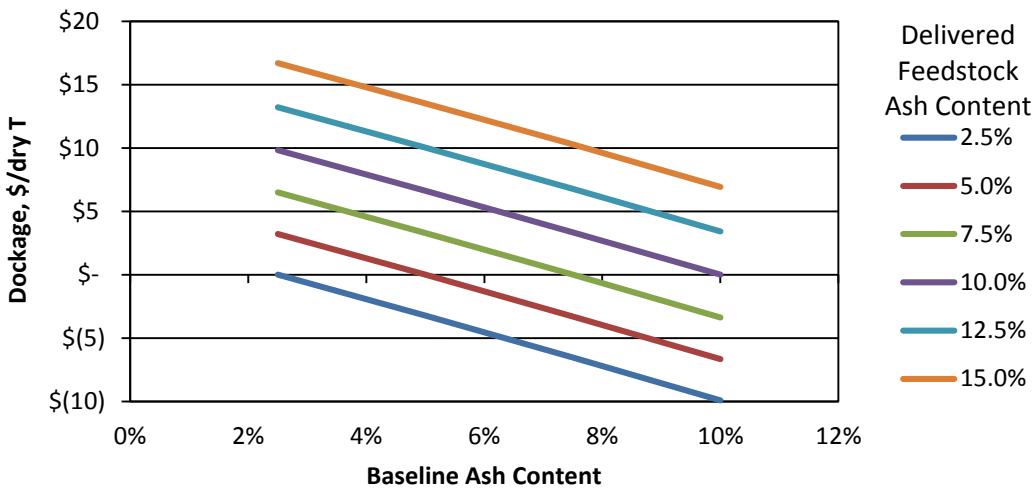


Figure C 3. Total dockage based on shifting baseline ash content for a range of received materials at a feedstock price of 58.50 \$/dry T⁸³.

Finally, the analysis can be used to demonstrate the necessity of defining an appropriate baseline specification for ash content (Figure C 3). Intuitively, as a baseline specification for ash content is raised, the dockage for above-spec material decreases. Figure C 3 shows this rate of change at 1.30 \$/% ash change for the highest ash material (15%) and increases to 1.32 \$/% ash change for the lowest ash material (2.5%). This data stresses the importance of accurately determining the ash content at which the end user's process truly begins to incur additional operating costs. In the case of these examples, increasing the baseline ash content to 7.5% would reduce the dockage of a 10% ash delivered material by 50%. While it remains to be seen if the costs on material conversion are as sensitive to ash content as the current baseline suggests, this analysis shows the large financial implications to feedstock suppliers when material is compared against a strict specification.

These analyses clearly show the negative implications of off-spec ash content in the baseline conversion system chosen. That said, the variability in dockage with respect to the magnitude of contamination, the price of feedstock, and the baseline ash content highlights the importance of properly defining and assessing a particular modeled feedstock logistics and conversion system. Alternatively, because of the large variability in dockage, it is reasonable to suggest that raw feedstocks purchased by a conversion facility need only be assessed in terms of ash content and biomass content (i.e., 'material other than ash') for preliminary determination of a feedstock's value. More rigorous analysis of what the 'material other than ash' consists of is much less variable than the ash content, as discussed previously in this report, decreasing its relative importance in determining dockage and feedstock value.

Appendix D

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 system⁸⁴. 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 dewateres the biomass. The solids are conveyed to a wet mill and then to a wet pelletizing 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 D 1.

Table D 1. 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	<ul style="list-style-type: none"> Herbaceous: 2-in. screen MSW: 6-in. screen
Leaching (water or dilute acid, steam heat with agitation)	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Pump not needed
Add water, agitate, and drain liquids to waste tank	<ul style="list-style-type: none"> Pump not needed 5 cycles of 30 minutes
Convey leached solids through roller press, send expressed water to drain tank	<ul style="list-style-type: none"> Exiting solids are 50% moisture Greater than 95% recovery of solids
Dry solids	<ul style="list-style-type: none"> Exiting solids are 30% moisture
Convey wet solids to wet mill	<ul style="list-style-type: none"> Particle size 6 mm or less for herbaceous and MSW
Convey wet solids to wet pelletization	NA
Neutralize liquids in waste tank	<ul style="list-style-type: none"> Final pH 6-8 Bicarbonate used for acid
Pump neutralized liquids to reverse osmosis unit and recycle permeate to makeup water	<ul style="list-style-type: none"> 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 silica⁴⁵. 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 separation⁴⁵.

Utilizing mechanical and chemical ash removal technologies in tandem to reduce the amount of non-specification 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-specification feedstock by either reducing the amount of feedstock requiring chemical ash removal, reducing the cost of chemical ash removal, or both.

Appendix E

Cost Calculation

The economic analysis was designed for an 800,000 ton/year pellet demand to produce hydrocarbon fuels.

About cost year indices: The cost-year of 2011 was chosen for this analysis to keep the consistency across all DOE-BETO platforms for which similar “design case target” reports are being established during 2013–2014 efforts. Capital costs provided in a year other than 2011\$ were adjusted using the Plant Cost Index from *Chemical Engineering Magazine* to a common basis year of 2011.

The general formula for year-dollar back-casting is:

$$2011 \text{ Cost} = (\text{Base Cost}) \left(\frac{2011 \text{ Cost Index}}{\text{Base Year Index}} \right)$$

Ownership cost: Ownership cost consists of interests and depreciation cost, and insurance, housing and taxes cost and owning the facility.

Interest and depreciation

The ASABE lists two different methods for costing depreciation and interest: (1) calculate depreciation and interest separately, or (2) calculate depreciation and interest on the value to be depreciated and then calculate interest on the salvage value. The AAEA uses the second method, which can be expressed as Equation (1):

$$I \& D = (P - S) \left[\frac{(i)(1+i)^n}{\{(1+i)^n\}-1} \right] + S \times i \quad (1)$$

where

- | | | |
|-------|---|--|
| I & D | = | Interest and Depreciation |
| P | = | purchase price of equipment |
| i | = | annual interest rate |
| n | = | life of the equipment in years |
| k | = | sum of rates for taxes, housing (shelter), insurance |
| S | = | salvage value (salvage value % × list price) (salvage value percent assumed in the present study is 30%) |

Salvage value (remaining value) must be known or estimated to determine interest and depreciation. The America Society of Agricultural and Biological Engineers⁸⁵ (ASABE) method was used for determination of salvage value (ASABE, D496.31, 2006, Section 6.2.2).

Insurance, Housing, and Taxes (IH&T)

Insurance, housing (cost of shelter for equipment), and taxes (IH&T) refer to the fixed costs related to the equipment, and these costs are estimated as percentages of the purchase price

(Equation 2). If actual data are not available, the ASABE suggests using the following percentages: taxes 1.00%, housing 0.75%, and insurance 0.25%, for a total of 2.00%.

$$IH \& T = \frac{(I_{Percentage} + H_{Percentage} + T_{Percentage}) \times average(purchase\ price,\ salvage)}{Work\ hours\ per\ year \times efficiency\ factor} = \frac{\$}{hr}$$

Operating cost: Operating cost consists of repair & maintenance, fuel and labor cost. Expenditures are necessary to keep a machine operable due to wear, part failure, accidents, and natural deterioration. The costs for repairing a machine are highly variable. Good management may keep costs low. In the present study, the following equation is used for calculating the repair and maintenance (R&M) costs.

$$R \& M = \frac{list\ price \times repairs\ and\ maintenance\ percentage}{life\ time\ (hr)} = \frac{\$}{hr} \quad (3)$$

Repairs and maintenance percentage is estimated based on percentage of machine price. Fuel consumption cost is calculated based on actual kW data obtained either from machinery specifications or from actual estimates obtained from laboratory-scale and pilot-scale experimental data. Labor rates were obtained from the Idaho Bureau of Labor Statistics, and labor hours were based on assumed shift schedules. The total working hours include three shifts, 40 hours/week, and 50 weeks per year. The assumed labor rate for horizontal bale grinder, hammer mill, dryer, pallet mill and chemical pretreatment are \$15.88, \$19.88, \$15.51, \$15.51 and \$19.88 respectively. Also, we have assumed that one person will be able to manage two machines.

Future Work

Foremost, efforts must build upon collaborative interactions with the biochemical and thermochemical conversion platforms to gain a better understanding of feedstock quality and conversion performance. Efforts must also focus on robust screening techniques and methodologies to verify feedstock quality. Relative to ash determinations, a bulk biomass screening tool that is easy to use, rugged, has low maintenance requirements and field-applicable is needed to better understand feedstock variability (temporal, seasonal), logistic and preprocessing intermediates changes and variability and options for mitigating impacts; bringing to bear all the “architectural” requirement to support the biorefinery quality specification, and the initial and intermediate specifications that sustain those specifications.