DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review

WBS 1.1.1.2 – Feedstock Supply Chain Analysis

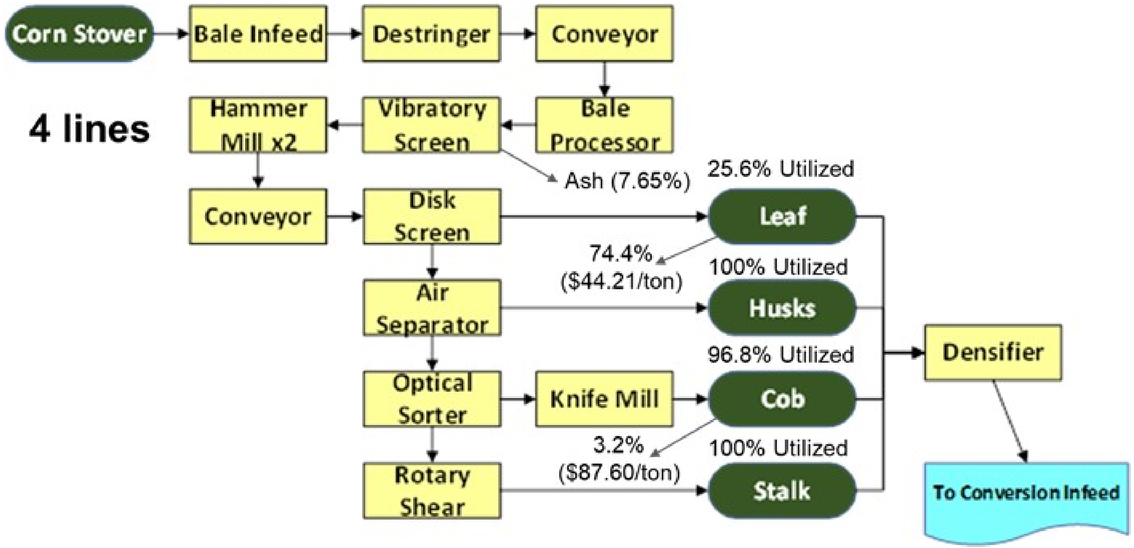
- March 11, 2021
- Feedstock Technologies Program

- David N. Thompson
- Idaho National Laboratory

Idaho National Laboratory

Project Overview

- Prior to FY18
  - Developed nth-plant feedstock supply system designs,
  - Delivered cost targets for conversion feedstocks, and
  - Tracked R&D progress toward those targets
- Industry feedback: Not capturing everything contributing to cost (<u>operational issues due to variability add cost</u>)
- FY17 Go/No-go developed a complementary TEA approach
  - Dynamic analysis of 1st-plant designs using stochastic feedstock properties to capture costs due to variability
- Redirected goals to maximize biorefinery economics by
  - Improving equipment and system operability, and
  - Improving delivered quality
  - Comparing 1st-plant estimates to nth-plant estimates
- Led to a fractionation approach
  - Separate the plant tissues that have different physical and compositional properties/qualities
  - Recombine tissues in ratios that meet cost and all CMAs for single or multiple conversion processes



Stochastic 1st-plant Herbaceous Feedstock Design Case used discrete event simulation to determine the R&D technical targets necessary to be able to simultaneously meet the cost, quality and reliability milestones in the BETO Multi-Year Plan (MYP) for 2022

Project Overview (continued): Heilmeier Catechism

What are you trying to do?

- Develop innovative, cost-effective solutions to provide conversion-ready feedstocks
- Meet MYP delivered cost, conversion CMAs and operating effectiveness targets
- Track R&D progress toward those targets
- <u>Relevance to BETO:</u> Inform BETO on its R&D investments (foundational to the Platform)

How is it done today and what are the limits?

- Conventional systems that are currently used seek to minimize feedstock costs by minimizing infrastructure and preprocessing operations

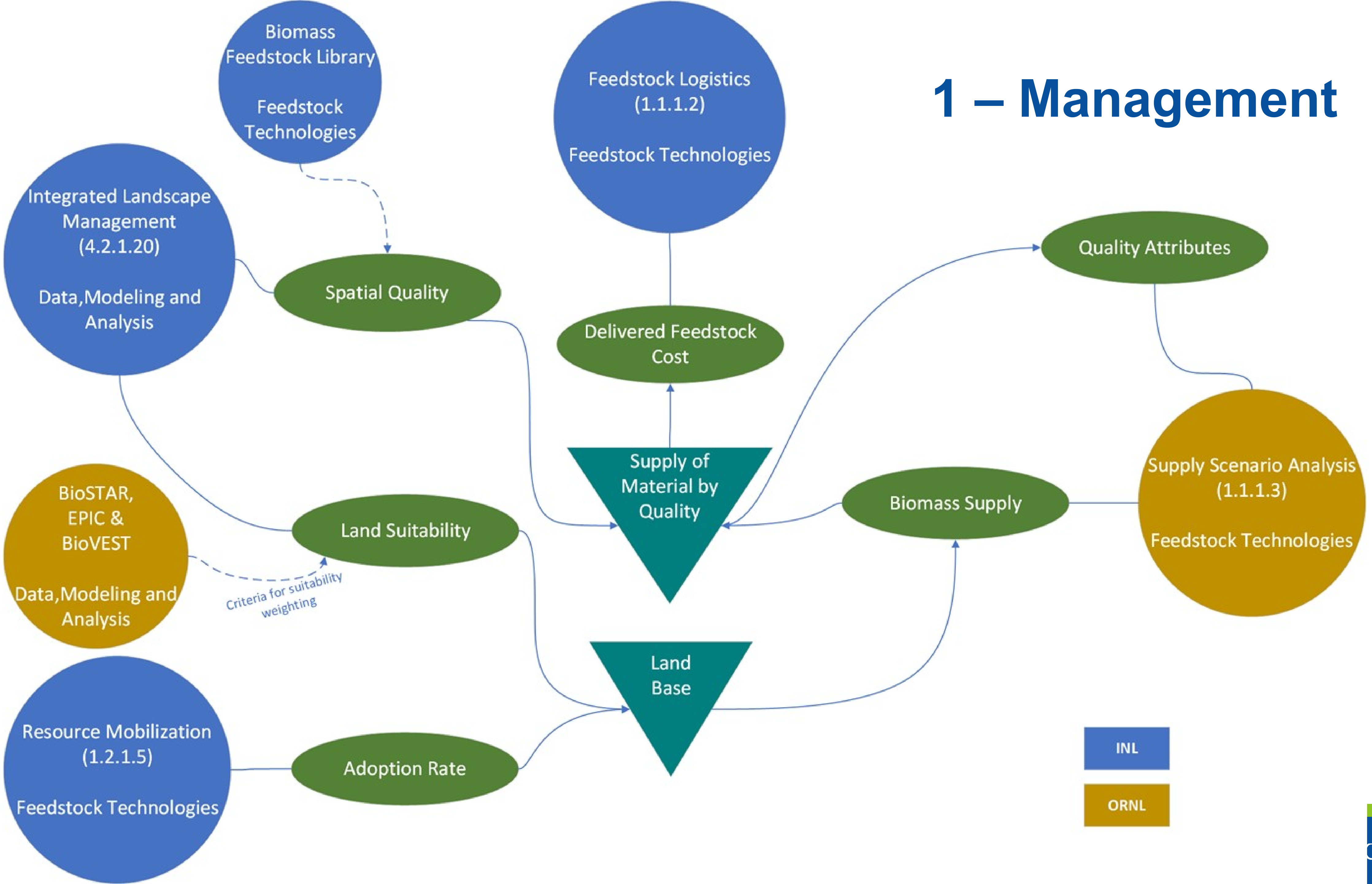
Why is it important?

- Inherent variability of biomass feedstocks affects the ability to optimize processing and conversion processes, ultimately decreasing plant economics
- The experiences of the BETO-funded pioneer biorefineries underscore this challenge

What are the risks?

- The primary risk is lack of sufficient scale-relevant data to adequately model the systems and understand cost/quality trade-offs

1 – Management



1 – Management (continued)

- Milestone-driven data collection and alignment through BETO feedstock R&D projects, industry outreach and stakeholder engagement to mitigate risks, which center around data availability and fidelity
- Close collaboration with analysis teams across the BETO program including ORNL (supply production), NREL and PNNL (conversion TEAs), and ANL (LCA)
- Monthly conference calls with BETO FT and also with BETO DMA
- Bi-weekly coordination calls with ORNL
- 5-7 milestones per year
  - Quarterly Progress Milestones drive schedule, forward-looking analysis of new approaches, and new tool development
  - SMART Annual Milestones for high-impact deliverables and outcomes such as Design Cases and SOTs
- Team Structure
  - <u>SOTs & Design Cases:</u> Damon Hartley, Yingqian (Tammy) Lin, Mohammad Roni
  - <u>New Tools & Forward-Looking Analyses:</u> Pralhad Burli, Mike Griffel, Damon Hartley, Ross Hays, Yingqian (Tammy) Lin, Mohammad Roni, Daniela Jones (NC State)

Enlarged grapple arms for the Tigercat wheeled skidder design developed through the DOE-funded Auburn University High-Tonnage Logistics Project

2 – Approach

Technical Approach

- Work with R&D staff, industry & stakeholders to understand barriers and potential technology solutions to meet cost and quality objectives
- Develop new computational capabilities to answer new questions
- Perform forward-looking "What-if" analyses to examine potential technology impacts on feedstock supply systems (e.g., fractionation approach)
- Develop Design Cases to identify specific R&D technical targets to achieve cost, quality and reliability targets
- Track annual R&D progress in State of Technology (SOT) reports toward BETO cost and technical targets established in the Design Cases

Top 3 Technical Challenges

- Existing paradigms related to feedstock supply (i.e., cheap vs. reliable and of consistent quality)
- Understanding and capturing all of the factors that contribute to cost
- Lack of complete datasets for harvest, composition, preprocessing and convertibility, across multiple biomass resources

Source: http://www.flickr.com/photos/mollivan_jon/3439072283/

2 – Approach (continued)

Go/No-go Decision Point

- Quantify 3-pass and 2-pass corn stover, and switchgrass volumes meeting quality specs available to supply at least 5 biorefineries at the 2022 MFSP target of $3/gge.
  - Moving the MFSP target from $3.00/gge to $2.50/gge by 2030 implies the need for a 17% lower delivered feedstock cost, from $85.51/dry ton to $71.26/dry ton (2016$) for biochemical conversion
  - Analysis assessed the delivered cost for industrially-relevant herbaceous feedstocks to meet a range of quality specifications delivered to the 2030 biochemical conversion design
  - Performed at both national and regional scales, over a range of biorefinery sizes
  - This information is critical to understand the required quantities and qualities of potential candidates for economically-advantaged feedstocks (e.g., MSW, biosolids, food waste)

Performance Metrics

- Historic Metric: Delivered feedstock cost at the conversion reactor throat
- New Additional Metric: Overall Operating Effectiveness (OOE)
  - Derived from Overall Equipment Effectiveness (OEE) from the manufacturing industries
  - Based on *Availability (A)*, *Production Rate (PR)* and *Quality Rate (QR)*

3 – Impact

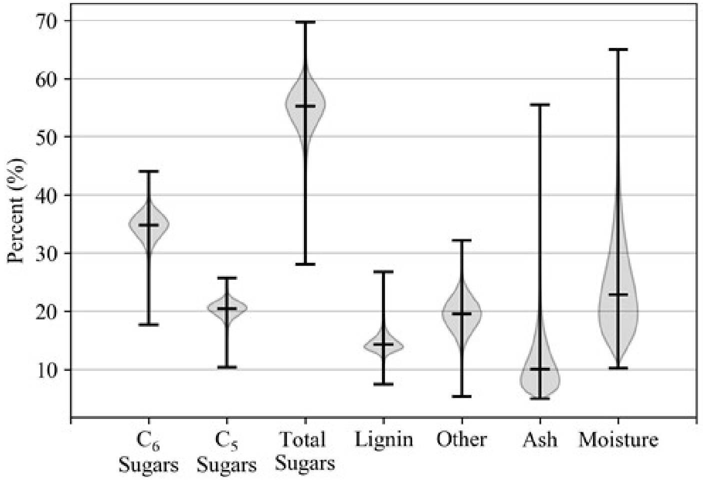
State of Technology & Industry Impacts

- Moves the state of technology forward by developing innovative approaches and tracking R&D progress
- We are directly addressing industry issues as regards operability, feedstock quality and actual delivered cost

Dissemination of Results

- Two 1^{st}-plant Reliability Design Cases in FY19 (external reports)
- Four n^{th}-plant SOTs and two 1^{st}-plant Reliability SOTs in annually (external reports)
- OOE paper published in *ACS Sustainable Chemistry and Engineering* (Impact Factor of 7.0)
- Expanded SOT case published in *Applied Energy* (Impact Factor of 8.4)
- n^{th}-supply scenario paper also submitted to *Applied Energy* (Impact Factor of 8.4)
- Presentations to Drax, ExxonMobil and Shell
- Multiple presentations at International Meetings

Quality Challenges



Operability Challenges

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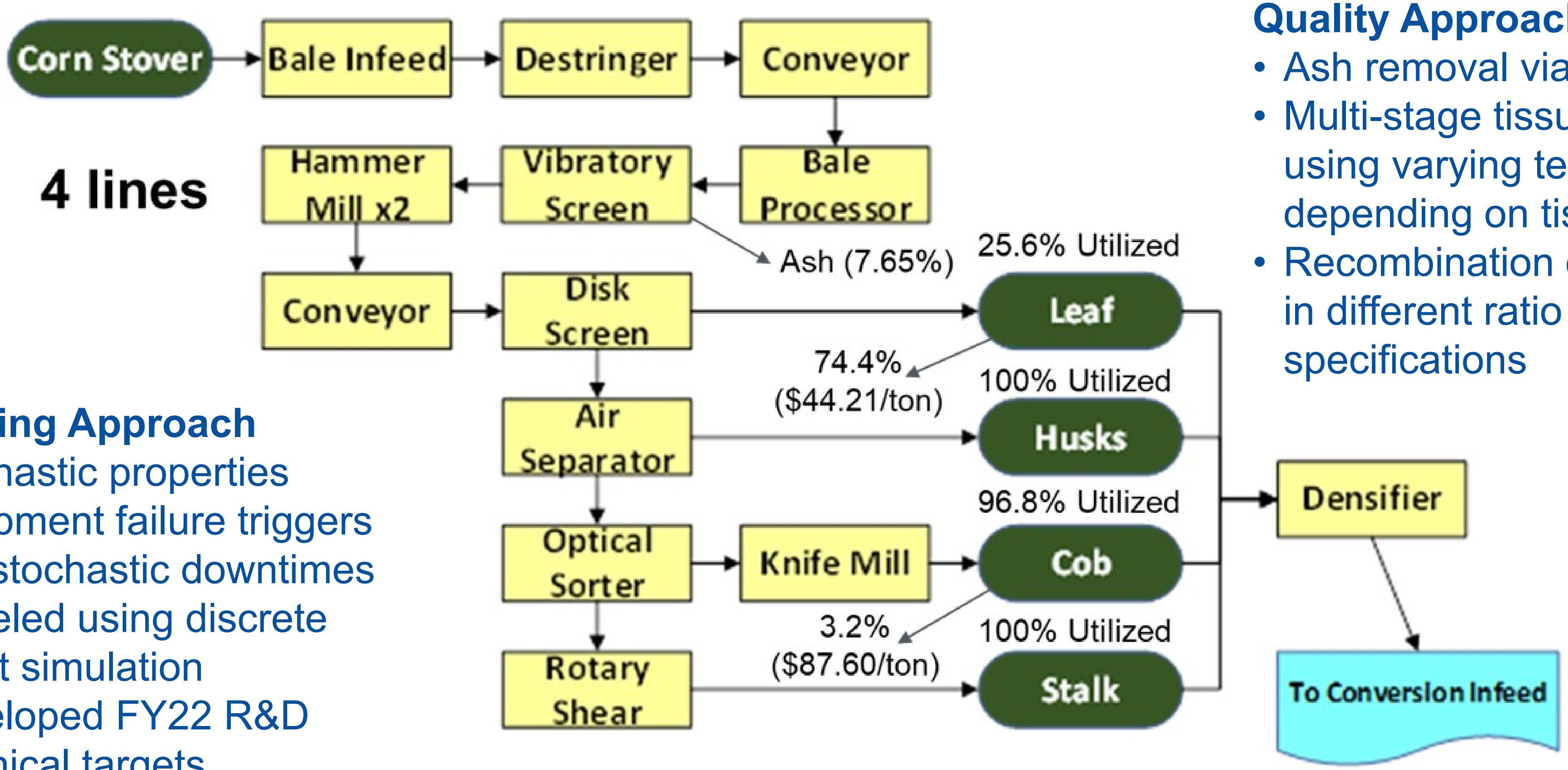
4 – Progress and Outcomes

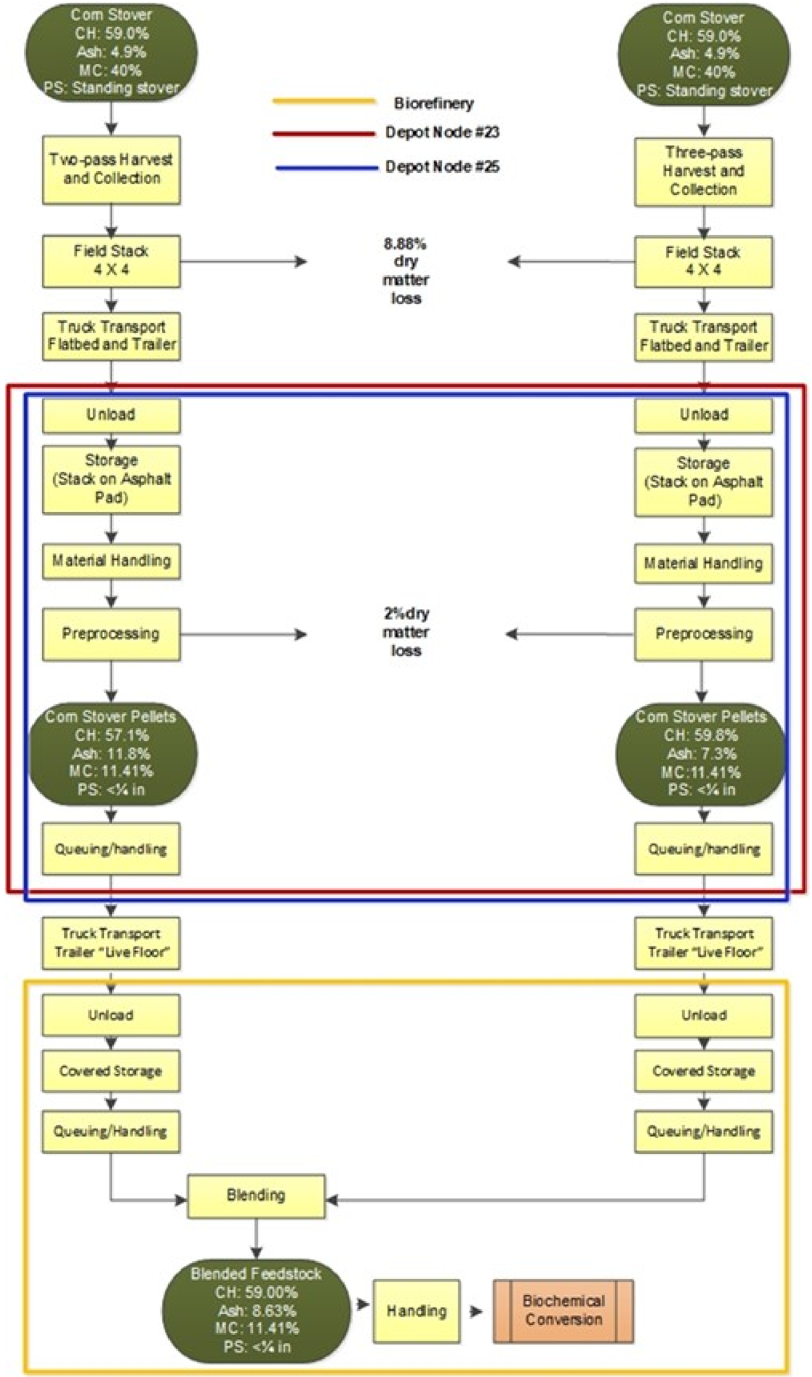
FY22 Reliability Design Case for Biochemical Conversion



Quality Approach
- Ash removal via screening
- Multi-stage tissue fractionation using varying technologies depending on tissue
- Recombination of tissue fractions in different ratio to meet quality specifications

Modeling Approach
- Stochastic properties
- Equipment failure triggers and stochastic downtimes
- Modeled using discrete event simulation
- Developed FY22 R&D technical targets

Models show progress toward cost and performance goals for biochemical conversion feedstock

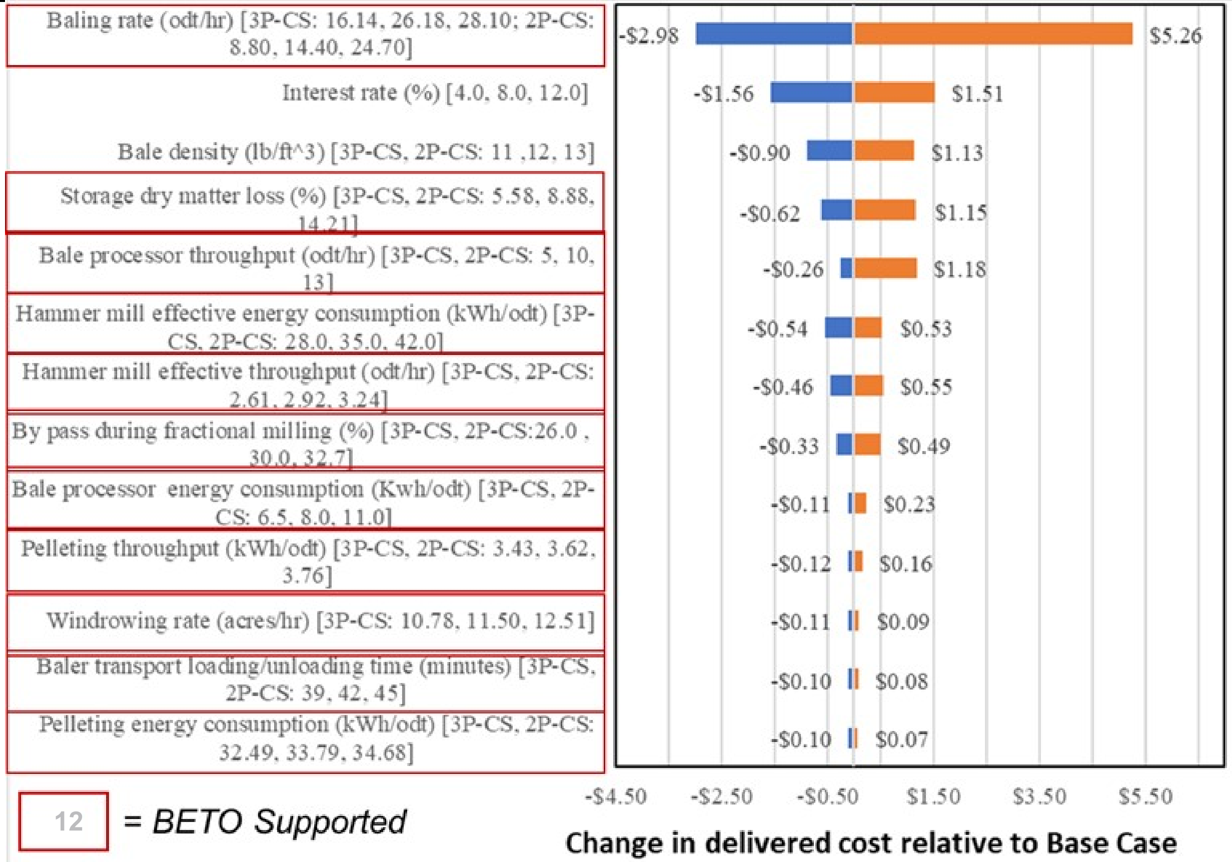


FY20 Biochemical nth-Plant & 1st-Plant Feedstock SOTs

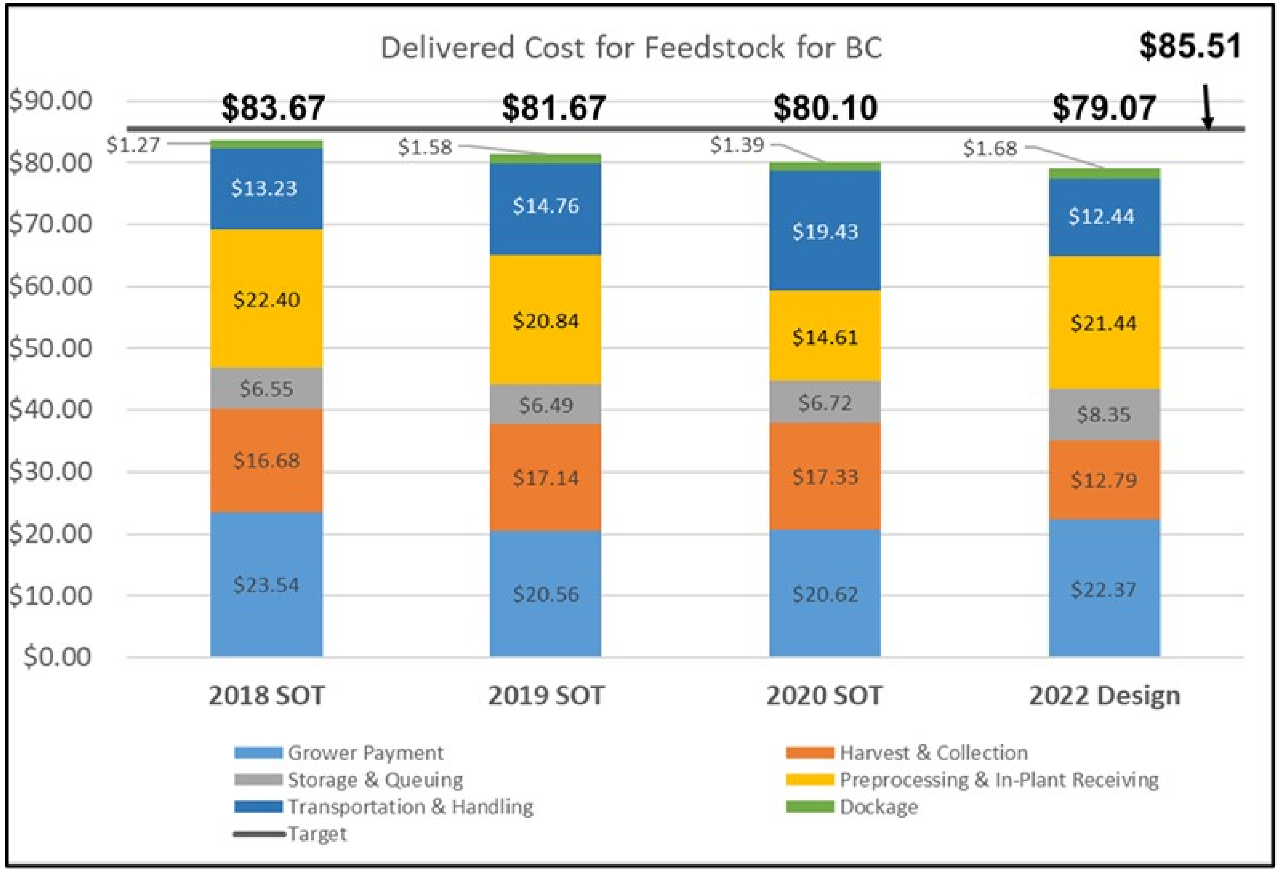
- 725,000 dry tons/year (2,205 dry tons/day) blend of 2-pass & 3-pass corn stover using 4 parallel preprocessing lines
- **nth-plant**
  - Lines sized to 23 tons/hr
  - Constant average moisture & composition
  - Utilizes dockages for not meeting ash and moisture
  - 70.37%:29.63% ratio of 2-pass:3-pass (optimal)
- **1st-plant**
  - Lines sized to 27 tons/hr (industry practice)
  - Moisture, some elements of composition & mean times to repair are stochastically generated
  - Units not meeting Carbohydrate CQA not fed to Conversion
  - 66.67%:33.33% ratio of 2-pass:3-pass
- **Preprocessing CQAs:**
  - 58.99% Total Carbohydrates (nth and 1st)
  - 4.93% Ash Content (nth only)
  - 20% Moisture Content (nth only)

FY20 Herbaceous nth-plant SOT for Biochemical Conversion

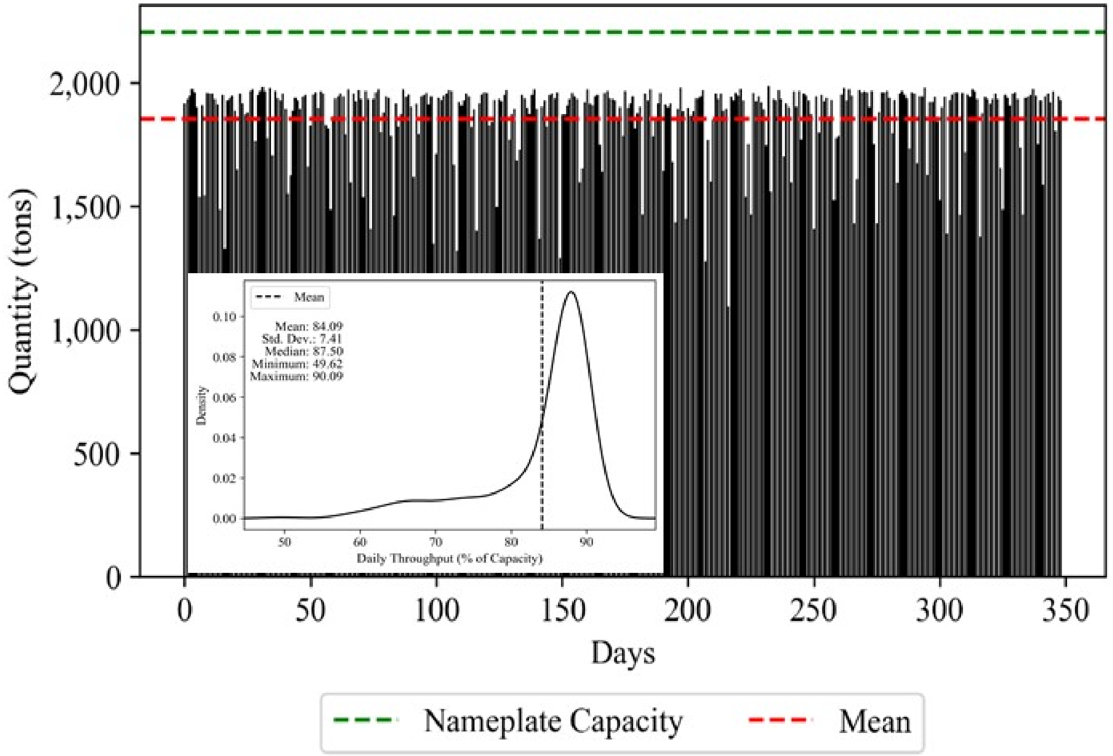
Cost Element	Cost ($/dry ton)			
	Three-Pass Stover	Two-Pass Stover	Least-Cost Blend[b]	GHG emissions (kg CO_2e/ton)
Blend Ratio	29.63%	70.37%	100.00%	
Grower payment	$21.71	$20.16	$20.62	
Harvest and collection	$13.84	$18.79	$17.33	11.17
Storage and queuing	$6.66	$6.74	$6.72	2.50
Transportation and handling	$13.74	$14.97	$14.61	16.60
In-plant receiving and preprocessing	$19.43	$19.43	$19.43	47.21
Dockage	$2.59	$0.89	$1.39	
Total	**$77.97**	**$80.98**	**$80.10**	**77.48**

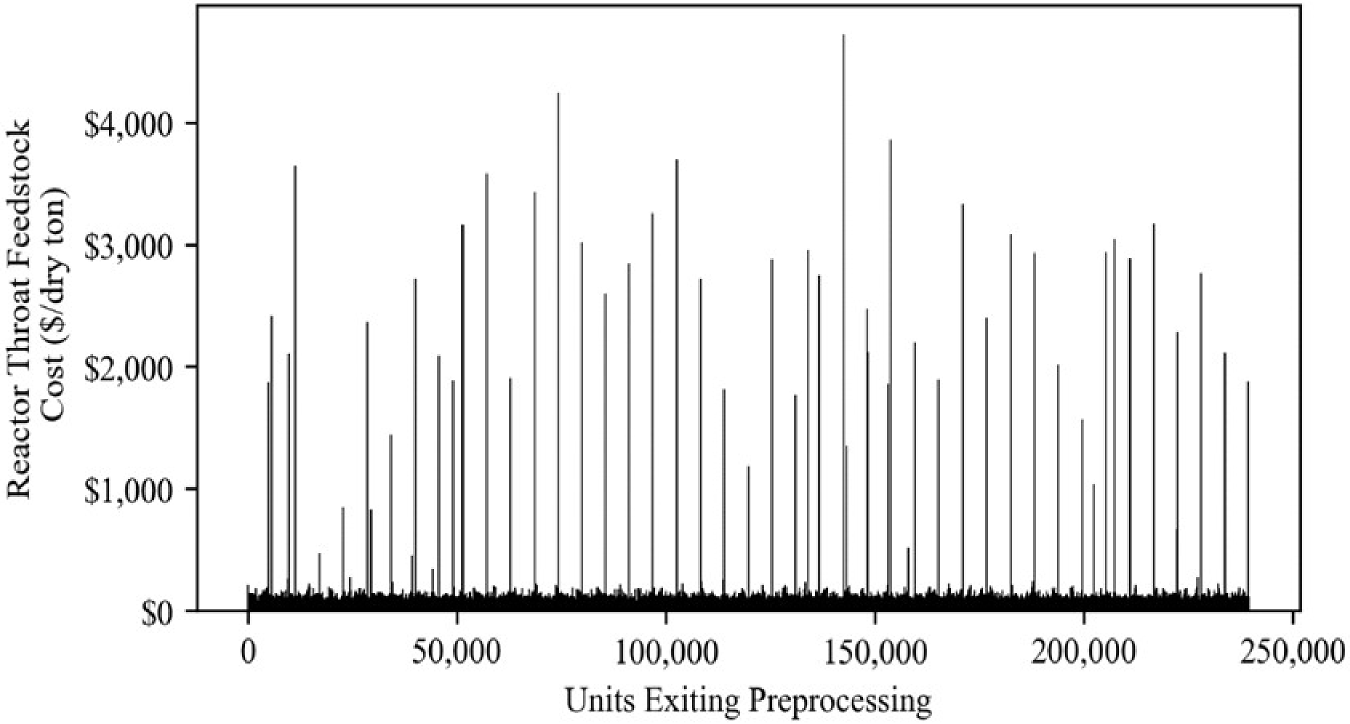


12 = *BETO Supported*



1^{st}-Plant: Modeled Daily Throughput and Cost of Preprocessing





Throughput Factor ($F_{f,P}$): 0.8950

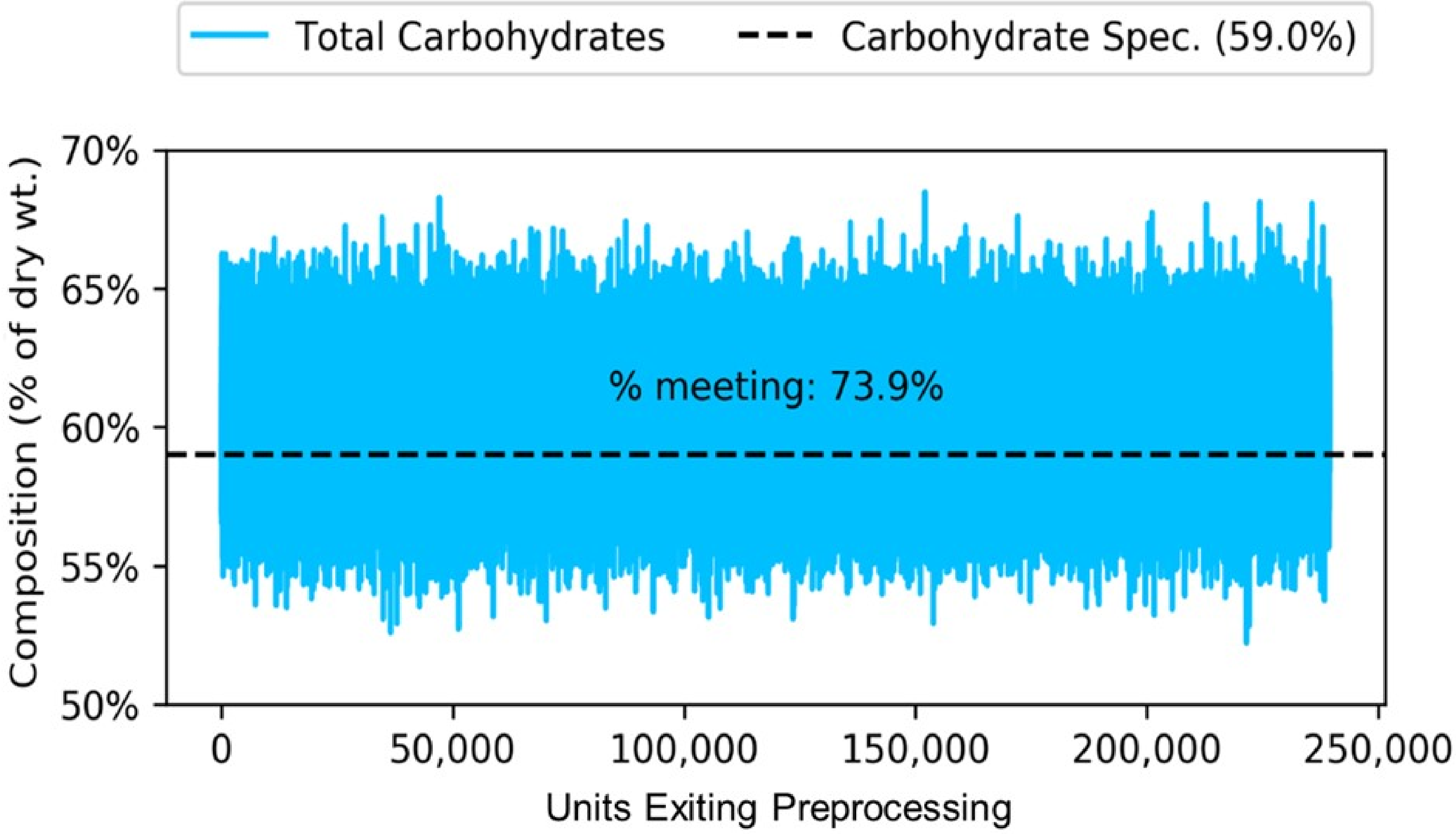
On-stream time: 84.63%

Mean: $90.25/dry ton (FY20 nth-Plant Estimate: $80.10/dry ton)

Median: $87.94/dry ton

Range: $72.77/dry ton - $4,726.22/dry ton

1st-Plant: Quality Distribution of Feedstock Units Leaving Preprocessing & OOE



Performance Factor ($F_{B,P}$): 0.7390

Supply Logistics:

$$OOE_S = F_{f,S} \times F_{B,S} \times 100$$
$$= 0.9158 \times 0.5972 \times 100$$
$$= 54.69\%$$

Preprocessing:

$$OOE_P = F_{f,P} \times F_{B,P} \times 100$$
$$= 0.8950 \times 0.7390 \times 100$$
$$= 66.14\%$$

Only the units meeting or exceeding the specification are fed to conversion

FY20 Herbaceous/Biochem Summary Comparison

- Delivered Feedstock Cost:
  - n^{th}-Plant: $80.10/dry ton
  - 1^{st}-Plant: Mean $109.91/dry ton (Median $107.60/dry ton)
    - Production Cost: Mean $90.25/dry ton (Median $87.94/dry ton)
      - Range: $72.77 - $4,726.22/dry ton
    - Quality Cost: Adds on average $19.66/dry ton if material not meeting quality is not fed

- OOE analysis revealed that using corn stover alone does not consistently meet quality
  - higher quality feedstock sources will be needed for blending, or
  - preprocessing steps added to improve quality

Summary: Future Direction and Path Forward

- **Challenge:** Inherent variability of biomass feedstock affects the ability to optimize processing and conversion processes, ultimately decreasing plant economics
- **Goal:** Maximize biorefinery economics by better process quality control of feedstock leading to greater plant availability and predictable yields of high value biofuels and co-products
- **Requirements:**
  - Minimize raw material variability
    - Composition → Yield
    - PSD → Convertibility & Losses
    - Flow properties → Throughput
    - Impacts of Moisture & Ash → Failures
  - Lower the mean cost and shift the cost-weighted distribution to the left
- **Approaches:**
  - Fractionate → Formulate to spec → send remaining material to alternate conversion process(es)

Shout out to the Projects and PIs that provide data…

Data/Information Sources & Principal Investigators by Project WBS

- 1.1.1.3 – Supply Scenario Analysis – *Matt Langholtz*
- 1.2.1.1 – Post-Harvest Management for Quality Preservation – *Bill Smith*
- 1.2.1.2 – Biomass Size Reduction – *Jaya Shankar Tumuluru*
- 1.2.1.5 – Resource Mobilization – *Damon Hartley*
- 1.2.1.1000 – Value-added process intensification – *Lynn Wendt*
- 1.2.2.2 – Biomass Supply Chain Risk and Material Attribute Analytics – *Rachel Emerson*
- 1.2.2.802 – FCIC INL – *Allison Ray, Vicki Thompson, Jordan Klinger, Neal Yancey*
- 3.4.1.202 – User Facility – *Quang Nguyen*
- 4.2.1.20 – Integrated Landscape Management – *Mike Griffel*
- 5.1.2.101 – MSW BioPower – *Jordan Klinger*

Quad Chart Overview

Timeline

- Project start date: 10/1/2020
- Project end date: 9/30/2023

	FY20	Active Project
DOE Funding	$1,000,000	$3,000,000

Project Partners

- Collaborators include all FSL R&D AOP Projects, industry projects (data source), and other BETO National Laboratories performing TEA and LCA.

Barriers addressed

- Ft-A. Feedstock Availability and Cost
- Ft-I. Feedstock Supply System Integration and Infrastructure
- Ft-J. Operational Reliability

Project Goal

Through leading-edge feedstock analyses that identify R&D technology performance, quality and cost targets to achieve BETO goals, maximize biorefinery economics by better process and quality control of feedstock leading to greater plant availability and predictable yields of high value biofuels and co-products.

End of Project Milestone

FY23 MYP Target Support TEA: Technoeconomic analysis supporting MYP waste feedstock inclusion. Identify preprocessing CPPs necessary to deliver the required CMAs for biochemical and thermochemical conversion of conventional and waste feedstocks for conversion at a modeled price of $86/dry ton (2016$).

Funding Mechanism

This project is a programmatic AOP project under the Feedstock Technologies Platform in BETO.

Idaho National Laboratory

Additional Slides

Responses to 2019 Peer Review Comments

2019 Peer Review Comment

- *"Herbaceous goals are based upon corn stover as a model substrate but project has suggested blends; it is not clear how these are being taken into other FSL projects, in particular, with regards to impact on plant uptime. Suggest defining a strategy to bring cost improvements into the demonstration/benchmarking process more clearly."*

FY19-20 Actions Taken in Response to Comment

- Corn stover quality is an issue that makes it necessary to either add preprocessing steps (at additional cost), or blend with higher quality energy crops to meet conversion specifications. As a residue that is produced as a byproduct of farming to produce a grain commodity, there is little incentive to the farmer to make harvest and collection modifications for corn stover that would improve its quality to meet conversion specifications, hence, a greater focus was needed on preprocessing approaches to mitigate variability.
- Recognizing this, we redoubled our efforts to identify approaches to meet cost, quality and operational goals using corn stover alone, which led our program to the tissue fractionation and reformulation approach. Additionally, we began comparing 1st-plant stochastic SOT results to the nth-plant deterministic SOTs, which clearly differentiates the costs arising from preprocessing the stover from those arising from variability in compositional quality.

Responses to 2019 Peer Review Comments (continued)

2019 Peer Review Comment

- *"Previous review comments indicate that the models may be too optimistic for these nth plants. Do the models still assume that all operational barriers have been overcome. If not, how can you add that risk to the model?"*

FY19-20 Actions Taken in Response to Comment

- n^{th}-plant assumptions assume 90% time on-stream, and our prior Design Cases and SOTs are aligned with n^{th}-plant conversion technology Design Cases and SOT assessments that also, as a rule, assume 90% time on-stream. Essentially, what is needed is direct comparison of the n^{th}-plant SOTs with 1^{st}-plant SOTs of identical or very similar supply system design.
- In response, we developed 1^{st}-plant reliability Design Cases and SOTs during FY19 to determine what preprocessing strategies and technologies could have the highest impact on achieving cost, quality and operational goals, as well as the necessary R&D performance targets. Additionally, we began the process of aligning the n^{th}-plant and 1^{st}-plant supply system designs to allow direct comparison of the two.

Highlights from FY19 Go/No-go Decision Point

FY19 Go/No-go Decision Point (March 31, 2019)

- Quantify 3-pass and 2-pass corn stover, and switchgrass volumes meeting quality specs available to supply at least 5 biorefineries at the 2022 MFSP target of $3/gge.
- Go: National volume of industrially-relevant herbaceous feedstocks available that are capable of supporting the $3.00/gge MFSP target in 2022, while meeting the quality requirements, will provide sufficient feedstock to supply at least 5 biorefineries.

Decision: Go

- Moving the MFSP target from $3.00/gge to $2.50/gge by 2030 for biochemical conversion implies the need for a 17% reduction in delivered feedstock cost, from $85.51/dry ton to $71.26/dry ton (2016$). Economically-advantaged feedstocks (e.g., MSW, biosolids) are targeted in 2030, which indicates a need for sufficient quantities of herbaceous feedstock to mitigate the low quality of the economically-advantaged feedstocks and enable meeting conversion in-feed specifications.
- We demonstrated the ability to site a maximum of seven biochemical biorefineries that meet the 2022 projected cost of $79.07/dry ton (2016$) while meeting a delivered carbohydrate specification of 59% and including dockage for ash content and moisture. This surpassed the Go criteria of supplying five biorefineries while meeting the quality requirements. This analysis utilized the same assumptions around performance and resource availability that were outlined in the 2018 SOT and 2022 Projection for Herbaceous Feedstocks.

Publications and External Reports

Publications Since Previous Peer Review

- Locating nth-plants for blended feedstock conversion and preprocessing nationwide: biorefineries and depots. T. Hossain, D. Jones, D. Hartley, M. Griffel, Y. Lin, P. Burli, D.N. Thompson, M. Langholtz, M. Davis, C. Brandt. Submitted to *Applied Energy*.
- The effect of biomass properties and system configuration on the operating effectiveness of biomass to biofuel systems. D.S. Hartley, D.N. Thompson, L.M. Griffel. *ACS Sustainable Chemistry & Engineering* (2020), 8, 7267-7277. DOI: 10.1021/acssuschemeng.9b06551.
- Distributed biomass supply chain cost optimization to evaluate multiple feedstocks for a biorefinery. M.S. Roni, D.N. Thompson, D.S. Hartley. *Applied Energy* (2019), 254. DOI: 10.1016/j.apenergy.2019.113660.

External Reports Since Previous Peer Review

- Woody Feedstocks 2019 State of Technology Report. D.S. Hartley, D.N. Thompson, H. Cai. (2020), Idaho National Laboratory, Idaho Falls, ID, INL/EXT-20-57181-Rev001, DOI: 10.2172/1607741.
- Herbaceous Feedstock 2019 State of Technology Report. M.S. Roni, Y. Lin, M. Griffel, D.S. Hartley, D.N. Thompson. (2020), Idaho National Laboratory, Idaho Falls, ID, INL/EXT-20-57182-Rev000, DOI: 10.2172/1607754.
- High-Temperature Conversion Feedstock 2019 Reliability State Of Technology and 2022 Reliability Design Case Report. D.S. Hartley, P. Burli, L.M. Mike Griffel, D.N. Thompson. (2019), Milestone Completion Report, U.S. DOE, Bioenergy Technologies Office, Idaho National Laboratory, September 30, 2019.
- Low-Temperature Conversion Feedstock 2019 Reliability State Of Technology and 2022 Reliability Design Case Report. D.S. Hartley, D.N. Thompson, L.M. Griffel. (2019), Milestone Completion Report, U.S. DOE, Bioenergy Technologies Office, Idaho National Laboratory, September 30, 2019.
- Woody Feedstocks 2020 State of Technology Report. D.S. Hartley, D.N. Thompson, H. Cai. (2020), Milestone Completion Report, U.S. DOE, Bioenergy Technologies Office, Idaho National Laboratory, September 30, 2020. INL/EXT-20-59976 Rev:000, not yet uploaded to OSTI.
- Herbaceous Feedstock 2020 State of Technology Report. Y. Lin, M. Roni, D.N. Thompson, D. Hartley, L.M. Griffel, H. Cai. (2020), Milestone Completion Report, U.S. DOE, Bioenergy Technologies Office, Idaho National Laboratory, September 30, 2020. INL/EXT-20-59958 Rev:000, not yet uploaded to OSTI.
- High-Temperature Conversion Feedstock 2020 Overall Operating Effectiveness State of Technology. D.S. Hartley, L.M. Griffel, D.N. Thompson. (2020), Milestone Completion Report, U.S. DOE, Bioenergy Technologies Office, Idaho National Laboratory, September 30, 2020. INL/EXT-20-59981 Rev:000, not yet uploaded to OSTI.
- Low-Temperature Conversion Feedstock 2020 Overall Operating Effectiveness State of Technology. D.S. Hartley, D.N. Thompson, L.M. Griffel. (2020), Milestone Completion Report, U.S. DOE, Bioenergy Technologies Office, Idaho National Laboratory, September 30, 2020. INL/EXT-20-59977 Rev:000, not yet uploaded to OSTI.

Presentations

Presentations Since Previous Peer Review

- Assessing the effect of biomass properties on biomass to biofuel system performance using Overall Operating Effectiveness. D. Hartley, D.N. Thompson, L.M. Griffel, Q. Nguyen, M. Roni, *2020 Virtual AIChE Annual Meeting*, November 16-20, 2020. Paper 737c, Oral presentation.
- Locating nth-plants for blended feedstock conversion and preprocessing nationwide: biorefineries and depots. D. Jones, T. Hossain, D. Hartley, L.M. Griffel, Y. Lin, P. Burli, D.N. Thompson, M. Langholtz, M. Davis, C. Brandt. *2020 Virtual AIChE Annual Meeting*, November 16-20, 2020. Paper 737e, Oral presentation.
- Optimizing the biorefinery supply chain: Impact of feedstock quality on logistics design. Y. Lin, P.H. Burli, D.S. Hartley, L.M. Griffel, M.S. Roni, D.N. Thompson. *2019 INFORMS Annual Meeting*, Seattle, WA, October 20-23, 2019. Poster.
- Optimization of national and regional bioenergy feedstock supplies as functions of price and biorefinery scale. D. Hartley, D.N. Thompson, L.M. Griffel, Y. Lin. *2019 AIChE Annual Meeting*, Orlando, FL, November 10-15, 2019. Paper 23d, Oral presentation.
- Impact of feedstock attributes on the performance of processing in cellulosic ethanol applications. D. Hartley, D.N. Thompson. *ICOSSE '19 – 8th International Congress on Sustainability Science and Engineering*, Kuala Lumpur, Malaysia, July 1-3, 2019. Oral presentation.
- Impact of feedstock attributes on the performance of preprocessing and conversion in cellulosic ethanol applications. D. Hartley, D.N. Thompson. *41st Symposium on Biotechnology for Fuels and Chemicals*, Seattle, WA, April 28 - May 1, 2019. Poster S86.

Supporting Slides

3 – Impact (Continued)

Feedstock State of Technology (SOT)

- **Purpose:** Report on accomplishments of funded R&D projects and evaluate modeled progress toward attainment of MYP milestones and goals which is foundational for BETO
- **MYP Goal**
  - By 2021, deliver feedstocks meeting the defined critical material attributes (CMAs) for the 2022 verification, in support of a modeled MFSP of $3/GGE and a 60% reduction in GHG emissions relative to currently predominant fuels.
- **MYP Milestones**
  - By 2020, identify the differences among the macro-scale attributes of anatomical feedstock fractions and quantify the impact of the properties during primary deconstruction and handling to support the 2021 goal of delivering a feedstock that meets all Critical Material Attributes (CMAs) for the 2022 verification.
  - By 2022, identify the preprocessing system and critical processing parameters necessary to deliver the required critical material attributes for biochemical and thermochemical conversion at 90% operating effectiveness that meet a delivered cost of $86/dry ton.

Technical Targets needed to meet 2022 MYP Goals - Biochem

- MYP Goals: n^{th}-plant Cost (\$79.07/dry ton), Quality (>58.99% total carbohydrates, <5% ash) and GHG (244 kg CO_2e/dry ton) goals
- FY21-FY22 R&D accomplishments needed to meet the MYP n^{th}-Plant Targets
  - Reduce delivered feedstock cost for Biochemical Conversion by \$1.03/dry ton
    - Reduce transportation distance (additional feedstock types)
    - Reduce ash dockage (could eliminate \$1.68/dry ton of delivered cost)
      - Blending of anatomical fractions in altered ratios
  - Reduce GHG emission contribution to 66.21 kg CO_2e/dry ton or below
    - Reduce transportation distance
    - Reduce energy consumption via more energy efficient processing methods
      - Shear vs impact milling
- Overall Operating Effectiveness (1^{st}-Plant)
  - Reduce amount of moisture-related downtime (increased throughput)
  - Reduce amount of wear-related downtime (increased equipment parts life)
  - Reduce variability of feedstock exiting preprocessing

Overall Operating Effectiveness

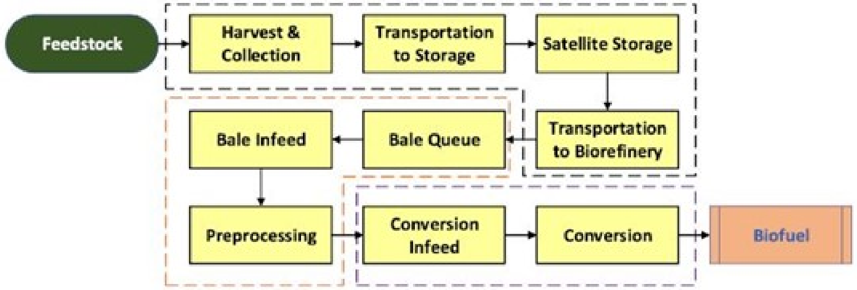
- Adapted from the concept of Overall Equipment Effectiveness (OEE), which focuses on individual pieces of equipment
  - Considers: Availability (*A*), Performance Rate (*PR*) and Quality Rate (*QR*)
  - Deterministic

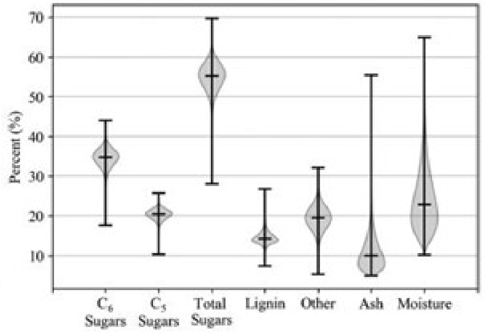
- Overall Operating Effectiveness (OOE), examines the performance of a system by modeling the operating and quality performance of individual pieces of equipment and their interactions in the system
  - Considers: Availability (*A*), Performance Rate (*PR*) and Quality Rate (*QR*)
  - Stochastic

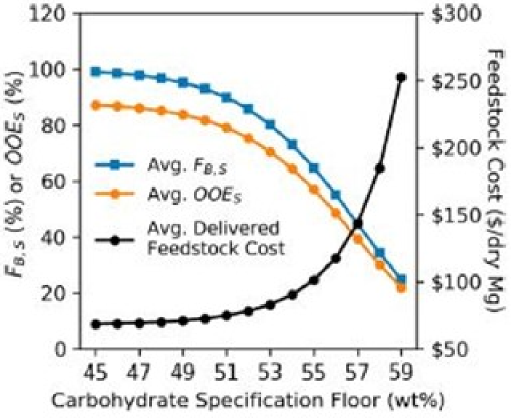
$$\mathbf{OOE} = (\boldsymbol{A} \times \boldsymbol{PR}) \times \boldsymbol{QR} \times \mathbf{100} = \left(\frac{\boldsymbol{Total\ Units\ Produced}}{\boldsymbol{Design\ Units\ Planned}}\right) \times \left(\frac{\boldsymbol{Units\ Produced\ Meeting\ Quality}}{\boldsymbol{Total\ Units\ Produced}}\right) \times \mathbf{100}$$

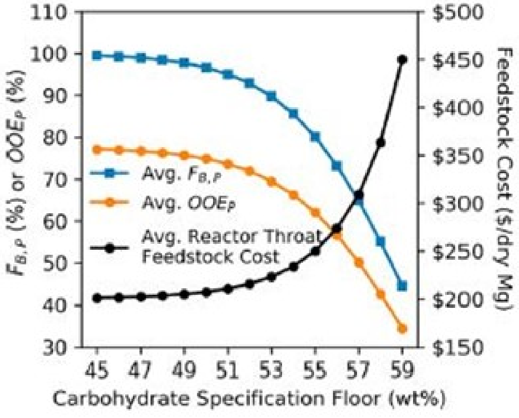
Understanding operability & cost impacts of variability

- **Knowledge Gap Addressed**
  - Quantifying of the impacts of quality variability on production & quality costs
- **Achievement**
  - Tied dynamic impacts of stochastic feedstock physical and compositional variability on operability and productivity over the complete field to biofuel supply chain
- **Relevance to SOT**
  - Cost impacts based on operability (throughput) and quality (units meeting all CMAs) to provide direction of R&D to address trade-offs across the field to biofuel system





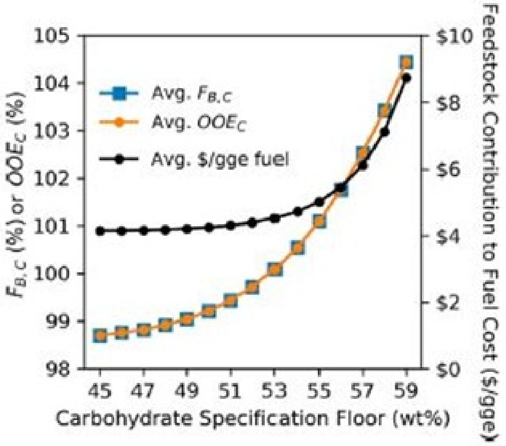




Supply Logistics

Preprocessing

Conversion



Hartley et al., *ACS Sustainable Chemistry & Engineering* (2020), 8, 7267-7277. DOI: 10.1021/acssuschemeng.9b06551

Equipment failure triggers and down times

In addition to dynamic changes to throughput as functions of material attributes, the individual unit operations can fail when certain triggers are reached

	Convey	Destring	Bale Proc.	Size Red.	Vib. Screen	Disk Screen	Air Sep.	Opt. Sort.	Knife Mill	Rotary Shear	Densifier
Capacity	25	25	25	25	25	25	25	25	25	25	25
MTTF (min)	252,000	120	252,000	262,800	252,000	252,000	252,000	252,000	262,800	262,800	262,800
TTR (min)	480	1	120	120	480	480	480	480	480	120	30
TTR_SD (min)	90	.25	90	30	90	90	90	90	90	30	10
Max_MC (%)	—	—	40	30	—	—	—	—	45	45	25
Max_MC_TTR	—	—	30	30	—	—	—	—	30	30	30
Max_MC_TTR_SD	—	—	15	15	—	—	—	—	15	15	10
Max_Ash (tons)	—	—	2000	250	—	—	250	—	125	250	—
Max_Ash_TTR	—	—	360	360	—	—	720	—	360	360	—
Max_Ash_TTR_SD	—	—	120	120	—	—	240	—	120	120	—

MTTF: Mean Time To Failure; TTR: Time To Repair; SD: Standard Deviation; MC: Moisture Content

FY22 Technical targets from the analysis

Unit Operation	2022 Technical Target	Supporting Work
Storage		
Dry Matter Loss	≤ 7% of total dry matter	WBS# 1.2.1.1
MC** Exiting Storage	Maximum of 30% w.b.	WBS# 1.2.1.1
Preprocessing		
Bale Processor		
Tine Life	2000 tons of total ash passing	WBS 1.2.3.3, WBS 1.2.1.2, FCIC Task 1
Vibratory Screen		
Effectiveness	Remove >80% of total ash	WBS 1.2.3.3 and Future FSL Scope
Disk Screen		
Effectiveness	Separate > 75% of leaf material	WBS 1.2.3.3 and Future FSL Scope

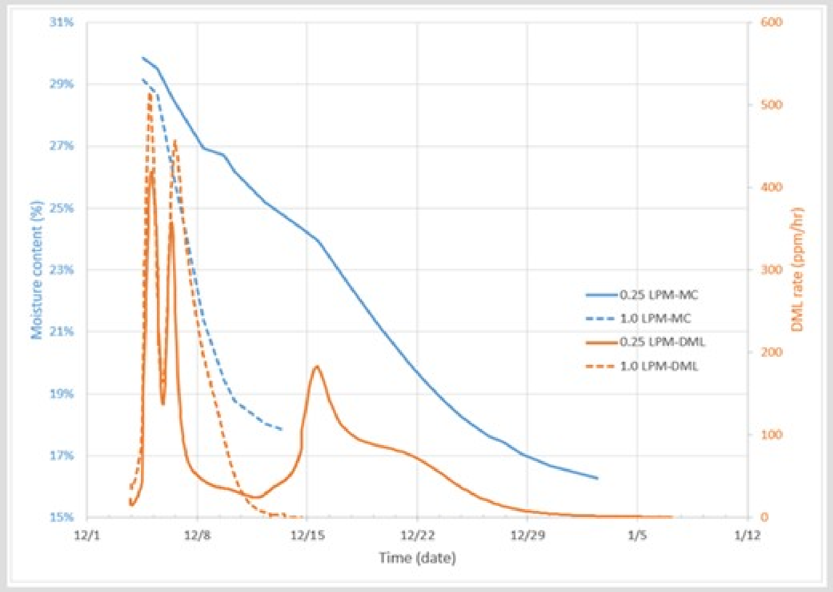
** MC = Moisture Content

2022 Technical targets from the analysis (continued)

Unit Operation	2022 Technical Target	Supporting Work
Air Separator		
Effectiveness	Separate > 75% of Husk material	WBS 1.2.3.3 and Future FSL Scope
Body Life	250 tons of ash passing	WBS 1.2.3.3, WBS 1.2.1.2, FCIC Task 1
Optical Sorter		
Effectiveness	Separate > 75% of Cob material	WBS 1.2.3.3 and Future FSL Scope
Knife Mill		
Knife Life	150 Tons of total ash passing	WBS 1.2.3.3, WBS 1.2.1.2, FCIC Task 1
Rotary Shear		
Blade Life	250 tons of total ash passing	WBS 1.2.3.3, WBS 1.2.1.2, FCIC Task 1

Enhanced drying of early harvested, high-moisture bales

- **Knowledge Gap Addressed**
  - Biodegradation is highest in stover bales that are harvested early in the season resulting in variability and feedstock losses
- **Achievement**
  - Developed a method to reduce moisture content from 30% to <20% and dry matter losses <6%
- **Relevance to SOT**
  - The reduction in dry matter loss leads to a reduction in the material purchased and lowers transportation cost
  - By controlling the moisture in storage, there are less mechanical failures, resulting in higher preprocessing throughput



FY20 Herbaceous/Biochem Summary Comparison

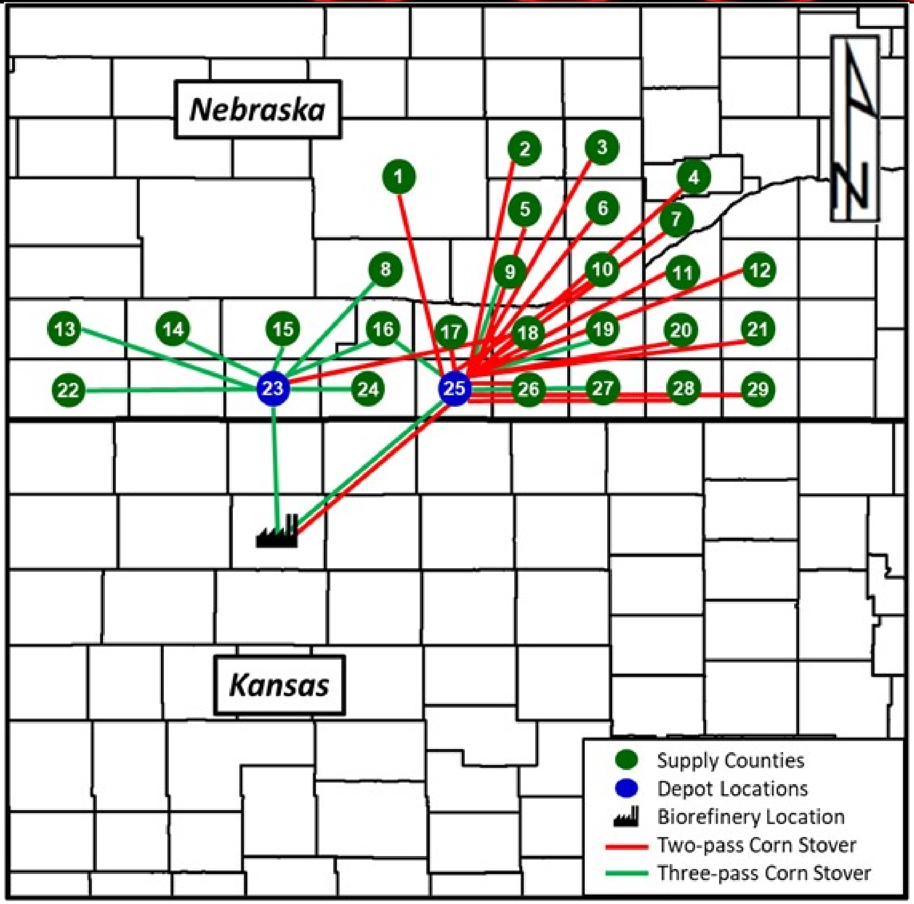
- Technology Advancement from FY19 to FY20: Advanced Storage w/ Drying
  - <u>n^{th}-Plant:</u>
    - Reduced mean moisture content lowered DML, increased throughput and reduced energy in size reduction
  - <u>1^{st}-Plant (OOE)</u>
    - Reduced moisture content eliminated moisture stoppages, increased on-stream time and throughput

Delivered feedstock composition assumptions for BC

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

Herbaceous SOT - Blendstocks & Delivered Feedstock

Biomass Type	Raw Biomass Purchased (dry tons)	Pelleted Blendstocks Produced (dry tons)	Pelleted Blendstocks		
			Total Carbohydrates (wt% db)	Ash (wt% db)	Delivered Cost ($/dry ton)
Three-pass corn stover	240,350	214,815	57.10%	11.80%	$77.97
Two-pass corn stover	570,830	510,185	59.80%	7.30%	$80.98
Totals	811,180	725,000	59.00%	8.63%	$80.10



Node	County	Node	County
-	Sheridan County, KS	15	Frontier County, NE
1	Custer County, NE	16	Gosper County, NE
2	Valley County, NE	17	Phelps County, NE
3	Greeley County, NE	18	Kearney County, NE
4	Nance County, NE	19	Adams County, NE
5	Sherman County, NE	20	Clay County, NE
6	Howard County, NE	21	Fillmore County, NE
7	Merrick County, NE	22	Dundy County, NE
8	Dawson County, NE	23	Red Willow County, NE
9	Buffalo County, NE	24	Furnas County, NE
10	Hall County, NE	25	Harlan County, NE
11	Hamilton County, NE	26	Franklin County, NE
12	York County, NE	27	Webster County, NE
13	Chase County, NE	28	Nuckolls County, NE
14	Hayes County, NE	29	Thayer County, NE

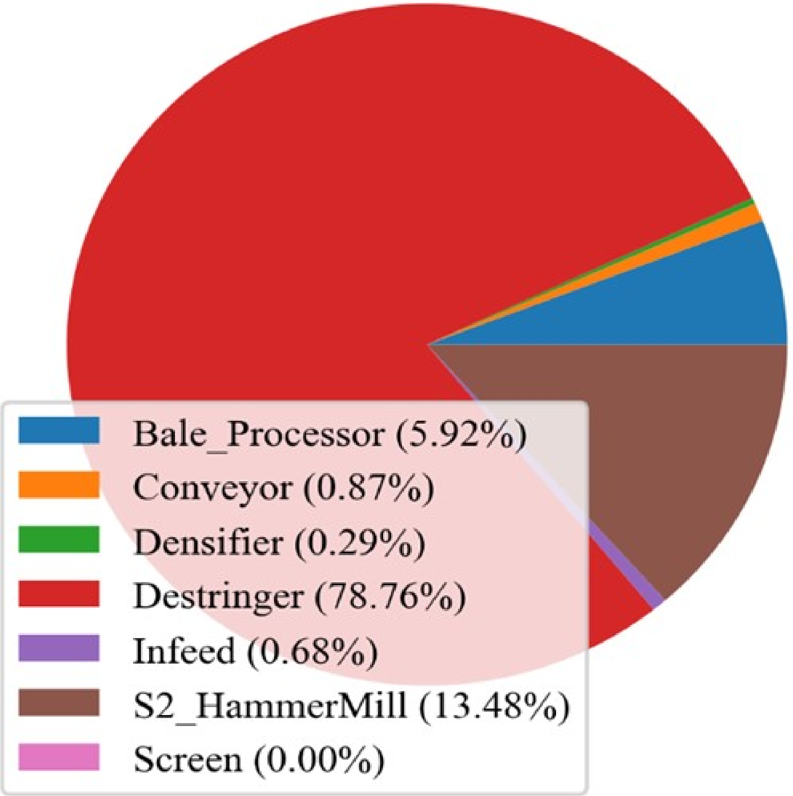
Progress – 2018 to 2022 for Herbaceous nth-plant Supply to BC

	Cost ($/dry ton) (2016$)			
	2018 SOT	2019 SOT	2020 SOT	2022 Projection
Feedstock	**Blend**	**Blend**	**Blend**	**Blend**
Net delivered cost ($/dry ton)	**$83.67**	**$81.37**	**$80.10**	**$79.07**
Grower payment ($/dry ton)	$23.54	$20.56	$20.62	$22.37
Feedstock logistics ($/dry ton)	**$60.13**	**$60.81**	**$59.47**	**$56.70**
Harvest & collection ($/dry ton)	$16.68	$17.14	$17.33	$12.79
Storage & queuing ($/dry ton)	$6.55	$6.49	$6.72	$8.35
Preprocessing ($/dry ton)	$22.40	$20.84	$19.43	$21.44
Transportation & handling ($/dry ton)	$13.23	$14.76	$14.61	$12.44
Dockage ($/dry ton)	$1.27	$1.58	$1.39	$1.68

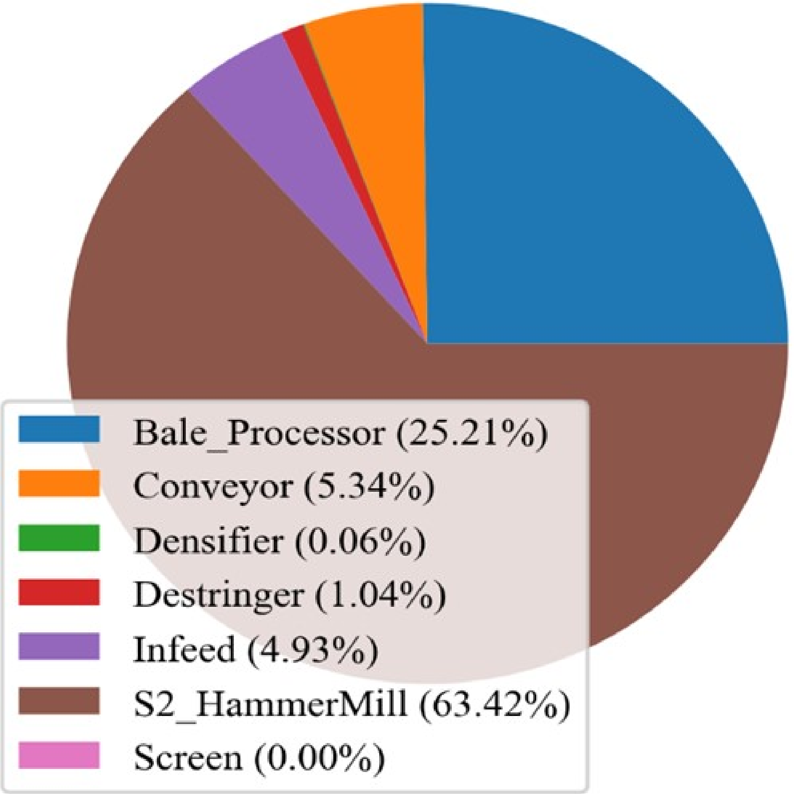
GHG Emissions – 2018 to 2022 for Herbaceous nth-plant Supply to BC

	GHG Emissions (kg CO_2e/dry ton)			
	2018 SOT	2019 SOT	2020 SOT	2022 Projection
Harvest & collection	10.78	11.38	11.17	8.49
Storage & queuing	3.31	2.43	2.50	2.54
In-plant receiving and preprocessing	20.12	21.00	16.60	13.73
Transportation & handling	39.84	49.35	47.21	41.45
Grand Total	**74.05**	**84.16**	**77.48**	**66.21**

Preprocessing Down Events & Down Time by Equipment

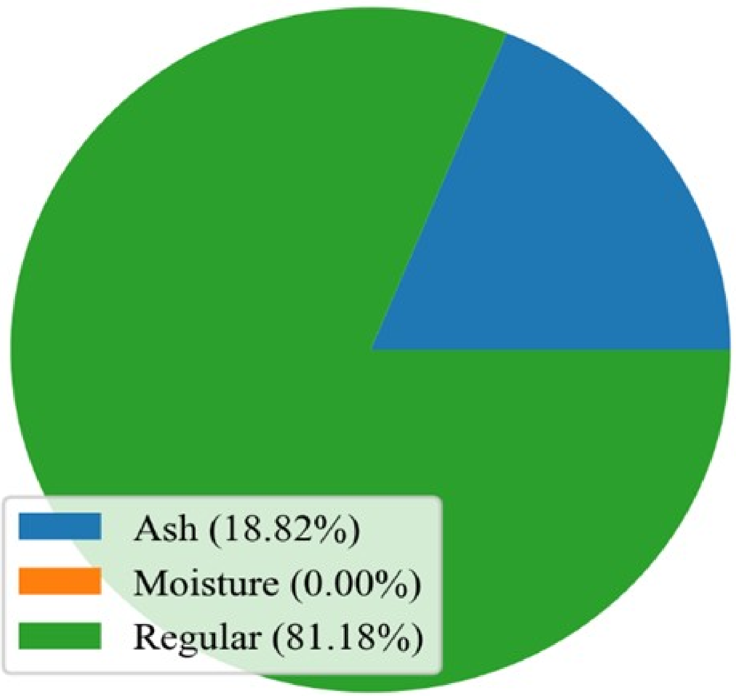


Down Events by Equipment

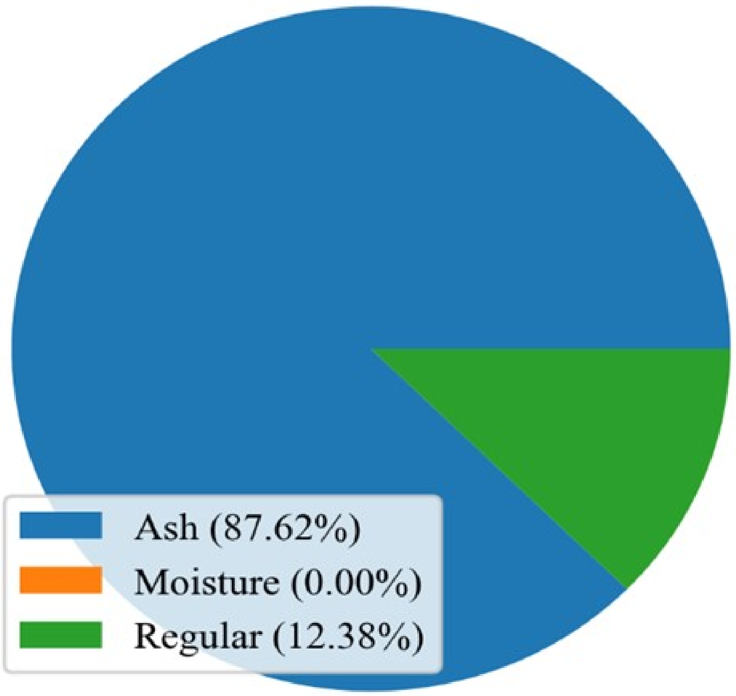


Down Time by Equipment

Preprocessing Down Events & Down Time by Cause

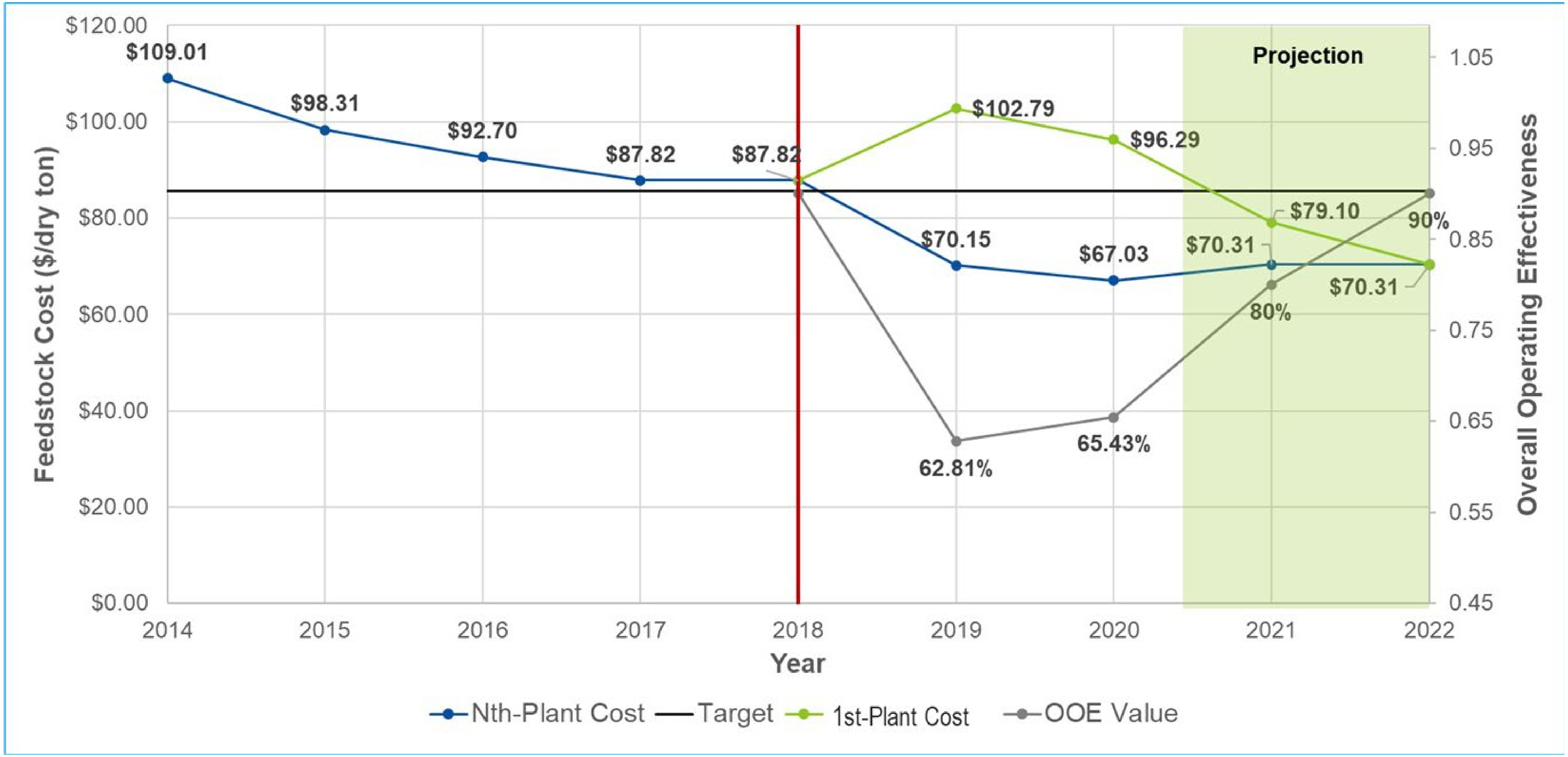


Down Events by Cause



Down Time by Cause

Progress toward cost and performance goals for CFP

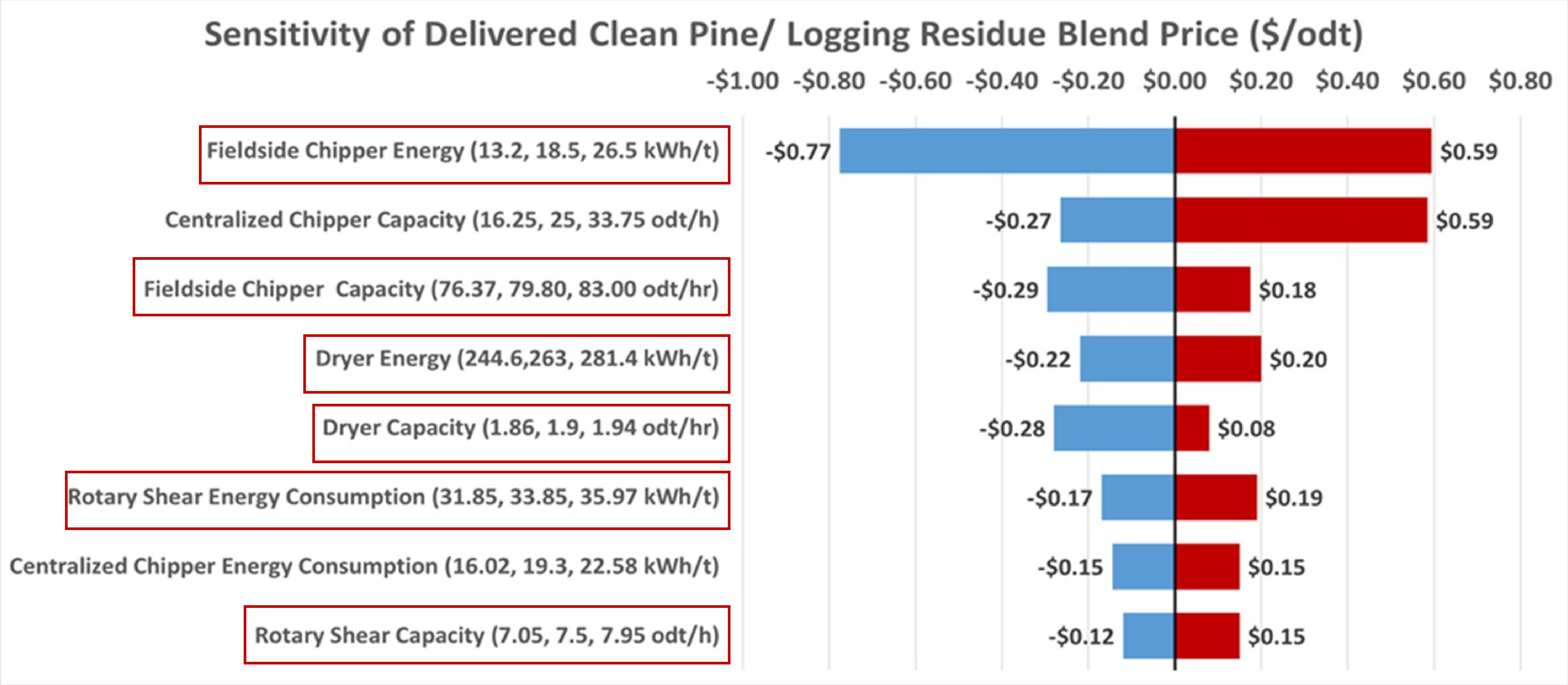


FY20 CFP nth-Plant Supply Costs and GHG Emissions

	Cost ($/dry ton) (2016$)			
	Clean Pine	Logging Residue	Total[a]	GHG Emissions (kg CO_2e/dry ton)
Grower Payment	$15.73	$3.75	$9.74	
Harvest & Collection	$9.88	$0.00	$4.94	6.74
Field-side Preprocessing	$4.73	$12.09	$8.41	10.04
Transportation	$7.67	$16.77	$12.22	11.64
Preprocessing	$27.32	$23.54	$25.43	133.37
Storage	$0.68	$0.68	$0.68	0.90
Handling	$2.65	$2.65	$2.65	0.81
Preprocessing Construction	$2.96	$2.96	$2.96	
Grand Total	**$71.62**	**$62.44**	**$67.03**	**163.50**

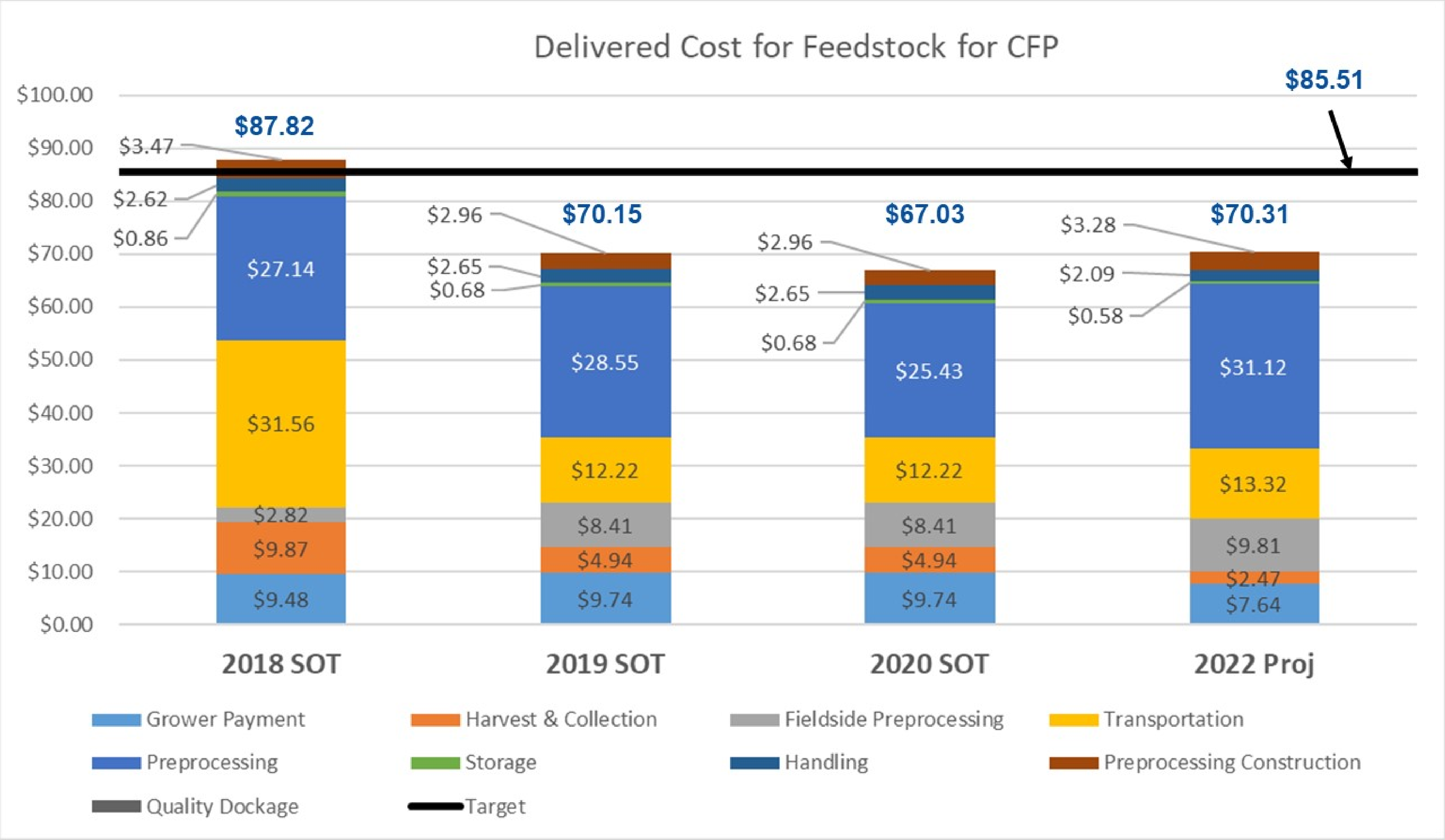
a The total is a weighted average of the blend components, with 50% clean pine and 50% logging residue.

Sensitivity of costs to unit operation performance



= BETO Supported

CFP cost progression – 2018 to 2022 (2016$)



FY20 Woody/CFP Summary Comparison

- Cost:
  - nth-Plant: $67.03/dry ton
  - 1st-Plant: Mean $96.29/dry ton (Median $95.42/dry ton)
    - Production Cost: Mean: $70.00/dry ton (Median: $69.13/dry ton)
      - Range: $66.11 - $4,935.92/dry ton
    - Quality Cost: Adds $26.29/dry ton if material not meeting quality is not fed

FY20 Woody/CFP Summary Comparison

- Technology Advancement: Specialized Processing Design
  - n^{th}-Plant:
    - Reduced fuel cost
    - Reduced GHG emissions
- 2022 verification shifts to <1% ash specification and will require the additional of more mechanical processes to remove ash from the material to meet quality targets. Unknown what the impact will be on material cost, depending on ability to offset technology cost increases with added value to conversion.

Technical Targets needed to meet MYP Goals (CFP)

- n^{th}-plant Cost ($70.31/dry ton), Quality (>50.51% total carbon, <1% ash) and GHG (244 kg CO_2e/dry ton) goals
- Ash removal from logging residue
    - Reduce ash content by 0.57 percentage points (assuming a 50/50 blend)
    - Cost must be less than $3.28/dry ton, including material losses
    - GHG emission contribution must be below 80.50 kg CO_2e/dry ton

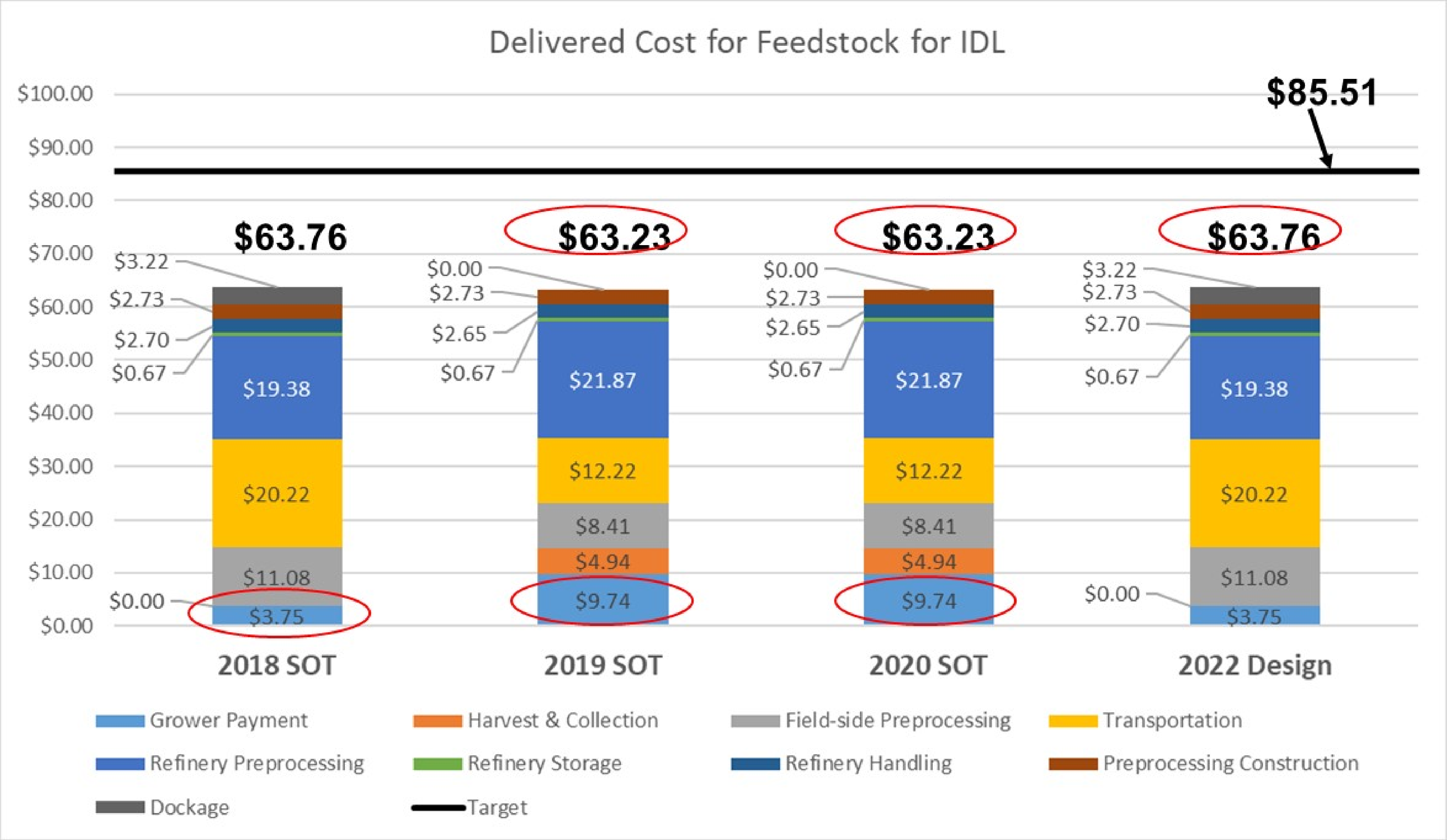
- Overall Operating Effectiveness – i.e., 1^{st}-Plant
    - Lower mean of ash distribution to meet spec of < 1% ash, ≥ 91% of tons
        - Technology changes must add less than $15.51/dry ton
        - Must attain at least an average throughput of 21.6 dry tons/hr

FY20 Woody nth-plant SOT for IDL – Modeled Supply Costs

	Cost ($/dry ton) (2016$)			
	Clean Pine	Logging Residue	Total[a]	GHG Emissions (kg CO_2e/dry ton)
Grower Payment	$15.73	$3.75	$9.74	
Harvest & Collection	$9.88	$0.00	$4.94	6.74
Field-side Preprocessing	$4.73	$12.09	$8.41	10.02
Transportation	$7.67	$16.77	$12.22	11.45
Preprocessing	$28.14	$15.59	$21.87	30.34
Storage	$0.67	$0.67	$0.67	0.89
Handling	$2.65	$2.65	$2.65	0.81
Preprocessing Construction	$2.73	$2.73	$2.73	
Grand Total	**$72.20**	**$54.25**	**$63.23**	**60.25**

a The total is a weighted average of the blend components, with 50% clean pine and 50% logging residue.

Progress – 2018 to 2022 for Woody n^{th}-plant Supply to IDL



FY20 Woody n^{th}-plant SOT for AHTL – Modeled Supply Costs

AHTL 2020 Cost Summary and Green House Gas Emissions		
	Cost (2016$) ($/dry ton)	GHG (kg CO_2e/dry ton)
Grower Payment	$3.75	
Harvest & Collection	$0.00	0.00
Field-side Preprocessing	$11.53	17.83
Transportation	$5.89	13.75
Preprocessing	$39.82	180.03
Storage	$0.67	0.84
Handling	$3.70	1.63
Preprocessing Construction	$4.95	
Grand Total	**$70.31**	**214.08**

Progress – 2018 to 2022 for Woody n^{th}-plant Supply to AHTL