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HERBACEOUS FEEDSTOCK 2021 STATE OF TECHNOLOGY REPORT

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EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) promotes the production of advanced liquid transportation fuels from lignocellulosic biomass by funding fundamental and applied research that advances the State of Technology (SOT). As part of its involvement with this mission, Idaho National Laboratory (INL) completes an annual SOT report for biomass feedstock logistics. This report summarizes supply system impacts of Bioenergy Technologies Office (BETO)-funded research and development efforts at INL and INL collaboration with external partners (e.g., Forest Concepts, Purdue University) that lead to improvements in feedstock supply systems. These include improvements to and observed performance of innovative harvest and collection methods, storage technologies, transportation and handling approaches, and advanced preprocessing technologies. Biomass quality and variability, and the interface between feedstock quality and conversion performance are key drivers in addition to delivered feedstock cost. In this report, we estimate the benefits of R&D technology improvements to individual supply system unit operations and present the status of feedstock logistics technology development for converting herbaceous biomass into biofuels. These analyses are supported by experimental data where possible and help to align the SOT relative to the cost goals defined in the Multi-Year Plan.

The 2021 Herbaceous SOT incorporates an advanced biomass fractionation system for separating anatomical fractions (e.g., leaf, stem, husk, and cob) of delivered corn stover, thus, to maximize the goal of reducing extrinsic ash and improving carbohydrate content in the pre-processed biomass. The air classification in the fractionation system is supported by a Spudnik

Air separator, which is a large-scale equipment that can efficiently remove soil contaminant (about 25%) and separate high ash content tissue such as leaf and husks. By eliminating extrinsic ash in biomass and the high ash content fractions, we have reduced ash content of three-pass corn stover from 11.20% to 6.00%, and increased carbohydrate content from 56.80% to 60.16%. This technical improvement has allowed us to eliminate two-pass corn stover from the biomass supply curve, therefore largely reducing the harvesting and collection cost, and transportation costs within the feedstock logistics system. In addition, the second stage hammer mill was replaced with rotary shear, which is less sensitive to moisture content than hammer milling and has higher throughput with lower energy consumption. The reduced energy consumption has also contributed to the modeled cost reduction. The 2021 n^{th}-plant Herbaceous SOT predicts a modeled delivered feedstock cost of \$78.21/dry ton (2016\$), this is a \$0.57/dry ton (2016\$) decrease from the 2020 Herbaceous SOT *n^{th}-Supply* case cost. Technology improvements that contributed to this modeled cost reduction include reduced cost in the feedstock harvesting, collection and transportation cost caused by eliminating two-pass corn stover, and reduced energy consumption cost by replacing the hammer mill with rotary shear. A preliminary greenhouse gas emissions (GHG) assessment was completed by scaling the 2020 Herbaceous n^{th}-plant GHG data from the 2020 Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model (GREET), shows a decrease of 9.77 kg CO_2e/ton from the 2020 SOT (77.48 kg CO_2e/ton in the 2020 Herbaceous Feedstock SOT to 67.71 kg CO_2e/ton in the 2021 Herbaceous Feedstock SOT). This net reduction is attributed to reduced transportation distances for biomass delivery from field to depot, and reduced energy consumption by using rotary shear, and will be updated once Argonne National Laboratory has completed their Supply Chain Sustainability Analysis for the 2021 SOTs.

In the 1st-plant analysis of the 2021 Herbaceous SOT system, the average throughput was 2,044 dry tons/day or 92.7% of the name plate capacity. During the simulation the daily throughput ranged from 848.1 dry tons/day to 2,338 dry tons/day, which equates to 38.5% to 106% of the daily nameplate capacity. After the year of operation 715,400 tons (98.3% of the annual nameplate capacity) of preprocessed feedstock were produced; the variability in throughput was primarily caused by equipment failures in the system. Failures due to wear were the largest cause of disruption within the system, accounting for 70.0% of the failures and 91.3% of the total downtime. Previously, moisture related failures were the cause of the majority of downtime, but new storage strategies and equipment (bale dryer for the first 25% of stover harvested) data from the Biomass Storage project (WBS 1.2.1.1) led to the elimination of moisture related downtime. Ultimately the system on-stream time was 87.7% during the simulation period. Considering the operational delays and material losses in the system, the average cost per ton of biomass was \$82.34/dry ton (2016\$), with a range from \$72.24/dry ton to \$1,045.56/dry ton. When compared to the ideal n^{th}-plant cost, the average cost from the 1st-plant analysis was \$4.13/dry ton greater than the n^{th}-plant estimate. However, approximately 7% of the tons of material were preprocessed in the system at a cost of less than the n^{th}-plant cost of

$78.21/dry ton. While the nth-plant analysis assumes a constant quality feedstock, the 1st-plant analysis utilizes variability in the material to assess the impact. In the 1st-plant analysis, it was assumed that any material that does not meet the minimum conversion quality specification of 59 wt% of total carbohydrate is discarded. From this simulation, 74.7% of the preprocessed material met or exceeded the minimum quality specification, requiring the disposal of 25.3% of the biomass. The material that is discarded due to quality, represents an additional cost that must be accounted for in the total cost of the material. When accounting for quality the average delivered cost of the material increased to $110.28/dry ton, ranging from $100.25 to $997.86. The resulting Overall Operating Effectiveness (OOE) for the system, from the simulation, was found to be 73.45%. A feedstock performance factor of 74.7% and a fully burdened cost that is $32.07/dry ton higher than the estimated nth-plant cost suggest that additional technology development is needed to further address the variability of quality within the feedstock to attain an OOE of 90% and cost parity with the nth-plant analysis.

From an overall system perspective for harvest through to the conversion reactor throat, it is clear from this analysis that the highest impacting R&D areas, once moisture variability is minimized, encompass the development of improved harvesting methods that minimize soil contamination (or conversely, fractionation methods to effectively remove extrinsic ash), improved storage practices and fractionation method development for anatomical fractions. It will be difficult to reduce the intrinsic compositional variability that exists among different varieties of corn stover due to in part to differences in the physical characteristics of the plants themselves, such as in differing ratios of tissue fractions. Anatomical fractionation followed by reformulation of the fractions into feedstocks meeting conversion specifications offers a pathway to accomplish this. It is important to note that sensors capable of measuring carbohydrate and ash on a moving conveyor on the fly will be critical to develop this strategy effectively.

Table of Contents

1. BACKGROUND

The Energy Independence and Security Act (EISA) of 2007 required a minimum supply of 36 million gallons of renewable fuels per year by 2022. In order to achieve these goals, the Bioenergy Technologies Office (BETO) has set cost and technology targets for producing advanced and cellulosic biofuels. One of the targets is to validate feedstock supply infrastructures and systems with 90% overall operating effectiveness (Hartley et al. 2020) and field-to-reactor throat delivered cost less than $85.51/dry ton (2016$). As stated by the 2017 Multi-Year Program Plan (DOE 2017), the research and development focus of the Feedstock Technologies (FT) platform is reducing the cost, improving the supply chain logistic efficiency, improving biomass quality, and increasing the supply volume. In addition, BETO oversees annual State of Technology (SOT) report that assesses current technologies that are relevant to BETO's targets based on actual data and experimental results.

Feedstocks are essential to achieving BETO goals because the cost, quality, and quantity of feedstock available and accessible at any given time limit the maximum volume of biofuels that can be produced. In accordance with the 2016 Multi-Year Program Plan (DOE 2016a), FT focuses on (1) reducing the delivered cost of sustainably produced biomass, (2) preserving and improving the physical and chemical quality parameters of harvested biomass to meet the individual needs of biorefineries and other biomass users, and (3) expanding the quantity of feedstock materials accessible to the bioenergy industry. This is done by identifying, developing, demonstrating, and validating efficient and economical integrated systems for harvest and collection, storage, handling, transport, and preprocessing raw biomass from a variety of crops to reliably deliver the required supplies of high-quality, affordable feedstocks to biorefineries as the industry expands. The elements of cost, quality, and quantity are key considerations when developing advanced feedstock supply concepts and systems (DOE 2016a).

Progression of Feedstock Supply System Designs

Feedstock supply systems are highly complex systems of operations required to move and transform biomass from a raw harvested material at the point of production into a formatted, on-spec feedstock at the throat of the conversion reactor. Feedstock logistics can be broken down into individual operations of harvest and collection, storage, transportation, preprocessing, and queuing and handling. Designing economic and environmentally sustainable feedstock supply systems, while providing necessary resource quantities at the appropriate quality, is critical for growth of the bioenergy industry. Research and development on feedstock supply systems aims to reduce delivered cost, improve and preserve feedstock quality, and expand access to biomass resources. Through 2012, BETO-funded research on feedstock supply systems focused on improving conventional feedstock supply systems (CFSS). CFSS designs rely on existing technology and systems to supply feedstock to biorefineries (Hess et al. 2009a). These designs tend to be vertically integrated with a specific conversion process or biorefinery. They also create the requirement to design extremely robust conversion systems capable of handling variability in feedstock quality at the biorefinery. Biorefineries strive to optimize efficiencies and capacities within the constraints of local supply, equipment availability, and permitting requirements. However, this approach makes the system vulnerable to variations in feedstock quality parameters, such as (a) high ash content, which negatively impacts operating costs related to acid consumption and ash disposal; (b) variable composition of convertible carbohydrates, which negatively impacts sugar yields due to suboptimal enzyme loading; and (c) variable moisture, which increases grinding costs and creates handling and flowability problems that significantly reduce the effectiveness of feedstock introduction to the conversion process.

CFSS designs are currently the backbone of the emerging biofuels industry. However, conventional supply systems have limitations that restrict widespread implementation on a national scale (Hess et al. 2009a, Hess et al. 2009b). Viability of the conventional supply system's design is reliant on geographical areas that have a concentrated supply of abundant, easily accessible, and low-cost biomass resources (such as corn stover in the Midwestern United States). Within these regions, variable weather, inherent compositional variability and harvest practices that are not designed to mitigate quality concerns, such as moisture and ash content, leads to considerable variability in feedstock cost and the biorefinery's ability to process the biomass. Low density bales in conventional systems combined with the short window of availability necessitate large-scale bale storage, leading to greatly increased fire risk. Moving outside these select regions, the feedstock supply system must be further adapted to accommodate a diversity of feedstocks to ensure adequate supply, which leads to changing cost, quality, and conversion yields that are directly tied to the conversion facility's size constraints. CFSS can only address feedstock quality indirectly through passive controls, such as resource selection or best management practices. For example, research at INL has shown that varying harvesting practices and equipment can reduce ash (i.e., dirt) entrainment during harvest and baling (Bonner et al. 2014). When positioned in a highly productive single resource area, biorefineries can be selective in contracting only biomass that meets their specifications. However, biomass quality (e.g., ash and moisture content) is highly variable both spatially and temporally (Kenney et al. 2013), and, in any given year, passive controls might not provide sufficient quality control for the feedstock to meet desired specifications. Therefore, biorefineries that rely on conventional designs are constrained to local resources, with cost-prohibitive expansion of the collection radius limiting plant size (Graham et al. 2013). Several analyses have shown that as the biofuels industry expands past the highly productive regions, CFSS will fail to meet supply requirements (Hess et al. 2009b, Bonner et al. 2014) economically or at the desired price target.

To meet the demands of the future bioenergy industry, the supply system must expand beyond CFSS in certain areas to what has been termed "advanced" feedstock supply systems

(Hess et al. 2009a, Hess et al. 2009b, Searcy et al. 2010, Jacobson et al. 2014). For advanced feedstock supply system (AFSS) designs, a distributed network of aggregation and processing centers, termed "depots," are employed near the point of biomass production (i.e., the field or forest) to reduce biomass variability and produce feedstocks of a uniform format, necessary to move toward biomass commoditization (Figure 1). The depots produce a stable, tradable, merchandisable intermediate that reduce downstream conversion inefficiencies and move the burden of feedstock variability away from the biorefinery.

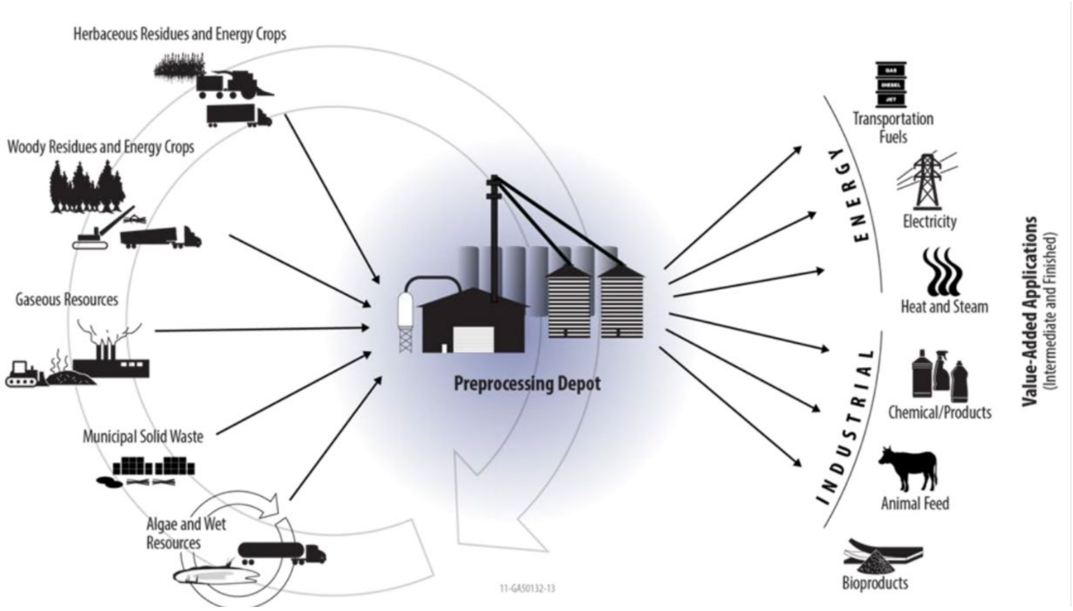

Figure 1. *Incorporation of stakeholder feedback has resulted in improvements in advanced feedstock supply systems, evolving depots from being vertically integrated to producing merchandisable intermediates and serving a variety of customers and markets.*

Advanced concepts have evolved (and continue to evolve) as new research and ideas emerge. Advanced concepts are also guided by input from stakeholders. In February 2015, the Advanced Feedstock Supply System Validation Workshop gathered experts from industry, DOE offices, DOE-funded laboratories, and academia to discuss approaches for addressing challenges associated with an expanding bioenergy industry and assumptions used in the Advanced Feedstock Supply System. The workshop was sponsored by DOE-BETO and feedback received is being considered as advanced concepts evolve (Searcy et al. 2015).

Depots can provide logistics solutions for sourcing multiple biomass resources to a biorefinery, whether these resources are dispersed or co-located. In such a scenario, depots may emerge as feedstock supply chain business elements to lessen the complexity to a biorefinery of managing a blended feedstock supply system. An economic advantage of a depot in this scenario may be its specialization to supply and preprocess single sources of improved quality, value-added biomass (referred to as a "blendstock") that can be formulated together with blendstocks from other depots to produce cost-effective feedstocks meeting the specifications of numerous customers. This specialization eliminates the need for a single entity to make a capital investment and establish expertise to contract, preprocess, and supply a diversity of resources that may have different preprocessing requirements. Relying on multiple biomass types and sources to produce blended feedstocks can also reduce the risk to industry by diversifying reliance on any one feedstock.

In the 2021 Herbaceous SOT, we incorporated an advanced biomass fractionation system into depot preprocessing, which could largely improve biomass quality of three-pass corn stover delivered from storage to the depots (ash content reduced from 11.20% to 6.00%, carbohydrate content increase from 56.80% to 60.16%) by reducing extrinsic ash content and eliminating high ash content fractions such as leaf and husk. This technology improvement allows us to remove the blending step and provide biomass pellets with sufficient quantity and quality by only using one type of biomass. An optimization model (Roni et al. 2019b) was used to determine the biomass quantity sourced from certain supply counties. The supply curves and optimal depot and biorefinery locations used in the 2021 Herbaceous SOT are the same as the nth-supply scenario used in the 2020 Herbaceous *nth-Supply* SOT, which was developed in conjunction with Oak Ridge National Laboratory, as a constant supply moving forward in order to focus on BETO-funded technology improvements. The 2021 Herbaceous SOT incorporates two depots that are located at a distance from the biorefinery nearer to higher-yielding counties that have significant corn stover available lower on the supply curve.

2. 2021 Herbaceous Feedstock SOT

2.1 Description of Logistics System Design

The 2021 Herbaceous SOT design assumes annual nth-plant delivery of 725,000 dry tons of herbaceous feedstock, with biochemical conversion in-feed feedstock compositional specifications presented in Table 1 (Davis et al. 2018). The shaded rows in Table 1 show the compositional specifications for the feedstock, namely, 59% carbohydrates, ≤ 4.93% ash, and 20% moisture. An additional specification is ¼"-minus particle size at the pretreatment reactor throat. The 2021 Herbaceous SOT is reported in 2016$ and includes grower payment, logistics costs, and ash and moisture dockages to reflect a modeled net delivered feedstock supply cost. The modeled logistics system for the 2021 Herbaceous SOT models the delivery of 725,000 dry tons of three-pass corn stover, utilizing the three-pass harvest, collection and transportation system described in the 2020 Herbaceous SOT report (Lin et al., 2020) and summarized in Appendix A. The 2021 Herbaceous SOT also incorporates an advanced biomass separation system that can effectively reduce extrinsic ash content and reduce the amount of anatomical fractions having higher ash content.

Table 1. *Delivered feedstock composition assumptions for dilute-acid pretreatment and enzymatic hydrolysis to sugars followed by biological conversion of sugars to hydrocarbons pathway (Davis et al. 2018).*

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***

2.1.1 Resource Availability and Transportation

The geographic area for the 2021 Herbaceous SOT is northwestern Kansas, with the biorefinery located in Sheridan County, which is unchanged from the 2020 Herbaceous SOT. During FY20, a nth-supply scenario was developed from a series of analyses developed jointly by INL and ORNL that examined biomass availability as the industry matures (Hossain et al, 2021). From this analysis corn stover and switchgrass supply is estimated as a demand-based supply in 2040. In the 2020 Herbaceous SOT, the nth-supply scenario was utilized to set the depot locations to align with the demand-based supply. For this and all future SOTs these locations will remain fixed, allowing the SOTs to focus effectively on the cost and quality impacts of BETO-funded technology advancements. Fixing the source and depot locations has also fixed the transportation utilized for supplying biomass. Transportation and handling include all steps involved in the movement of biomass from multiple local locations to a centralized location (such as a preprocessing facility or biomass depot), including loading, trucking, and unloading. Feedstock transportation in the 2021 Herbaceous SOT includes both bale and pellet transportation, which are described in the 2020 Herbaceous SOT (Lin et al., 2020). In bale transportation, biomass bales are loaded onto semi-trucks after the field side storage, transported, and unloaded at the depots. After pelleting at the depot, biomass pellets are then loaded and transported to the biorefinery.

The 2021 Herbaceous SOT scenario depot locations, biomass source counties and biorefinery location are listed in Tables 2 and 3 and are shown pictorially in Figure 2. The least cost supply chain network utilized two distributed depots (Nodes 6 and 7 in Figure 2) for a biorefinery located in Sheridan County, Kansas. Because of the higher biomass availability around Node 7, the depot at Node 7 is sized larger than the depot at Node 6. The results also show that a biorefinery with a design capacity of 725,000 dry tons/year, would need to procure at least 910,012 dry tons of biomass annually to account for losses in the system. This procured biomass is 98,832 dry tons more than the 2020 Herbaceous SOT, mainly because of the 11.24% dry matter loss in the preprocessing system (soil removal (6.34%), and leaf and husk removal (4.90%)).

Table 2. *Node IDs and county names for the biomass source counties for the supply system depicted in Figure 2 for the 2021 Herbaceous SOT. Decatur County, KS and Phillips County, KS are not identified in the table because they are depot locations, not farm-gate sources of biomass.*

Node	County
-	Sheridan County, KS
1	Frontier County, NE
2	Gosper County, NE
3	Phelps County, NE
4	Harlan County, NE
5	Franklin County, NE

Table 3. *Locations and sizes of distributed depots for least cost delivery of 725,000 dry tons/year of feedstock to Sheridan County, KS for the 2021 Herbaceous SOT. Source nodes are identified by county name in Table 2 and are shown geographically in Figure 2.*

Node	Identifier	County	Capacity (dry tons/yr)	Biomass Type	Biomass Source Nodes
-	Biorefinery	Sheridan, KS	725,000	three-pass corn stover	6,7
6	Depot	Decatur, KS	268,286	three-pass corn stover	1, 2
7	Depot	Phillips, KS	560,962	three-pass corn stover	3, 4, 5

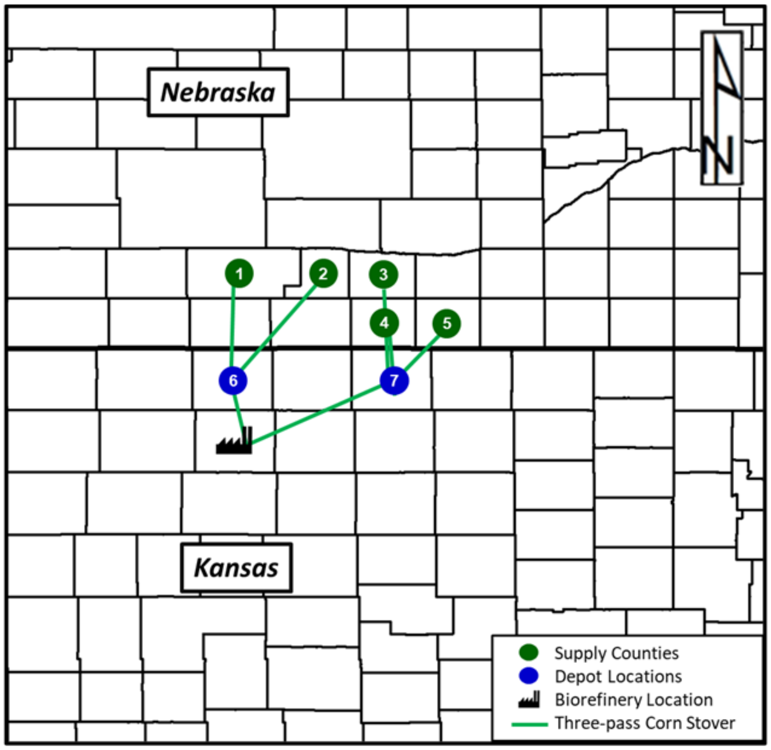

Figure 2. *Supply chain network design for the 2021 Herbaceous SOT. The supply chain has 2 distributed depots (Nodes = 6 and 7) with the biorefinery located in Sheridan County, Kansas. Three-pass corn stover is sourced from Nodes 1, 2, 3, 4 and 5. County names are shown with their node identifiers in Table 2 and Table 3.*

2.1.2 Harvest and Collection

Corn stover is the only type of biomass used in the 2021 Herbaceous SOT design. It is assumed that corn stover is harvested using the three-pass (conventional) harvesting practice. The three-pass corn stover harvest and collection method refers to the conventional stover harvest strategy and is also referred to as a “multi-pass harvesting system.” The harvest yield of three-pass corn stover remains unchanged from the 2019 Herbaceous SOT (Roni et al., 2018), and are referenced from studies conducted by Smith and Bonner (2014).

2.1.3 Storage

The 2021 Herbaceous SOT incorporates the identical storage system introduced in the 2020 Herbaceous SOT (Lin et al., 2020), which is comprised of a combination of best management practices and “farm-scale technologies” such as enhanced in-storage drying of high-moisture early harvested bales to achieve storage stability objectives. With the same moisture content assumptions, an average field-side stack dry matter loss of 8.88%/year was estimated for the overall corn stover storage. Dry matter loss and compositional change of each anatomical fraction during storage were calculated based on the results published by Garlock et al. (2009).

2.1.4 Preprocessing

In the 2021 Herbaceous SOT design, the first stage size reduction uses the same equipment as the 2020 design, which is an EZ Ration Processor. It requires lower rpm and energy and eliminates the slugging flow observed in the first stage hammer mill used in SOTs prior to 2019. After the first stage size reduction, there are two modifications to feedstock preprocessing in the 2021 Herbaceous SOT design compared to the 2020 design. First, a Spudnik air classifier (Figure 3) is integrated into the system to separate soil and a fraction of high-ash anatomical tissues from the three-pass corn stover, and second, the hammer mill is replaced with a Forest Concepts Crumbler® which size reduces using rotary shear and has lower energy consumption than a hammer mill. The Spudnik air classifier was designed to handle fresh harvested potato so it has a high tolerance for dirt and moisture in the incoming material.

Figure 3. *Spudnik air classifier for corn stover anatomical fraction separation.*

2.2 2021 nth-Plant Herbaceous Feedstock SOT Analysis

The Biomass Logistics Model (BLM) was used to model feedstock logistics cost and energy consumption estimates for the 2021 nth-Plant Herbaceous Feedstock SOT design. The BLM incorporates information from a collection of databases that provide (1) engineering performance data for hundreds of equipment systems; (2) spatially explicit labor cost data sets; and (3) local tax and regulation data. The BLM's analytic engine is built in the system dynamics software package Powersim^{TM}. The BLM is designed to work with thermochemical- and biochemical-based biofuel conversion platforms and to accommodate a range of lignocellulosic biomass types (e.g., herbaceous residues, short-rotation woody and herbaceous energy crops, woody residues, and algae). The BLM simulates the flow of biomass through the entire supply chain while tracking changes in feedstock characteristics (i.e., moisture content, dry matter, carbohydrate content, ash content, and dry bulk density) and calculating cost and energy consumption (Cafferty et al. 2013). The energy consumption and other parameters (e.g., transportation distance, density) from BLM are also inputs to the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model (GREET 2020), to perform a cursory farm gate-to-plant gate life-cycle assessment on GHG emissions (this is completed by colleagues at Argonne National Laboratory).

2.2.1 Cost Summary and Energy Usage

Results of the supply chain analysis are summarized in Table 4, which provides the detailed cost breakdown and greenhouse gas emissions. The greenhouse gas emissions (GHG) preliminary assessment was completed by scaling the 2020 Herbaceous nth-plant GHG data from the 2020 Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model (GREET®) and will be updated once Argonne National Laboratory has completed their Supply Chain Sustainability Analysis (SCSA) for the 2021 SOTs. ANL will employ the most up to date version of the GREET® model (Argonne National Laboratory, 2017) to conduct their detailed life-cycle analysis of farm gate-to-biorefinery gate GHG emissions in the 2021 SCSA.

Table 4. *The 2021 Herbaceous SOT modeled cost and GHG estimates for an herbaceous feedstock supply system supplying 725,000 dry tons/yr in northwestern Kansas. Design details are in Appendix A.*

Cost Element	Cost ($/dry ton) Three-Pass Stover	GHG emissions (kg CO_2e/ton)
Grower payment	$21.71	
Harvest and collection	$13.84	10.28
Storage and queuing	$6.66	5.20
Transportation and handling	$12.20	16.81
In-plant receiving and preprocessing	$23.40	38.79
Dockage	$0.40	
Total	**$78.21**	**71.08**

Table 5 shows the modeled cost estimates for the herbaceous feedstock supply system for the 2020 *n*th*-Supply* SOT, 2021 SOT and the 2022 Projection. The 2021 Herbaceous SOT predicts a modeled delivered nth-plant feedstock cost of $78.21/dry ton (2016$); this is a $0.57/dry ton decrease from the 2020 Herbaceous *n*th*-Supply* SOT. The increase of $1.09/dry ton in grower payment from the 2020 Herbaceous *n*th*-Supply* SOT is a result of eliminating the two-pass corn stover. The $3.49/dry ton and $0.06/dry ton decreases in harvest and collection costs and in storage costs from the 2020 results were due to the lower harvesting and storage costs of three-pass corn stover. In the preprocessing system, cost of adding the Spudnik air classifier was about $8.98/dry ton, nearly half of which is the cost of dry matter loss (11.24% dry matter loss). In order to compensate material loss in the air classification process, 98,832 more dry tons of biomass needed to be delivered to the selected depot locations. For the depots, the larger plant capacity reduced the construction costs by about $0.23/dry ton. Replacing the hammer mill with a Crumbler® led to a cost reduction of $4.86/dry ton. As a result, the preprocessing cost for the 2021 nth-plant Herbaceous SOT design is about $3.80/dry tons higher than the 2020 result. The transportation and handling costs in the 2021 nth-plant Herbaceous SOT is about $0.92/dry ton lower than the 2020 *n*th*-Supply* SOT. The main reason for this result is because the availability of three-pass corn stover is about two times higher than two-pass corn stover, so by only using three-pass corn stover, sufficient biomass can be sourced from counties with shortest distances to depots. Due to the lower ash content (from 11.20% to 6.00%) in the processed feedstock, the dockage cost was reduced by about $0.99/dry ton.

Table 5. *Summary of modeled cost estimates for the herbaceous feedstock supply system for the biochemical conversion pathway for the 2020 nth-Supply SOT, 2021 SOT and 2022 Projection.*

	2020 nth-Supply SOT	**2021 SOT**	**2022 Projection**
Feedstock	**Blend**	**Three-pass**	**Blend**
Net delivered cost ($/dry ton)	**$78.78**	**$78.21**	**$79.07**
Grower payment ($/dry ton)	$20.62	$21.71	$22.37
Feedstock logistics ($/dry ton)	**$58.16**	**$56.50**	**$56.70**
Harvest & collection ($/dry ton)	$17.33	$13.84	$12.79
Storage & queuing ($/dry ton)	$6.72	$6.66	$8.35
Preprocessing ($/dry ton)	$19.60	$23.40	$21.44
Transportation & handling ($/dry ton)	$13.12	$12.20	$12.44
Dockage ($/dry ton)	$1.39	$0.40	$1.68

A preliminary greenhouse gas emissions (GHG) assessment was completed by interpolating the 2020 Herbaceous n^{th}-plant SOT GHG output from Argonne National Laboratory using the 2020 Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model (GREET®). The GHG assessment shows a decrease of up to 9.77 kg CO_2e/ton from the 2020 SOT (67.71 kg CO_2e/ton in the 2021 Herbaceous Feedstock SOT). This net reduction is attributed to reduced transportation distances for biomass delivery from field to depot, and replacement of energy intensive hammer mill by rotary shear and will be updated once Argonne National Laboratory has completed their Supply Chain Sustainability Analysis (SCSA) for the 2021 SOTs.

As stated above, the amount of harvested biomass (prior to storage) required to produce the delivered feedstock are shown in Table 6, along with its average carbohydrate and ash contents. The results also show that a biorefinery with a design capacity of 725,000 dry tons/year, would need to procure at least 910,012 dry tons of biomass annually to account for losses in the system.

Table 6. *Delivered (reactor-throat) cost and composition of the three-pass corn stover. The modeled cost estimates discussed in detail in Appendix A. An ash dockage of $1.37/dry ton and a moisture dockage of $0.03/dry ton are included in the total delivered cost. All costs are in 2016$.*

Biomass Type	Raw Biomass Purchased (dry tons)	Pelleted Feedstock Produced			
		Feedstock Delivered (dry tons)	Total Carbohydrate (wt% db)	Ash (wt% db)	Delivered Cost ($/dry ton)
Three-pass corn stover	910,012	725,000	60.16%	6.00%	$78.21

2.2.2 Sensitivity Analysis of Costs

Sensitivity analysis was performed on the delivered feedstock cost for the 2021 Herbaceous SOT. Critical process parameters were investigated to determine the impact of uncertainty in their values on the delivered feedstock cost. The parameters varied and their ranges are shown in Table 7 for the sensitivity analysis.

Figure 4 shows the results of the sensitivity analysis; delivered cost was found to vary from $74.24-$82.56/dry ton (2016$). The top five factors impacting uncertainty in the delivered cost included baling rate, interest rate, bale density, storage dry matter loss, and bale processor throughput; all of these except for interest rate are prior or current FT-funded R&D topics. Based on the observed variation, baling throughput is a key contributor to uncertainty, with its maximum value reducing the delivered feedstock by $3.02/dry ton, whereas its minimum value would increase the delivered feedstock cost by $5.32/dry ton. Additional parameters that had

Table 7. *Model parameters varied for the sensitivity analysis. Each parameter was varied independently based on actual variations observed in experimental and field data except for air classifier dry matter losses, for which there were no data and we assumed a range based on anecdotal experimental observations.*

Parameter	Units	Minimum	Average (SOT)	Maximum
Effective windrowing rate[a]	acres/hr	10.78	11.50	12.51
Effective baling rate[b]	dry ton/hr	16.14	26.18	28.10
Field side storage dry matter loss[c]	%	5.580%	8.880%	14.21%
Bale transport loading/unloading time[d]	minutes	39	42	45
Bale density[e]	lb/ft^3	11	12	13
Rotary shear effective throughput[f]	dry tons/hr/ machine	4.78	7.50	14.33
Rotary shear energy consumption[f]	kWh/dry ton	11.66	14.58	17.49
Bale processor throughput[f]	dry tons/hr/machine	5.0	10	13
Bale processor energy consumption[f]	kWh/dry ton	6.50	8.00	11.0
Pelleting throughput[f]	dry tons/hr/ machine	3.43	3.62	3.76
Pelleting energy consumption[f]	kWh/dry ton	33.79	32.49	34.68
Air classification dry matter loss[g]	%	9.10	11.24	15.00
Interest rate[h]	%	4.00	8.00	12.0

a: Effective windrowing rate is variated based on variation of field efficiency measured from time series data (Roni et al., 2018).
b: Depends on variation of yield and equipment capacity. Empirical field data from DOE co-sponsored Biomass Alliance for Logistics Efficiency and Specifications (BALES) project (Comer, 2017) and DOE-sponsored "Growing Bioeconomy Markets: Farm-to-Fuel in Southside Virginia" project.(DOE.,2017).were utilized to measure the variation in two-pass corn stover and switchgrass .The variation in three-pass corn stover was estimated by normalizing the two-pass corn stover data by applying actual baling rate during three-pass corn stover baling.
c: Assumed based on observed variation during storage
d: Bale load time variation is measured from variation of bale loads by Stinger ALSS (STINGER,2015).
e: Variation is measured based on empirical data from DOE funded integrated landscape design project (Roni et al., 2018).
f: INL PDU data and Forest Concepts data were utilized to measure the variation in throughput and energy consumption under base case process conditions (e.g. moisture, screen size) for corn stover
g: Assumptions based on anecdotal experimental variations
h: Assumptions based on expected variations

measurable effects on the uncertainty in delivered feedstock price included storage dry matter loss, interest rate, air classification dry matter loss and bale density. Uncertainties in interest rate, led to delivered cost ranges of -$1.58/dry ton to +$1.53/dry ton.

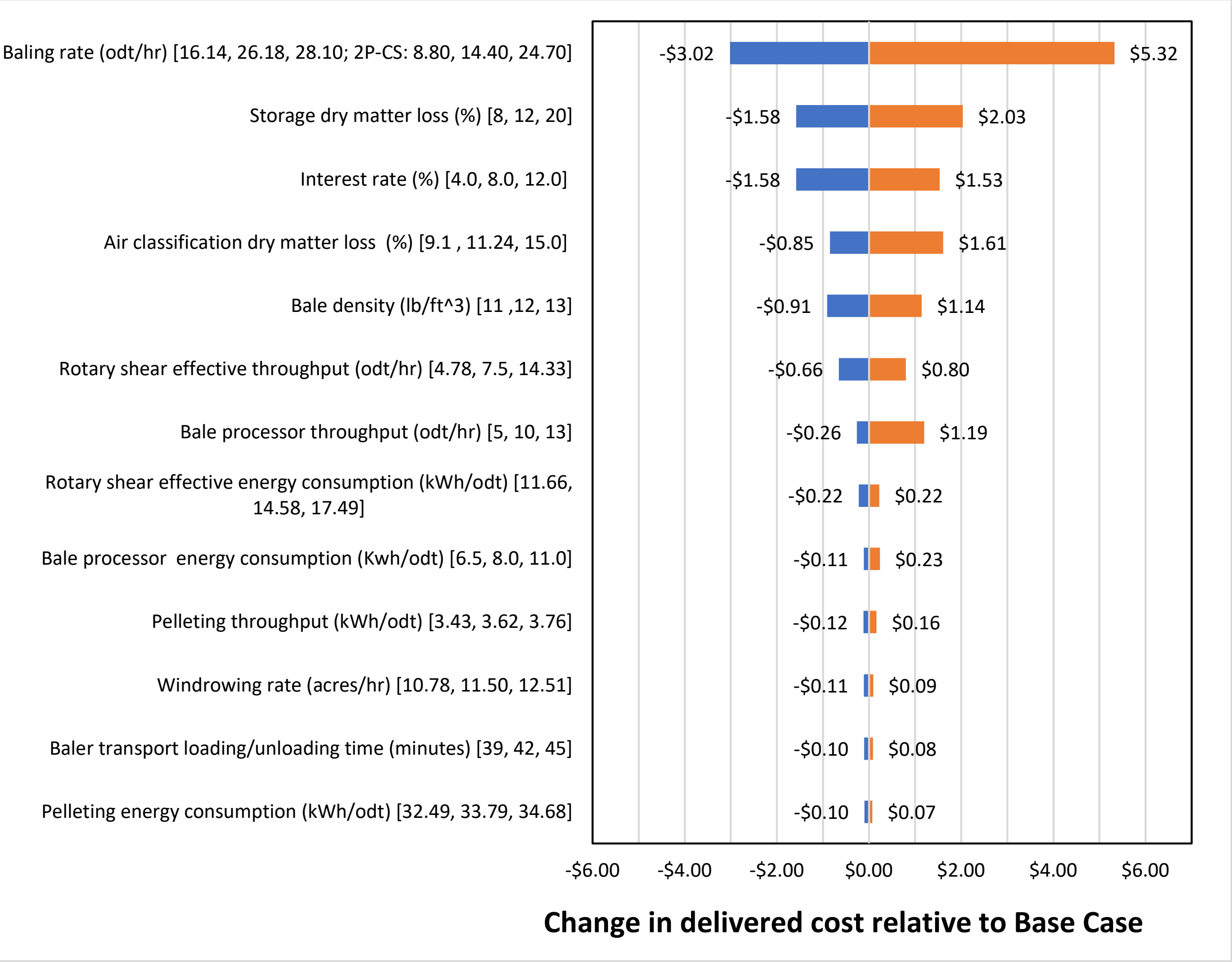

Figure 4. *Tornado chart showing sensitivity of cost to individual operational parameters used to model the 2021 nth-plant Herbaceous SOT Design. Values in the parenthesis represent the minimum, SOT and maximum value of each parameter for the different biomass sources.*

2.3 2021 1st-Plant Herbaceous Feedstock SOT Analysis

2.3.1 Operational Efficiency Analysis and Approach

The properties of agricultural residues, herbaceous energy crops, and woody biomass resources including moisture, ash, convertible organic content, and aging (i.e., loss of dry matter and cell wall structural integrity due to microbial degradation over time in storage prior to reaching the biorefinery) have been shown to vary significantly over time following harvest. These changes lead to significant differences in friability, compressibility, surface properties, elasticity, shear strength and other properties that can greatly impact how biomass handles and physically and chemically deconstructs in preprocessing and conversion equipment. In preprocessing equipment, these impacts lead to dynamic throughputs that are too low to meet the minimum daily capacity (dry tons/day preprocessed) needed to continuously supply the infeed to the conversion process. Very high moisture levels can lead to unexpected failures of preprocessing equipment due to clogging and plugging, resulting in unplanned downtime (zero throughput). High ash contents lead to higher rates of erosive and abrasive wear of equipment, thus requiring additional unplanned downtime for frequent replacement of hammers and knives in grinders. On the conversion side, variation of convertible organics composition and of particle size distribution resulting from differing moisture content and aging of the biomass impact conversion performance. Once fed to the conversion process, these additional (and unexpected) forms of variability can have significant impacts to actual throughput, rates, titers and yields of products, and thus to the profitability of the biorefinery. Additional downtime in the downstream conversion process can be caused by aged biomass due to higher generation of fines in preprocessing during size reduction, leading to failures of feeding equipment and reduced downstream yields.

A traditional nth-plant design assumes a fixed average feedstock quality (moisture, ash, composition) together with experimentally determined average rates, titers and yields of products to develop steady state process simulations. An on-stream time lower than the full calendar year is generally assumed to account for routine maintenance (for example, 90% on-stream, or 328 days/year, 24 hours/day). Process simulations deterministically estimate average plant throughputs of feedstock, intermediates and products, and thereby equipment size requirements and capital costs (CAPEX), and the average energy and chemical usage are estimated to determine operational costs (OPEX). For nth-plant designs, both the CAPEX (i.e., plant size) and OPEX are allowed to vary to define the “optimal” design, and sensitivity analysis is performed within the expected bounds of uncertainty around key parameters, to understand the variation in plant size requirements that would occur within the bounds of known variability. In contrast, a significant issue with 1st-plant designs especially for biomass conversion, is that they are often developed from incomplete or missing data on the expected operational impacts of physical properties of the feedstock on the plant equipment. Additionally, feedstock preprocessing is rarely piloted in an integrated fashion with the conversion process. Commercial handling, grinding and feeding equipment designed for different types of biomass (i.e. woody materials) are commonly assumed to perform similarly regardless of the biomass feedstock type. Hence, there is substantial need for analysis to predict *dynamic* plant throughput and operational efficiency outcomes to achieve nth-plant design capacities and economics.

2.3.1.1 Simulation Approach and Assumptions

To conduct the throughput analyses performed for this report, Discrete Event Simulation (DES) was employed from the entry to long term satellite storage through to the conversion reactor throat to model the interactions of satellite storage and preprocessing equipment throughput and performance. The discrete event model begins with the introduction of one dry ton of feedstock (2,000 dry lb) into satellite storage. The anatomical fractions contained within the bale were generated stochastically based on Shinners (2007), while the moisture content and extrinsic ash were sampled from distributions developed from various INL and public data sources. The C_6 and C_5 sugar contents and intrinsic ash contents were assigned to the anatomical fractions based on Garlock et al. (2009). Distributions of the moisture, ash, glucan, xylan and lignin contents exiting storage that would be available throughout the year of operation were generated assuming the dry matter losses utilized in the nth-plant 2020 Herbaceous Feedstock SOT (Lin et al. 2020). For all three storage scenarios utilized in that analysis, losses of specific components as percentages of total dry matter lost were assumed to be in ratios derived from Garlock et al. (2009) and described in Appendix A.

Failure modes and the resulting down times for at-scale preprocessing equipment were derived from operational experience with the equipment and described in Hartley et al. (2020). For dynamic throughputs greater than zero, regression models describing throughputs, energy consumption, particle size distributions and compositional impacts as functions of feedstock attributes (moisture and ash) were developed for each individual piece of equipment based on historical data collected in the INL PDU. The regression models were used as instantaneous functions to predict impacts for each equipment or subsystem sequentially, based on a mass step moving through that equipment or subsystem.

2.3.2 Throughput Analysis

The nth-plant preprocessing system consists of 4 processing lines that process three-pass corn stover. The nameplate biorefinery design capacity of each of the four lines is 551.25 dry tons/day (22.97 dry tons/hr), totaling 2,205 dry tons/day for the system. During FY18, through discussions with the Industry Advisory Board for the Feedstock-Conversion Interface Consortium (FCIC) we learned that a common practice in industry is to set nameplate biorefinery design capacity at the value necessary to be profitable, but to size plant equipment at a higher capacity to account for unexpected operational issues. Hence, for this analysis we sized the preprocessing lines for 25 dry tons/hr (about 9% higher throughput capacity).

2.3.2.1 Daily Production

The modeled mean daily production of the preprocessing system, shown in Figure 5, was approximately 2,044 dry tons of material per day or 92.7% of the daily nameplate capacity. The daily production varied over the course of the year, ranging from 848.1 dry tons/day (38.5% of the daily nameplate capacity) to 2,338 dry tons (106% of the daily nameplate capacity), with an overall standard deviation of 324.7 dry tons (14.7% of the daily nameplate capacity).

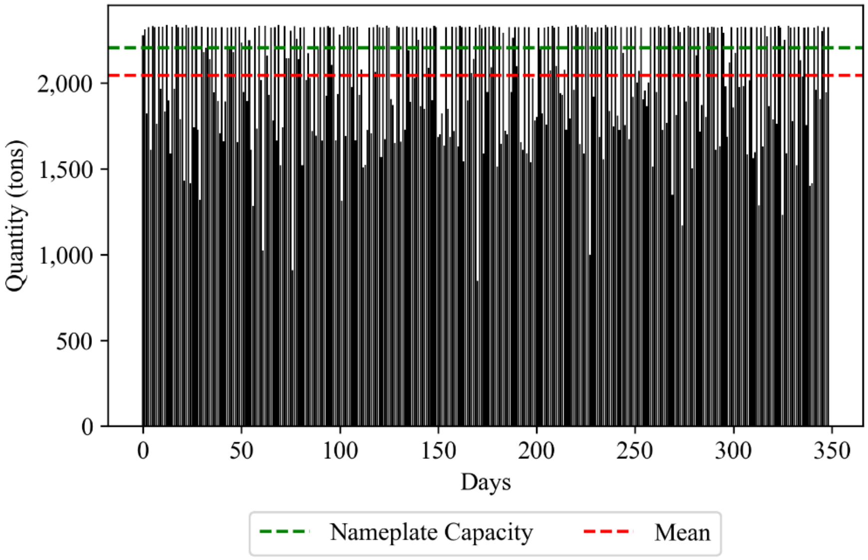

Figure 5. *Daily output of the simulated preprocessing system. The green line indicates the daily nameplate biorefinery design capacity, while the red line indicates the mean daily production rate for the year.*

In the 2021 SOT we aligned to the 90% time on-stream assumptions used in the nth-plant feedstock and conversion SOTs represented in the annual BETO Multi-Year Plan and State of Technology Report, leading to an annual nameplate capacity of 725,000 dry tons/year. A result of this is that if the modeled time on-stream exceeded the assumed 90% time on-stream, the average annual throughput capacity factor $F_{f,P}$ can exceed 100% if the daily throughput is high throughout the year—even if it does not exceed the daily nameplate capacity on any day during the year (this is also due to the oversizing of the equipment). The modeled time on-stream for the preprocessing system in the 2021 OOE SOT for low-temperature conversion feedstock supply was 87.64%, however, the average daily throughput was not high enough to lead to an annual throughput capacity factor (annual tons processed divided by the nameplate capacity) greater than 100%, with the modeled annual throughput capacity factor $F_{f,P} = 0.9833$ (98.33% of the annual nameplate capacity). While this did not occur this year, it is important to note that as the achievable daily throughput increases in future OOE SOTs due to technology improvements, the possibility exists that the annual throughput capacity factor may exceed 100% in the future.

2.3.3.2 Shutdowns (Time Off-stream)

During the simulation, equipment failures were tracked to compare the relative impacts of individual pieces of equipment on downtime. For the system, ash-related wear dominated both total failures and total downtime (Table 8). From a unit operation perspective, the rotary shear accounted for approximately 60.33% of the down events, and 78.57% of the total downtime. The equipment that had the second highest occurrence of down events was the destringer with 24.47% of the total down events, however these events accounted for only 0.094% of the downtime. The failures in the rotary shear are largely caused by increased wear due to the ash content of the feedstocks. In addition, ash has the largest impact on the operation of the bale processor, with 10.5% of the down events and 13.12% of the down time.

Table 8. *Modeled failures, downtime and time on-stream for the 1st-plant analysis. In the labels, "Regular" refers to downtime caused by manufacturer-specified mean time to failure (the expected time between recommended maintenance).*

	2021 SOT
Total Failures	**948**
Moisture Failures (% of Total)	0%
Ash (Wear) Failures (% of Total)	70.04%
Regular Failures (% of Total)	29.06%
Total Operating Time (350 days) (min)	**504,000**
Total Downtime (min)	**62,234**
Moisture Downtime (% of Total)	0%
Ash (Wear) Downtime (% of Total)	91.28%
Regular Downtime (% of Total)	8.720%
Actual time-onstream (350 days) (%)	**87.65%**
Actual time-onstream (365 days) (%)	**84.05%**

Historically, moisture has been the largest cause of downtimes in the Herbaceous 1st-plant SOTs, as it affects both comminution and destringing. Last year we incorporated additional data from WBS 1.2.1.1 on storage practices that make it unlikely that bales over 35% would be introduced into storage; that change, in addition to the improved performance of the storage system, led to a lower average moisture content and there being no failures in comminution. Additionally, the reduced moisture led to maintaining bale integrity and reduced the failure rate of the destringer.

2.3.3 Quality and Cost Analysis

2.3.3.1 Cost Assumptions

For the quality and cost analysis, we utilized the nth-plant modeled cost estimates and underlying cost assumptions from the 2021 nth-plant Herbaceous Feedstock Analysis (section 2.2 above). That analysis was for three-pass corn stover bales delivered to two optimally-sited distributed depots, preprocessed into pellets and delivered to the biorefinery. Costs for areas other than preprocessing were not adjusted for the small operational differences as they represent the best cost estimates that we currently have. Note that the assumptions leading to the cost/dry ton basis information were converted before use from a cost per ton basis to a cost per minute basis for the dynamic analysis.

Additionally, we sized the preprocessing lines in a manner utilized in industry to better approximate engineering design and equipment sizing practices. Hence, for the preprocessing the equipment was scaled to represent the larger preprocessing system modeled here. The cost estimates in nth-plant represent equipment with a design capacity of 22.97 dry tons/hr. To adequately and accurately represent the rated maximum capacity of 25 tons/hr that is needed for this model the costs of the processing equipment were scaled using the following equation:

$$New\ cost = Previous\ Cost\left(\frac{New\ Capacity}{Old\ Capacity}\right)^{0.6}$$

2.3.3.2 Annual Units Meeting both Cost and Quality Requirements

Supply Logistics

Due to the moisture content of material as it enters storage, there is a dry matter loss that occurs, resulting in there being less material able to come out of storage than went in. As a result, the throughput factor ($F_{f,S}$) for supply logistics is less than 1. From the simulation there was an average of 10.11% dry matter loss in storage (1.23 percentage points higher than the 8.88% average storage dry matter loss in the nth-plant case), resulting in a supply logistics throughput factor of 0.8989. The total carbohydrate specification at the biorefinery gate, adjusted for losses in preprocessing, was ≥ 58.77 wt% (dry basis). Coming out of storage, 25.17% of the three-pass corn stover material met the conversion requirements for composition. The quality performance factor (tons delivered to the biorefinery gate meeting quality divided by the total tons delivered to the biorefinery gate) for the combined biomass from Supply Logistics is 25.17% of the material meeting the quality requirements, resulting in a feedstock quality performance factor ($F_{B,S}$) of 0.2517.

Preprocessing

In the preprocessing system the cost of an aliquot of material exiting the system is dependent on the amount of time that the aliquot resides in the preprocessing system. If the dynamic throughput of a given unit operation were to decrease or if the unit operation failed completely, the cost for all aliquots of material in the system will increase. Hence, variable throughput makes the costs become more variable, and the mean cost increases. Figure 6 shows the cost distribution of preprocessed feedstock units that leave the preprocessing system over the course of a year of operation, without consideration of quality. Just considering the production cost, the average cost is $79.18/dry ton (1.2% higher than the $78.21/dry ton delivered feedstock cost in the nth-plant case). The stochastic cost ranged from a minimum of $67.91/dry ton to a maximum of $1,025/dry ton, with a standard deviation of $29.02/dry ton. Under this scenario, 644,206 tons of feedstock (88.9% of the nameplate capacity) were simulated to be delivered at a cost of less than $86/dry ton.

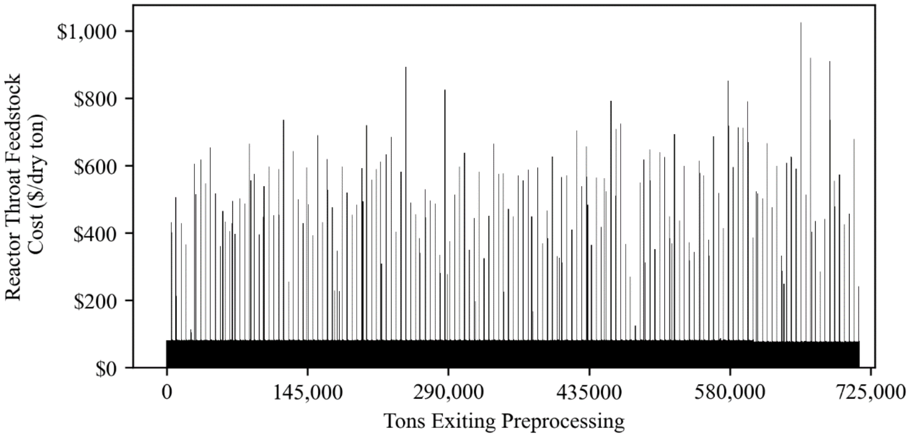

Figure 6. *Cost per ton for material exiting preprocessing.*

During the processing of biomass, inevitably material is lost from the system either from dry matter losses such as in grinders or from discarded material (from the air classifier) that has properties that lead to failures. When these losses are accounted for the costs increase to an average of $82.34/dry ton (5.3% higher than the $78.21/dry ton delivered feedstock cost in the nth-plant case) with a minimum of $72.24/dry ton, a maximum of $1,045.56 and a standard deviation of $29.71/dry ton (Figure 7). This highlights the importance of being able to find additional markets for off-spec material that is separated out to improve the quality of the delivered feedstock.

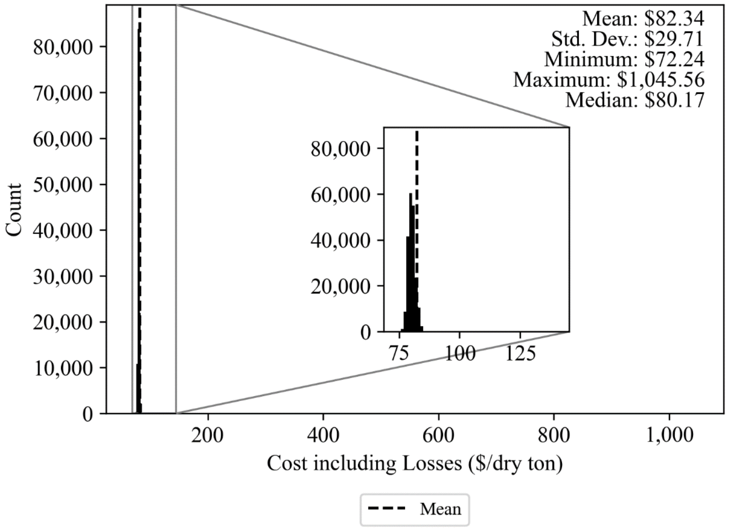

Figure 7. *Distribution of cost when considering system dry matter losses.*

The yield potential (quality) of the material that leaves preprocessing is critical to the performance of the conversion process, and directly affects the quality performance factor $F_{f,B}$. The requirements of the feedstock entering conversion that directly impact conversion yield are a total sugar content $\geq$ 59 wt%. The modeled distribution of total sugar content of the corn stover is shown in Figure 8. It is evident that most sugar contents were greater than the minimum threshold of 59 wt%, with 74.7% of the feedstock meeting the minimum carbohydrate requirement. This resulted in preprocessing performance factor ($F_{B,P}$) of 0.7470. Of the tons meeting or exceeding the threshold, 67.66% of the material met or exceeded the exiting n^{th}-plant value of 60.16 wt% total carbohydrates.

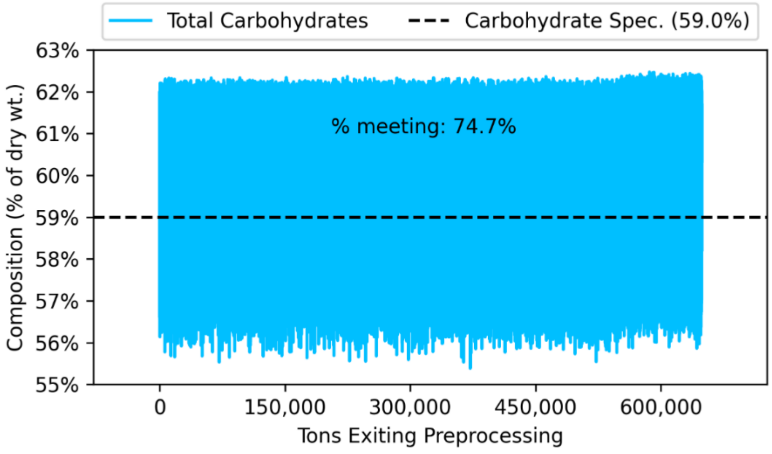

Figure 8. *Distribution of total sugar content of delivered feedstock leaving preprocessing.*

When costs are fully burdened for the system disruptions, material lost during operation, as well as material removed for not meeting the required quality specifications; the average cost per ton is $110.28/dry ton (41% higher than the $78.21/dry ton delivered feedstock cost in the nth-plant case), with a minimum cost of $100.25/dry ton, a maximum cost of $997.86/dry ton and a standard deviation of $29.71 (Figure 9). Hence, of the factors increasing the production cost in preprocessing (operational impacts such as downtime, dry matter losses in the preprocessing system and yield potential below the conversion requirement), once moisture impacts are minimized the highest impacting factor becomes compositional variability. This variability arises from inherent varietal differences in corn stover as well as harvest method, harvest location, weather conditions during harvest and to uneven degradation during storage. Finally, it can also be seen that the maximum per ton cost observed was reduced when low quality material is removed; this occurred because the highest cost tons also did not meet quality and thus the cost was distributed to all the units that met the quality requirements.

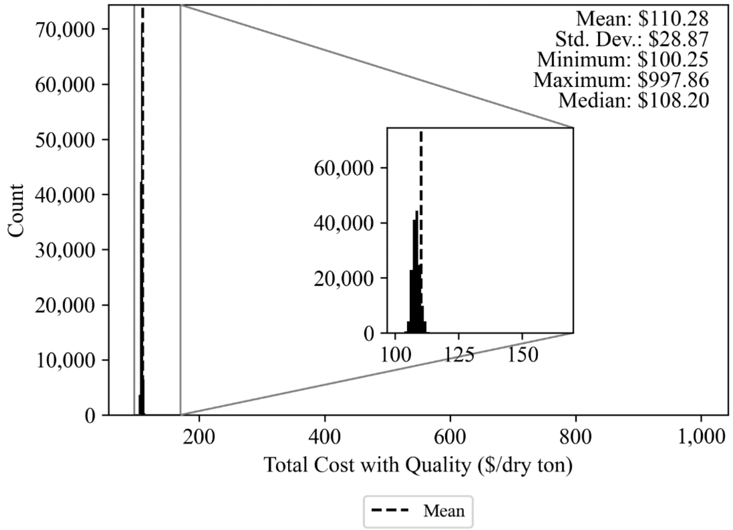

Figure 9. *Distribution of cost when considering losses of material due to not meeting the minimum carbohydrate content quality specification.*

2.3.4 Overall Operating Effectiveness for the 2021 Herbaceous SOT

The results of this analysis indicate modeled Supply Logistics throughput capacity utilization factor and quality performance factors of 0.8989 and 0.2571, respectively and for Preprocessing they were found to be 0.9833 and 0.7470 respectively. These values lead to overall operating effectiveness values for the feedstock subsystems as shown below:

$$Supply\ Logistics: \qquad OOE_S = F_{f,S} \times F_{B,S} = 0.8989 \times 0.2571 = 0.2311\ (23.11\%)$$

$$Preprocessing: \qquad OOE_P = F_{f,P} \times F_{B,P} = 0.9833 \times 0.7470 = 0.7345\ (73.45\%)$$

From an overall system perspective for harvest through to the conversion reactor throat, it is clear from this analysis that the highest impacting R&D areas, once moisture variability is minimized, encompass the development of improved harvesting methods that minimize soil contamination (or conversely, fractionation methods to effectively remove extrinsic ash), improved storage practices and fractionation method development for anatomical fractions. It will be difficult to reduce the intrinsic compositional variability that exists among different varieties of corn stover due in part to differences in the physical characteristics of the plants themselves, such as in differing ratios of tissue fractions. Anatomical fractionation followed by reformulation of the fractions into feedstocks meeting conversion specifications offers a pathway to accomplish this. It is important to note that sensors capable of measuring carbohydrate and ash on a moving conveyor on the fly will be critical to develop this strategy effectively.

3. INDUSTRIAL RELEVANCE OF THREE-PASS CORN STOVER

The availability of a biomass resource is not static, nor does it have a single definition. For the purposes of this report, availability is defined as the quantity of biomass materials that can be mobilized into the supply chain at a price that meets current cost targets. More specifically, resource availability assumed in this report is the quantity of three-pass pass corn stover that can be purchased at average grower payments of $21.71/dry ton. The current availability of three-pass corn stover was determined through use of the *n*th*-Supply* analysis that was performed jointly by INL and ORNL in FY20 and published by Hossain et al. (2021), which presents projections based on expectations of how the market will develop based on sustained investment and technology improvement. In the nth-plant analysis it was estimated that there were 144 million dry tons of corn stover available nationally, with 20.8 million dry tons of corn stover within the 50 counties surrounding the study area. The region of interest for the 2021 herbaceous SOT remains the same as the 2020 SOT, with the assumed biorefinery location in Sheridan County, KS. Northwest Kansas was chosen to demonstrate the barriers and cost of operating outside the niche, high-yield areas, which are more representative of yield conditions encountered when operating a national-scale bioenergy industry. However, the feedstock properties that are important to the conversion process, (i.e., ash, moisture, and carbohydrate content) were conservatively assumed to maintain applicability of the supply chain operations at a national scale.

4. SUMMARY

The Feedstock Technologies platform within BETO focuses on (1) reducing the delivered cost of sustainably produced biomass; (2) preserving and improving the physical and chemical quality parameters of harvested biomass to meet the individual needs of biorefineries and other biomass users; and (3) expanding the quantity of feedstock materials accessible to the bioenergy industry. To support BETO and its bioenergy production goals, INL completes annual SOT reports for herbaceous and woody biomass feedstock logistics. This report provides the status of technology development of feedstock logistics for herbaceous biomass to biofuels utilizing experiment-based data and results and provides a relative comparison to technical targets and costs goals from design cases.

Although CFSS forms the backbone of the emerging biofuels industry, they have limitations that restrict widespread implementation on a national scale. To meet the demands of the future industry, the feedstock supply system must shift from the conventional system to what has been termed "advanced" supply systems. In advanced designs, a distributed network of aggregation and processing centers, termed "depots," are employed near the points of biomass production (i.e., the field or forest) to reduce feedstock variability and produce feedstocks of a uniform format, moving toward biomass commoditization. The 2021 Herbaceous SOT is part of a longer-term vision of achieving an implemented advanced feedstock supply system, which produces a stable, tradable commodity at the decentralized distributed depot.

The 2021 Herbaceous SOT incorporates an advanced biomass fractionation technology to remove extrinsic ash and fractions with high ash content. By integrating this technology, we have reduced ash content of three-pass corn stover from 11.20% to 6.00%, and increased carbohydrate content from 56.80% to 60.16%. This technical improvement has allowed us to remove two-pass corn stover from the biomass supply curve. Because the biomass availability of three-pass corn stover is about two times higher than two-pass corn stover, eliminating the need of using two-pass corn stover increase resource availability and reduced transportation costs. Using three-pass corn stover also largely reducing the harvesting, collection and storage cost within the feedstock logistics system. In addition, the second stage hammer mill was replaced with rotary shear, which is less sensitive to moisture content than hammer milling and has higher throughput with lower energy consumption. The reduced energy consumption has also contributed to the modeled cost reduction. The 2021 nth-plant Herbaceous SOT predicts a modeled delivered feedstock cost of $78.21/dry ton (2016$), this is a $0.57/dry ton (2016$) decrease from the 2020 Herbaceous SOT *nth-Supply* case cost. Technology improvements that contributed to this modeled cost reduction include reduced cost in the feedstock harvesting, collection and transportation cost caused by eliminating two-pass corn stover, and reduced energy consumption cost by replacing hammer mill with rotary shear. A preliminary GHG assessment was completed by scaling the 2020 Herbaceous nth-plant GHG data from the 2020 GREET model a decrease of 9.77 kg

CO_2e/ton from the 2020 SOT (77.48 kg CO_2e/ton in the 2020 Herbaceous Feedstock SOT to 67.71 kg CO_2e/ton in the 2020 Herbaceous Feedstock SOT). This net reduction is attributed to reduced transportation distances for biomass delivery from field to depot, and reduced energy consumption by using rotary shear.

In the 1st-plant analysis of the 2021 Herbaceous SOT system, the average throughput was 2,044 dry tons/day or 92.7% of the name plate capacity. During the simulation the daily throughput ranged from 848.1 dry tons/day to 2,338 dry tons/day, which equates to 38.5% to 106% of the daily nameplate capacity. After the year of operation 715,400 tons (98.3% of the annual nameplate capacity) of preprocessed feedstock were produced; the variability in throughput was primarily caused by equipment failures in the system. Failures due to wear were the largest cause of disruption within the system, accounting for 70.0% of the failures and 91.3% of the total downtime. Previously, moisture related failures were the cause of the majority of downtime, but new storage strategies and equipment (bale dryer for the first 25% of stover harvested) data from the Biomass Storage project (WBS 1.2.1.1) led to the elimination of moisture related downtime. Ultimately the system on-stream time was 87.7% during the simulation period. Considering the operational delays and material losses in the system, the average cost per ton of biomass was $82.34/dry ton (2016$), with a range from $72.24/dry ton to $1,045.56/dry ton. When compared to the ideal nth-plant cost, the average cost from the 1st-plant analysis was $4.13/dry ton greater than the nth-plant estimate. However, approximately 7% of the tons of material were preprocessed in the system at a cost of less than the nth-plant cost of $78.21/dry ton. While the nth-plant analysis assumes a constant quality feedstock, the 1st-plant analysis utilizes variability in the material to assess the impact. In the 1st-plant analysis, it was assumed that any material that does not meet the minimum conversion quality specification of 59 wt% of total carbohydrate is discarded. From this simulation, 74.7% of the preprocessed material met or exceeded the minimum quality specification, requiring the disposal of 25.3% of the biomass. The material that is discarded due to quality, represents an additional cost that must be accounted for in the total cost of the material. When accounting for quality the average delivered cost of the material increased to $110.28/dry ton, ranging from $100.25 to $997.86. The resulting Overall Operating Effectiveness (OOE) for the system, from the simulation, was found to be 73.45%. A feedstock performance factor of 74.7% and a fully burdened cost that is $32.07/dry ton higher than the estimated nth-plant cost suggest that additional technology development is needed to further address the variability of quality within the feedstock to attain an OOE of 90% and cost parity with the nth-plant analysis.

From an overall system perspective for harvest through to the conversion reactor throat, it is clear from this analysis that the highest impacting R&D areas, once moisture variability is minimized, encompass the development of improved harvesting methods that minimize soil contamination (or conversely, fractionation methods to effectively remove extrinsic ash), improved storage practices and fractionation method development for anatomical fractions. It will be difficult to reduce the intrinsic compositional variability that exists among different varieties of corn stover due to in part to differences in the physical characteristics of the plants themselves, such as in differing ratios of tissue fractions. Anatomical fractionation followed by reformulation of the fractions into feedstocks meeting conversion specifications offers a pathway to accomplish this. It is important to note that sensors capable of measuring carbohydrate and ash on a moving conveyor on the fly will be critical to develop this strategy effectively.

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APPENDIX A – 2021 Herbaceous State of Technology Feedstocks Logistics Design and Assumptions

The 2021 Herbaceous SOT provides an annual herbaceous feedstock supply to a biorefinery located in Sheridan County, Kansas (northwestern Kansas) consisting of 725,000 dry tons of 100% three-pass stover. The 2021 Herbaceous SOT incorporates two depots (identified as Nodes 6 and 7 in Figure 2 and Table 3 of the main document, and Figure A-1 in this appendix).

The 2021 Herbaceous SOT couples feedstock logistics with resource availability, reflected as grower payment, to estimate the delivered feedstock cost required to supply the biorefinery. The design is located in an area of relatively low biomass productivity, consistent with the 2013-2020 Herbaceous SOTs, to conservatively include the barriers and cost implications for meeting national targets for a national scale biorefinery industry. When biomass must be sourced in locations where there is insufficient biomass supply at the specified quality but there is also a diversity of biomass types available, blending options become available to assist in meeting conversion quality specifications. In the 2021 SOT, fractionation was used to improve the quality of three-pass corn stover so that blending with higher quality (but higher cost) two-pass corn stover was not necessary as a blendstock. Grower payments were calculated from farm gate prices by subtracting modeled harvest and collection costs and scaling to the appropriate year. The three-pass corn stover harvest and collection method modeled in this analysis is consistent with those used in conventional systems referred to as “multi-pass harvesting systems”. The three-pass stover are harvested, collected, and then stored field-side (tarped) until being transported by truck to the main depot in bales.

The modeled supply chain for the 2021 Herbaceous SOT utilizes depots to produce pelleted feedstock for delivery to the biorefinery (see Table 3 and Figure A-1). The baled biomass delivered from road-side storage at the farm gates of the supplying counties is size reduced using a bale processor, air classified to remove soil and a small fraction of organic matter as leaves, milled using fractional milling, densified using high moisture pelleting, and then cooled and placed into temporary depot storage until shipping to the biorefinery when needed. Pellets shipped from these depots to the biorefinery are placed into silos when received and held there until metering to the reactor throat.

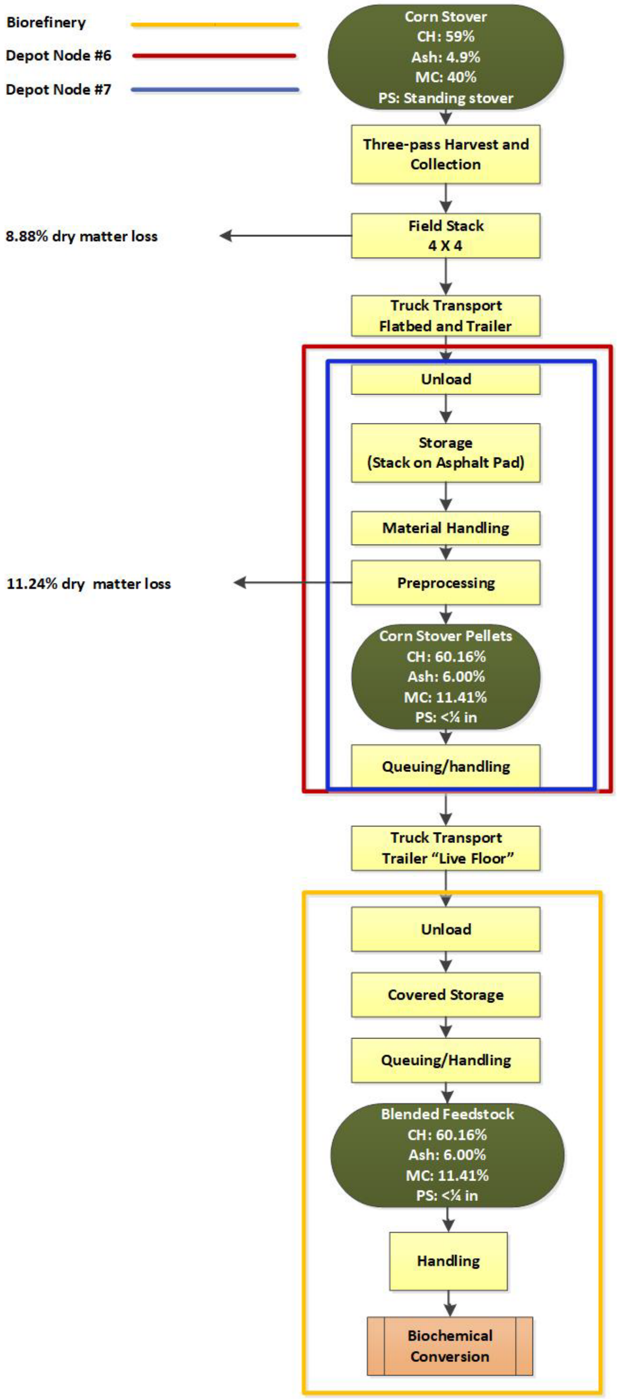

Figure A-1. *The modeled 2021 Herbaceous SOT feedstock supply system. CH=Carbohydrate content, MC = moisture content, PS=Particle size. Depots are identified as nodes 6 and 7. Optimal locations and sizes of these nodes are listed in Figure 2 and Table 3 of the main body of this report.*

Resource Availability

The geographic area chosen for the 2021 Herbaceous SOT is northwestern Kansas, with the biorefinery located in Sheridan County. It was assumed that all corn stover and switchgrass biomass as identified in the BT16 report located in Kansas, Nebraska and Colorado would be potentially available to meet the demand of 725,000 dry tons delivered to the pretreatment reactor throat at the biorefinery. The available corn stover was estimated based on the same supply curve that was developed in the 2020 Herbaceous n^{th}*-Supply* SOT (Lin et al., 2020). Corn stover availability in BT16 is representative of conventional three-pass harvesting. We assumed that three-pass harvesting could also be utilized in both high-yielding (stover yields ≥ 2.0 tons/acre) and low-yielding areas.

Process Design and Cost Estimation Details

In this section, the costs of different supply chain operations are described along with key assumptions and input parameters.

A.1 Interest Rate and Energy Cost Assumptions

The 2021 Herbaceous SOT uses the same interest rate and energy cost assumptions used for the 2020 Herbaceous SOT as shown in Table A-1.

Table A-1. *Energy prices and interest rates used to model herbaceous feedstock logistics costs for the 2021 Herbaceous SOT.*

Component	2020 Assumptions	2021 Assumptions
Interest Rate	8%[a]	8%[a]
Electricity Price	\$0.0672/kWh[b]	\$0.0672/kWh[b]
Natural Gas Price	\$3.36/MMBtu[b]	\$3.36/MMBtu[b]
Off-Road Diesel Price	\$2.011/gal[b]	\$2.011/gal[b]

a See Jones et al. (2013)
b See EIA (2018). Updated from the 2018 Herbaceous SOT using the Producer Price Index

A.2 Harvest and Collection

The optimized 2021 Herbaceous SOT design utilizes only three-pass corn stover biomass. Corn stover harvest is assumed to be available via two different harvesting methods, three-pass (conventional) harvesting and two-pass harvesting (advanced). Conventional three-pass harvesting has the advantage of high yield, but the disadvantage of low quality with respect to carbohydrates (lower) and ash (higher). Conventional three-pass systems involve cutting the feedstock, collecting the material into a windrow, and then baling the windrowed material (Figure A-2).

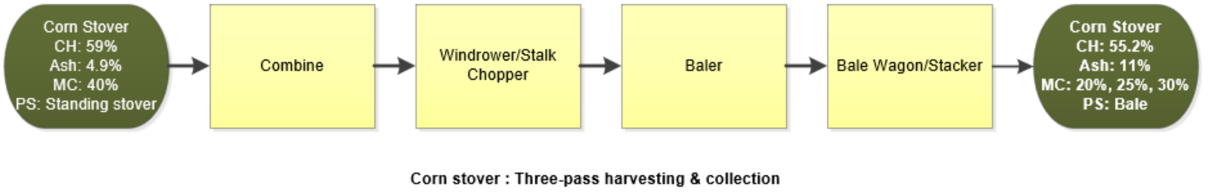

Figure A-2. *The 2021 Herbaceous SOT harvest and collection operations for corn stover. It is assumed that prior to baling there is some amount of field drying such that 50% of the total biomass will reach 25% moisture, 25% of the biomass will reach 20% moisture, and the remaining 25% of the biomass will reach 30% moisture. CH=Carbohydrate content, MC = moisture content, and PS=Particle size.*

Table A-2 summarizes the harvest and collection design assumptions for the 2021 Herbaceous SOT. The assumed yield, capacity, and efficiency of harvest and collections equipment, moisture content, and ash content were estimated based on published data (Anderson et al. 2013, Lindsey et al. 2013, Bonner et al. 2014, DOE 2016b, Owens et al. 2016), data from field trials (Smith et al. 2012, Smith et al. 2014, Brue et al. 2015), data taken from the INL Bioenergy Feedstock Library (INL 2016), and from personal communications[1,2].

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[1] Personal communication from Magen E. Shedden, a researcher at Oak Ridge National Laboratory (ORNL)

[2] Personal communication from William Smith, INL researcher

Table A-2 *Harvest and collection design assumptions in the 2021 Herbaceous SOT for three-pass corn stover.*

Component	Corn stover Three-Pass Harvest
Harvest time	
Operational hours	6 weeks/year, 6 days/week, 14 hours/day
Combine	
Capacity	41 tons/hour
Field efficiency	70%
Collection efficiency	43%
Stalk chopping windrower	
Capacity	11.5 acres/hour
Efficiency	80%
Bale wagon/stacker	
Capacity	12 bales/load
Baler	
Capacity	50 bales/hour
Harvest yield	
Harvest yield	1.2 tons/acre

A.3 Storage

The 2021 Herbaceous SOT incorporates an actively managed storage system comprised of a combination of best management practices and “farm-scale technologies” such as enhanced in-storage drying to achieve storage stability objectives. Storage research (WBS 1.2.1.1) evaluated modeled operational performance of actively managed storage systems. This actively storage managed storage consists of a microbial self-heating and advective flow system, supplied by a commercial grain dryer blower. Experimental results from the bale dryer (Fig. A-3 in the main document) show that a single bale can be dried from 30% moisture to <20% in two to four days, which implies that a stack that is 12 bales in length could be dried in 30 days. Drying experiments (Smith and Plummer, 2020) performed in INL’s storage simulators showed that stover can be dried from 30% to 20% moisture at a range of flow rates and incur dry matter losses of 5% or less. The primary factors that drive biological dry matter loss are moisture content of the biomass entering storage, the temperature and relative humidity as a function of time, oxygen availability, pH, and the presence of inhibitory compounds in the biomass extractives component.

Figure A-3. *Bale dryer/bale permeameter fabricated and used by INL to measure drying, internal temperatures, and moisture loss in whole bales. Air flow is from the right to the left in the photograph. The instrumentation on the right records the temperature and relative humidity of the air entering and exiting the bale, the internal bale temperatures, and the pressure drop across the bale. The instruments on the left periodically sample the inlet and outlet gases and measure CO2, water vapor, and gas tracer (SF_6), which is metered in from the silver bag at bottom right.*

As the actively managed storage system only applies to the early harvested high moisture biomass, the 2021 Herbaceous SOT assumes that the moisture content of biomass prior to storage is distributed as follows: 25% of the biomass has 30% initial moisture (early harvested bales), 50% of the biomass has 25% initial moisture (bales harvested during the middle 50% of the harvest window), and the remaining 25% of the biomass has 20% initial moisture (late harvested bales). In the 2021 Herbaceous SOT, the dry matter losses are partitioned to individual corn stover components using the average observed losses of individual corn stover components during 3-month storage tests (Wendt et al. 2013) in the INL storage simulators at initial moisture contents ranging from 20-52%. Tables A-3 and A-4 summarize dry matter loss and storage design assumptions applied in the 2021 Herbaceous SOT.

Table A-3. *Average distribution of dry matter losses among corn stover components by initial moisture content.*

Biomass moisture content distribution		DML after field storage
% of the total biomass weight	**Initial Moisture content**	
25.00%	20.00%	7.70%
50.00%	25.00%	11.40%
25.00%	30.00%	5.00%[a]

[a] Smith and Plummer, 2020

Table A-4. *Field storage design assumptions for the 2020 Herbaceous SOT.*

Component	Storage TEA parameters 1	Storage TEA parameters 2	Storage TEA parameters 3
Storage moisture content	30%	25%	20%
Storage dry matter loss	5.0%	11.4%	7.7%
Storage moisture loss	10%	5%	0%
Stack configuration	3x12 wrapped stack	4 x 4 tarped	4 x 4 tarped
Dryer Cost Basis[a]	\$3.11/dry ton[b]	-	-
(Dryer model: GSI 5-hp model GGI-80711)			

[a] Dryer is used during daylight only.

[b] Smith and Plummer (2020).

In lieu of experimental data from WBS 1.2.1.1 which were not available at the time of the analysis, we turned to the literature to estimate the relative susceptibilities of the different stover anatomical fractions to microbial degradation during storage. Garlock et al. (2009) conducted a study to identify the corn stover anatomical fractions having the highest sugar yield after ammonia fiber expansion pretreatment and enzymatic hydrolysis. We utilized the extent of release of C_5 and C_6 sugars via enzymatic hydrolysis from their untreated corn stover anatomical fraction controls as a proxy measure of the biodigestibility of the individual tissue fractions while in storage, equating the sum of their glucose and xylose yields from enzymatic hydrolysis to total C_5 and C_6 carbohydrate degradation during long term storage. The sugar enzymatically released from each anatomical fraction was then used to account for differing recalcitrance of the anatomical fractions (Table A-5). Based on the relative digestibility (susceptibility to microbial degradation), the dry matter loss of each anatomical fraction was calculated and normalized by the dry matter loss rates for the different moisture levels listed in Table A-3. Relative biopolymer degradation ratios measured in Wendt et al. (2013) were used to account for uneven degradation

Table A-5. *Relative proxy digestibilities of C_5 and C_6 sugars in late harvested corn stover anatomical fractions (Garlock et al. 2009).*

	Carbohydrate Digestibility
Leaf	33.83%
Stem	16.98%
Husk	32.75%
Cob	18.24%

of cellulose, hemicellulose, lignin and other organic components (Table A-6). The weight percentage and compositions of each corn stover fraction after storage is presented in Table A-7.

Table A-6. *Average distribution of dry matter losses among corn stover components observed in 3-month storage tests in the INL storage simulators at initial moisture contents ranging from 20-52% (Wendt et al. 2013).*

Component	Fraction of Dry Matter Lost (%)
Total C_6	18.46%
Total C_5	28.93%
Lignin	6.45%
Ash	0.00%
Protein	3.00%
Extractives	29.99%
Acetate	13.18%
SUM	100.00%

Table A-7. *Weight fractions of plant tissues and soil in the whole stover and compositions of each corn stover fraction after storage.*

	Percent of whole stover[a]	Composition (wt%, dry basis)				
		C_6	C_5	Physiological ash	Soil	Other
Leaf	19.18%	36.89%	21.13%	6.56%	0.00%	35.42%
Stem	48.87%	40.27%	22.92%	2.71%	0.00%	34.10%
Husk	7.94%	39.69%	26.42%	2.17%	0.00%	31.72%
Cob	14.96%	27.82%	32.42%	1.14%	0.00%	38.62%
Soil	9.05%	0.00%	0.00%	0.00%	100.00%	0.00%

[a] The weight percentages of each anatomical fraction on a soil-free basis were taken from Shinners and Binversie (2007) and adjusted to account for soil content.

A.4 Preprocessing

In the preprocessing system, an EZ Ration Processor was used for the first stage size reduction, which is a horizontal bale processor originally designed for blending cattle feed components such as hay and corn stalks. The design of the 3-rotating-drum de-baling head of the bale processor (Figure A-4) requires lower rpm and energy and eliminates the slugging flow observed in the first stage hammer mill used in SOTs prior to 2019. Moreover, the EZ Ration bale processor can feed two bales at separate feed rates (this feature was originally developed by the manufacturer for the cattle feed blending function). This could be an advantage for blending bales with different moisture contents to mitigate very wet bales, or for blending bales of different biomass types. Pilot-scale testing was performed during FY20 in the Biomass Feedstock User Facility (BFNUF) at INL (WBS 1.2.3.3) to collect the parametric data for preprocessing.

After the first stage size reduction, a key change in the 2021 Herbaceous SOT is the integration of a Spudnik air classifier, which can effectively remove soil contaminants and biomass fractions with high ash content. By including the fractionation system, the ash content of three-pass corn stover can be reduced to 6.00%, with a carbohydrate content at 60.16%.

The 2021 Herbaceous SOT design utilizes high moisture pelleting in corn stover preprocessing. In high moisture pelleting, the biomass is preheated to approximately 110°C for short durations (typically 5 min) prior to pelleting. Depending on the temperature used, preconditioning biomass by preheating it can affect both its chemical composition and its behavior during mechanical densification processes such as pelleting. When these changes impact mechanical properties, thereby changing the way the feedstock responds during densification, the overall quality of the pellets can be improved (Bhattacharya et al. 1989, Tumuluru et al. 2010). Preheating can also increase the throughput of the pellet mill and reduce the energy requirement per kilogram of biomass pellets produced. When the preheat temperature is high enough to impact chemical composition, preheating can also enable production of higher-quality densified products for multiple end-use applications (Aqa et al. 1992, Bhattacharya 1993). Preheating in the presence of moisture can also promote softening of the natural binders in the biomass, including starch, lignin, and protein (Tumuluru 2014). Laboratory experiments performed under INL WBS 1.2.1.2 using flat-die and round-die pellet mills has shown that high durability pellets can be produced at an intermediate moisture content of 33-34% (wet basis), preheating temperatures > 70°C, and die speeds > 50 Hz (Tumuluru 2014).

As in the 2020 Herbaceous SOT, the 2021 Herbaceous SOT eliminates the drying step during preprocessing of corn stover. Pilot-scale testing of high moisture pelleting and cooling performed under INL WBS 1.2.1.2 indicated that the conservative moisture loss assumptions used in 2016 during grinding and pelleting could be increased, which eliminated the need for drying the pelleted biomass. Reduced energy consumption for high moisture pelleting was also observed in the pilot-scale ring die pellet mill tests, as compared to the lab-scale flat die pellet mill values utilized in the 2016 Herbaceous SOT.

Since the 2021 Herbaceous SOT utilizes rotary shear which has an integral orbital screen to return overs to the cutter, there is no biomass bypassed for fractional milling as in 2020. The modified preprocessing line is shown in Figure A-3, fractional milling inserts a screening operation (disk screen) between the first stage and second-stage size reduction operations (the bale processor and rotary shear, respectively) to remove the material that already meets the size specification before the material enters second-stage comminution. This reduces the amount of material that flows through the second-stage comminution, thereby reducing its size (cost) and energy consumption. In addition, fewer fines are produced because the material already meeting the particle size specification is not further size reduced. Hence, a tighter particle size distribution is achieved.

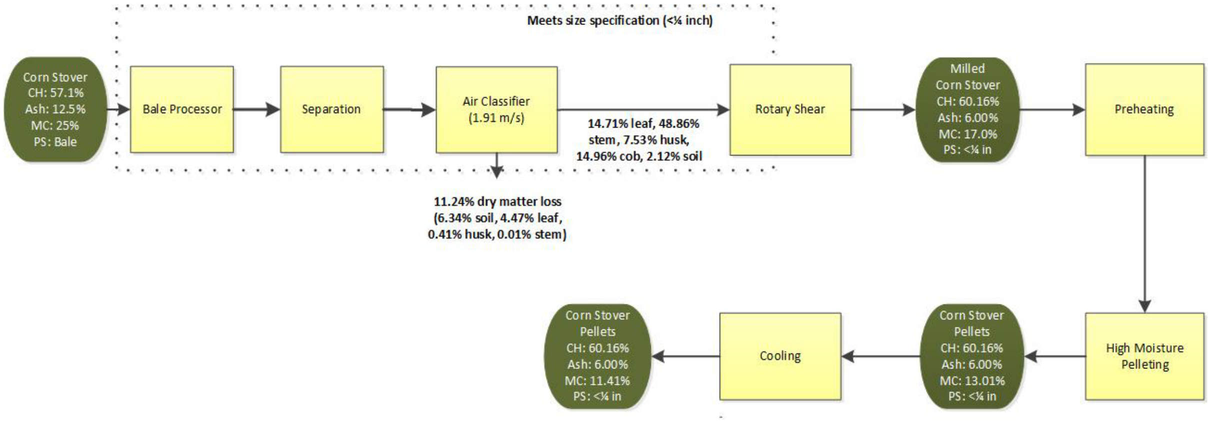

Figure A-3. *2021 Herbaceous SOT preprocessing configurations for corn stover. CH=Carbohydrate content, MC = moisture content, PS = particle size*

Particle size distribution analysis shows that 30% of the corn stover material meets particle size requirements after the first-stage grinder and can bypass the second-stage size reduction, thereby leading to significant savings. Experiments performed in the Biomass Feedstock User Facility (BFNUF) at INL (WBS 1.2.3.3) have shown that 1-2% of feedstock dry matter that arrives at the biorefinery gate is lost as dust during grinding, of which as much as 25% is ash.[3] The organic fraction is generally comprised of fines generated from the leaves, which are thin and brittle and shatter from the hammer impacts during grinding.

Corn stover preprocessing for the 2021 Herbaceous SOT design is shown above in Figure A-3. It is assumed that in the Spudnik air classifier (1.91 m/s), about 25.24% of the total soil contaminants (2.28% of total dry weight) can be removed by the screen, and another 44.85% of the total soil contaminants (4.06% of total dry weight) is removed together with the discarded light weight material, which consists of leaf (4.47% of total dry weight), stem (0.01% of total dry weight), and husk (0.41% of total dry weight). The soil removal was assumed using the results published by Thompson et al. (2016). Input parameters (such as throughput and energy

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[3] Personal communication regarding dust collection during preprocessing from Neal Yancey, INL researcher

consumption) have been updated in Table A-8 for three-pass corn stover, based on pilot-scale results (WBS 1.2.1.2).

Table A-8. *Summary of 2021 Herbaceous SOT preprocessing assumptions.*

Component	Three-Pass Corn Stover
Location of operation	Depot Nodes 6 and 7
Stage 1 size reduction	
Grinder type	Bale processor
Energy (kWh/dry ton)	8
Throughput (dry ton/hour/machine)	10
Operating conditions (moisture %)	20.0%
Spudnik Air Classifier	
Energy (kWh/dry ton)	0.623
Throughput (dry ton/hour/machine)	1.9
Operating conditions (moisture %)	20%
Stage 2 Grinder	
Comminution method	Rotary Shear
Energy (kWh/dry ton)	14.56
Throughput (dry ton/hour/machine)	7.5
Operating conditions (moisture %)	19%
Densifier	
Densifier type	Pellet mill
Energy (kWh/dry ton)	33.79
Throughput (dry ton/hour/machine)	3.625
Operating conditions (moisture %)	17.0%
Pellet density (lb/ft^3)	39.42
Pellet durability	98.70%
Cooler	
Moisture removed	13.11%
Energy (kWh/dry ton)	3.02
Throughput (dry ton/hour/machine)	5

Table A-9 shows percentage of weight and composition of each tissue fraction after all the preprocessing steps. The resulting carbohydrate content for the processed feedstock (containing the retained leaves, husks, stems, cobs and soil) is at 60.16%, with a total ash content of 6.00%.

Table A-9. *Weight percentage and composition of each corn stover fraction after preprocessing.*

	Percent of whole stover	Composition (wt%, dry basis)				
		C_6	C_5	Physiological ash	Soil	Other
Leaf	16.57%	36.89%	21.13%	6.56%	0.00%	35.42%
Stem	55.04%	40.27%	22.92%	2.71%	0.00%	34.10%
Husk	8.48%	39.69%	26.42%	2.17%	0.00%	31.72%
Cob	16.86%	27.82%	32.42%	1.14%	0.00%	38.62%
Soil	3.05%	0.00%	0.00%	0.00%	100.00%	0.00%

A.5 Transportation and Handling

The 2021 Herbaceous SOT incorporates both bale and pellet transportation. Baled biomass is shipped from field side storage to the depots, while pellets are shipped from depots to the biorefinery. Transportation operations include truck transportation and loading/unloading. Design assumptions for transportation and handling are outlined in Table A-10. Transportation and handling comprise all steps involved in the movement of biomass from multiple local locations to a centralized location (such as a preprocessing facility or biomass depot), including loading, trucking, and unloading. Like the 2020 Herbaceous SOT, the 2021 SOT uses the faster and more efficient Advanced Load Securing System (ALSS) developed in the AGCO-led High-Tonnage Feedstock Logistics project (Webb et al. 2013a) and ensures that each load meets transportation regulations (Figure A-4) using industry data for loading and unloading times. By automating the operation, the ALSS allows the load to be secured without the driver leaving the cab of the tractor (STINGER 2015). The ALSS is reported to load an entire truck in as little as 6 minutes (STINGER 2015). Additional handling operations are required to transfer and queue biomass during preprocessing, and to transfer the feedstock to the pretreatment reactor. Surge bins, conveyors, and a truck tipper are used in handling operations.

Table A-10. *Transportation and handling design assumptions in the 2021 Herbaceous SOT.*

Component	Three-pass corn Stover
Biomass characteristics during transportation from field to depot	
Format	Bale
Density	12 lb/ft^3
Moisture content	20%
Biomass characteristics during transportation from depot to biorefinery	
Format	Bulk pellets
Density	39.4 lb/ft^3
Moisture content	11.5%
Truck used during both transportation from field to depot and depot to biorefinery	
Speed	50 miles/hour
Type	Day cab
Trailer used during transportation from field to depot	
Type	53-ft flatbed with ALSS
Volume	3,600 ft^3
Trailer used during transportation from depot to biorefinery	
Type	Trailer "Live Floor" 48 feet, 2-axle
Volume	3,600 ft^3
Bale Loader	
Capacity	120 tons/hour

(a) Manual bale securing system ***(b) Advanced load securing system***

Figure A-4. *Advanced Load Securing System (ALSS) replacing intense physical requirements to secure a load of bales in 2021 SOT (Source: Stinger)*

Flowability is defined as the relative movement of bulk particles in comparison to neighboring particles and is a measurement of the cohesion and shear stresses in bulk materials. Ground materials (such as bulk corn stover) tend to bridge and clog openings. Flow obstruction, bridging, or arching in addition to inconsistent and unreliable movement of material are common problems in biomass handling and reactor feeding. Figure A-5 shows three common issues experienced in material handling. Arching (bridging) occurs when an arch-shaped obstruction forms above the hopper outlet and stops flow. Ratholing (funneling) occurs when discharge takes place only in a flow channel located above the outlet; once the central flow channel is empty, flow stops. Finally, incomplete clean-out is when not all of the material empties from the sides of the holding container. To address these characteristics, the 2021 Herbaceous SOT incorporates densification to improve feedstock flowability.

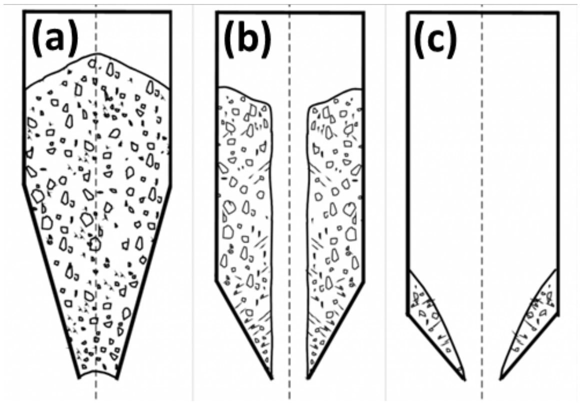

Figure A-5. *Common flow and handling issues encountered when handling biomass. (a) Cohesive arch; (b) Rathole; and (c) Incomplete cleanout. (Source: www.pharmtech.com)*

The 2021 Herbaceous SOT estimates transportation cost based on biomass physical characteristics and equipment used during transportation. Transportation cost has two components, the distance variable cost (DVC) and the distance fixed cost (DFC). The distance variable cost includes the cost of fuel and labor, while the distance fixed cost includes the cost of loading and unloading the truck. Linear regressions were performed to estimate DVC and DFC for each of the biomass bale and pellet types based on the transportation and handling design assumptions shown above in Table A-11 The regression models were used to estimate the DVC of corn stover and switchgrass bales at $0.114/dry ton/mile, while the DFC for bale transportation was estimated at $3.42/dry ton. The DVC for corn stover was estimated to be $0.083/dry ton/mile with the DFC estimated at $0.841/dry ton. The values of DVC and DFC were utilized in the expanded least cost optimization model (Roni et al., 2018) to determine the cost-optimum resource usage based on both transportation distance and grower payment. The total transportation costs for bales and pellets (including loading and unloading) are shown as a function of distance from the biorefinery in Table A-11.

Table A-10. *Total transportation costs for biomass bales and pellets.*

Distance (mi)	Bale Transportation Costs ($/dry ton)	Pellet Transportation Costs ($/dry ton)
10	$4.57	$1.66
20	$5.72	$2.49
30	$6.83	$3.33
40	$8.00	$4.16
50	$9.12	$4.95
60	$10.24	$5.79
70	$11.40	$6.63
80	$12.52	$7.46
90	$13.69	$8.26
100	$14.80	$9.09
120	$17.09	$10.76
140	$19.37	$12.39
160	$21.66	$14.07
180	$23.95	$15.69
200	$26.23	$17.38
220	$28.46	$19.00
240	$30.74	$20.68

Once the optimum resource supply, volume and depot locations were determined, an average weighted transportation distance was calculated for the biomass bales and the pellets. Table A-12 summarizes the transported biomass, weighted transportation distance and average transportation cost for various biomass and pellet from field to depot and depot to biorefinery in the 2021 Herbaceous SOT. The average weighted transportation distance from field to biorefinery of three-pass corn stover was 34.84 miles.

Table A-12. Summary of transported biomass, weighted transportation distance and average transportation cost for biomass and pellet from field to depot and depot to biorefinery in the 2021 Herbaceous SOT case.

Biomass Type	Raw Biomass Purchased (dry tons)	Fields to Depots			Depots to Biorefinery		
		Biomass Trans-ported (dry tons)	Weighted Trans-portation Distance (miles)	Average Trans-portation cost ($/ dry ton)	Pellets Trans-ported (dry tons)	Weighted Trans-portation Distance (miles)	Average Trans-portation cost ($/ dry ton)
Three-pass corn stover	910,012	829,248	34.84	$7.00	725,000	51.70	$5.05

A.6 Depot construction cost for different depot sizes

Construction and infrastructure costs for depots were estimated as follows. For a fixed depot size, the total installed capital investment cost per ton was estimated for the preprocessing, storage and handling operations in the depot. The installed capital cost included all preprocessing, handling and storage equipment; the estimate included instrumentation and control, piping and electrical installation, yard improvement, engineering and supervision, contractor fees, construction and contingency. To estimate the capital layout for construction and infrastructure for individual preprocessing equipment similar to the equipment in this design, an installation factor value of 1.49 was applied, estimated based on Peters et al. (1968). Land cost was calculated assuming 160 acres per distributed depot (including onsite bale storage) at a cost of $500/acre and was added to the capital cost to determine the loan amount. The required acreage for a 725,000 dry tons/year depot (including onsite bale storage) was estimated at 226 acres. The total cost was amortized over 30 years, assuming a 20% down payment and an 8% interest rate and divided by the number of delivered tons to give the per ton cost of depot construction and infrastructure, which totaled $2.30/dry ton for a depot scaled to 725,000 dry tons/year. The above steps were repeated for depot scales ranging from 25,000-700,000 dry tons/year, and the results are shown in Figure A-6.

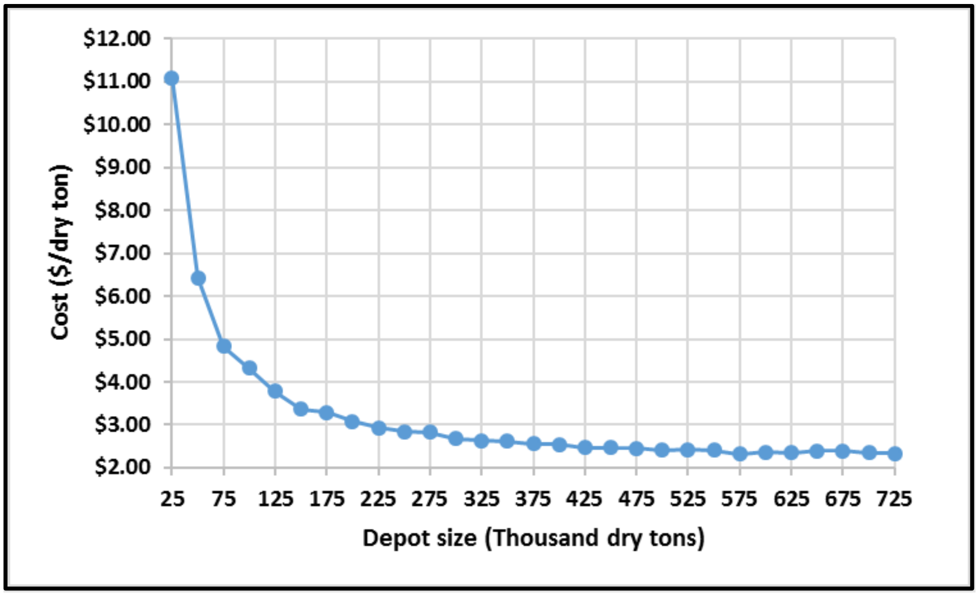

Figure A-6. *Estimated depot construction costs as a function of depot scale.*

A.7 Cost Breakdown by Operation

As described above, an ash dockage equivalent to the biorefinery cost of disposing of ash in excess of the ash specification is applied in the 2021 Herbaceous SOT. Ash disposal costs are assumed to be $37.63/dry ton of ash (Davis et al. 2013). Delivering the feedstock at 10% rather than 20% moisture would incur a cost of to the biorefinery in the form of additional make-up water. This value was calculated from the assumed make-up water cost of $0.31/ton of water used by Davis et al. (2013). Table A-13 shows the cost breakdown by operation, while Table A-14 provides cost information for the three storage types employed.

Table A-13. *2021 Herbaceous SOT modeled costs for production of three-pass corn stover pellets, by operation.*

Cost Element	Three-Pass Corn Stover ($/dry ton)
Grower payment	**21.71**
Harvest and collection	**13.84**
Combine	0.00
Shredder	4.10
Baler	6.29
Stacker	3.45
Storage & queuing	**6.66**
Field side storage	4.23
Depot storage	0.88
Refinery storage	0.12
Handling and queuing at depot	1.21
Handling and queuing at refinery	0.22
Transportation and handling	**12.20**
Transportation from field to depot	7.09
Transportation from depot to refinery	5.11
In-plant receiving and preprocessing	**23.40**
Depot construction cost	2.43
Bale processor	1.80
Air classifier	8.98
Rotary shear	2.52
Densifier	5.61
Cooling	0.88
Conveyors	0.16
Dust collection	0.75
Surge bin	0.05
Misc. Equipment[a]	0.22
Dockage	**0.40**
Ash dockage[b]	0.38
Moisture dockage[c]	0.03
Total delivered feedstock cost	**78.21**

a Miscellaneous equipment consists of destringers, moisture meters, bale rejecters, electromagnets, etc.

b Ash dockage includes both physiological and extrinsic (soil) ash and derives from the cost to the biorefinery of disposing ash greater than 4.93% (see Table 3 in the main document).

c Moisture dockage includes the estimated cost of process water at the biorefinery to bring the feedstock up to the 20% (wet basis) moisture content specification at the reactor throat.

Table A-14. *2021 Herbaceous SOT modeled storage cost breakdown for three-pass corn stover.*

Component	Storage TEA parameters 1	Storage TEA parameters 2	Storage TEA parameters 3
Storage cost	$5.54	$1.84	$1.84
Dry matter loss cost	$0.82	$2.00	$1.31
Total storage cost	$6.36	$3.85	$3.15

APPENDIX B – Overall Operating Effectiveness

B.1 Definition of the Operating Effectiveness of a System

In the field of Reliability Engineering, the Reliability (R) is defined as "the probability of a system or system element performing its intended function under stated conditions without failure for a given period of time" (ASQ 2011). This metric is aimed at the time that an equipment is operating and not idle (zero throughput) because of failure, and can be approximated using an exponential distribution (SEBoK contributors 2019) as shown in equation (1):

$$R = e^{-\left(\frac{Scheduled\ Time}{Mean\ Time\ Between\ Failures}\right)} \tag{1}$$

Utilization, the ratio of time spent by a piece of equipment on productive efforts to the total time consumed, is another reliability metric that is often utilized in reliability analysis (Miyata and Steinhilb 1981); however, it too lacks a connection to dynamically changing equipment performance:

$$U = \left(\frac{Working\ Time}{Scheduled\ Time}\right) \tag{2}$$

An approach developed in the manufacturing industry to measure the performance of an equipment over a specified period is overall equipment effectiveness (OEE) (Nakajima, 1988). OEE (eq 3) considers availability (A), performance rate (PR), and quality rate (QR) to define a quantitative metric that assesses how well the equipment is performing its intended purpose (da Costa et al. 2002), and is defined as

$$OEE\ (\%) = A \times PR\ \times QR \times 100 \tag{3}$$

While OEE has been widely used in many industries to improve equipment effectiveness and productivity, its use has been limited to individual equipment (Muchiri and Pintelon 2008). To extend the concept to complete systems, several metrics have been developed in the manufacturing industries including overall factory effectiveness (OFE), overall plant effectiveness (OPE), overall throughput effectiveness (OTE), production equipment effectiveness (PEE), overall asset effectiveness (OAE), and total equipment effectiveness performance (TEEP) (Muchiri and Pintelon 2008). While these metrics consider the operating effectiveness of entire systems and can be used for debottlenecking, they are deterministic in nature and provide only average effectiveness of the plant. Zammori et al. (2011) extended the concept of OEE to include stochastic variability in cycle and maintenance times by considering the availability, production rate and quality rate as normal probability distributions. For the present analysis, our goal was to develop a stochastic approach to support the identification of the dynamic impacts of widely varying biomass feedstock properties on individual equipment and on the overall system.

While Zammori et al.(2011) extended the OEE concept to include stochastic generation of the underlying factors used to calculate the metric, our aim was to enable a direct tie between material properties and system performance as impacted at the individual equipment level. Overall equipment effectiveness as defined in eq 1 can be rewritten (eq 4)

$$OEE(\%) = (A \times PR) \times QR \times 100 \tag{4}$$

To simplify calculations for use with discrete event throughput analysis, we note that the two terms of OEE in eq (5) reduce to

$$OEE(\%) = \left(\frac{Total\ Units\ Produced}{Design\ Units\ Planned}\right) \times \left(\frac{Units\ Produced\ Meeting\ Quality}{Total\ Units\ Produced}\right) \times 100 \tag{5}$$

While eq 5 could be simplified further, it is useful in this form because it differentiates between physical/mechanical feedstock property impacts to throughput, and physical (convertibility) and compositional property impacts to biorefinery product yield. The first term measures the throughput performance over the specified time period, while the second term measures the degree of quality attainment (yield potential) achieved.

Because OEE is explicitly defined in the literature for individual equipment and is deterministic in nature, for our stochastic throughput analysis we thus define the **"overall operating effectiveness" (OOE)** (eq 6) as the product of the fraction of feedstock nameplate throughput achieved, which we define as F_f (eq 7), and the fraction of conversion design performance achieved, which we define as F_B (eq 8).

$$OOE(\%) = F_f \times F_B \times 100 \tag{6}$$

$$F_f = A \times PR = \left(\frac{Total\ Units\ Produced}{Design\ Units\ Planned}\right) \tag{7}$$

$$F_B = QR = \left(\frac{Units\ Produced\ Meeting\ Quality}{Total\ Units\ Produced}\right) \tag{8}$$

B.2 OOE in the Herbaceous Feedstock Supply Chain

The low-temperature field to biofuel supply chain consists of three subsystems, (1) Supply Logistics; (2) Preprocessing; and (3) Low-Temperature Conversion. The low-temperature conversion process consists of deacetylation/mechanical refining followed by enzymatic hydrolysis and separate fermentation/upgrading trains for sugars to hydrocarbon fuel and lignin to adipic acid (Davis et al. 2018). Herbaceous biomass sources are best suited for this process, and the best studied biomass feedstock is corn stover. Supply Logistics for corn stover consists of three-pass or two-pass corn stover harvest followed by long term satellite bale storage and delivery of the bales to the biorefinery for subsequent Preprocessing of the corn stover to a set of conversion specifications.

If the three subsystems are decoupled from one another by maintaining a buffer of downstream input material as the last step of each subsystem, then they can operate essentially independently and from an operating effectiveness perspective they can each be treated separately. This does not change the working definition of operating effectiveness; for each subsystem the operating effectiveness remains equal to the product of the fraction of design material throughput capacity achieved ($F_{f,i}$) and the fraction of potential conversion performance achieved ($F_{B,i}$) measured as potential product yield/ton of material), where "i" denotes the subsystem. Thus, for the three subsystems the overall operating effectiveness would be

$$Supply\ Logistics: \qquad OOE_S = F_{f,S} \times F_{B,S} \tag{9}$$

$$Preprocessing: \qquad OOE_P = F_{f,P} \times F_{B,P} \tag{10}$$

$$Conversion: \qquad OOE_C = F_{f,C} \times F_{B,C} \tag{11}$$

In equations (9)-(11), the $F_{f,i}$ are defined as the fraction of design material throughput capacity achieved in each subsystem, while the $F_{B,C}$ factor remains the same as the original F_B for the complete field to biofuel system (fraction of design biofuel yield/ton of feedstock supplied to conversion). The $F_{B,i}$ factors for Supply Logistics and for Preprocessing are defined as the fraction of total tons delivered that meet or exceed the CMAs for the next downstream subsystem, where the CMAs are the compositional attributes that directly lead to downstream impacts on potential biofuel yield/ton of material. In Supply Logistics these would include moisture content, ash content, and organic composition (glucan, xylan, lignin and "other" compositional components such as extractives, acetyl and protein contents). In Preprocessing they would include moisture content, ash content, and organic composition (glucan, xylan, lignin and "other"), as well as physical attributes such as particle size. For the purposes of the SOT presented in this report, the conversion factors $F_{f,C}$ and $F_{B,C}$ are assumed to be equal to 1 if all compositional and physical conversion specifications are met or exceeded 100% of the time; for this reason we did not consider Conversion further in the analysis. The following sections describe the approach to estimate dynamic and total throughput, downtime occurrences, and aggregated downtimes caused by variable feedstock physical properties.

B.3 Discrete Event Simulation Approach

Supply Logistics consists of the operations from harvest to the biorefinery gate. Harvest, collection and delivery of corn stover bales to satellite storage (the material buffer for preprocessing) occur within a short 3-month timeframe, while satellite storage and transportation to the biorefinery occur on a 1-year timeframe. Preprocessing and Conversion both occur on a 1-year timeframe. Hence, while the fraction of Supply Logistics throughput achieved in the 3-month harvest window will impact cost, it will have minimal impact on the throughput capacity utilization for either Preprocessing or Conversion. In contrast, dry matter losses and other changes to the corn stover bales while in satellite storage will have direct impacts downstream. Thus, for the purposes of the SOT we chose to begin the throughput analysis and tracking of compositional and physical changes following harvest and collection, at the entry to satellite storage.

Preprocessing consists of all operations needed to adjust moisture content, fractionate (if desired), size reduce to conversion specifications, provide the material buffer needed to decouple Preprocessing from Conversion, and feed material meeting specifications from this buffer to the mouth of the first stage of deconstruction in Conversion. Throughput analysis was thus utilized for the entirety of the Preprocessing subsystem. For Conversion, throughput analysis and tracking of compositional and physical changes were not done.

To conduct the throughput analyses performed for this report, Discrete Event Simulation (DES) was employed from the entry to long term satellite storage through to the conversion reactor throat to model the interactions of satellite storage and preprocessing equipment throughput and performance. The discrete event models began with the introduction of one dry metric ton of feedstock (2,205 dry lb) into satellite storage. The moisture, ash, glucan, xylan and lignin contents were randomly sampled from distributions developed from various INL and public data sources. Details on the individual data sources and distribution generation methods for the various distributions are provided in this report. Distributions of the moisture, ash, glucan, xylan and lignin contents exiting storage that would be available throughout the year of operation were generated assuming the dry matter losses.

Failure modes and the resulting down times for at-scale preprocessing equipment were derived from operational experience with the equipment. For dynamic throughputs greater than zero, regression models describing throughputs, energy consumption, particle size distributions and compositional impacts as functions of feedstock attributes (moisture and ash) were developed for each individual piece of equipment based on historical data collected in the INL PDU. The regression models were used as instantaneous functions to predict impacts for each equipment or subsystem sequentially, based on a mass step moving through that equipment or subsystem. For example, for each individual equipment or subsystem modeled,

$$\begin{aligned} &Preprocessing\ Equipment\ or\ Subsystem\ Throughput \\ &\qquad = f_1(moisture\ content, ash\ content) \end{aligned} \tag{7}$$

$$\begin{aligned} &Convertible\ Composition\ Exiting\ Preprocessing\ Equipment\ orSubsystem \\ &\qquad = f_3(moisture\ content, ash\ content) \end{aligned} \tag{8}$$

The modeled daily feedstock throughputs and quality were tracked over the course of a year of operation (350 days, 24 hours/day, assuming an approximate 2-week shutdown for plant maintenance) to determine the modeled annual feedstock capacity and modeled annual performance. The assumption is made in the analysis that if the feedstocks meet a minimum quality threshold equivalent to the conversion specification, then the conversion operation will perform as designed in terms of both capacity utilization and conversion performance. The following method was used to calculate the annual capacity utilization and performance factors for estimation of the overall operating effectiveness.

B.3.1 Supply Logistics

If $T_{S,i}$ (dry tons) is the DES-modeled total daily throughput of biomass into the biorefinery gate on day *i*, then the modeled annual Supply Logistics biomass feedstock capacity $T_{S,delivered}$ (dry tons) of the biorefinery is

$$T_{S,delivered} = \sum_{i=1}^{N} T_{S,i} \tag{9}$$

If a ton delivered to the biorefinery gate meets the minimum quality threshold equivalent to the conversion-specified carbohydrate content (adjusted for preprocessing losses), then that ton is considered to meet the conversion requirement. Note that this is a change from how the quality was assessed at the biorefinery gate in the 2019 OOE SOT and 2022 OOE Design Case, for which the total carbohydrates were compared to the conversion specification of ≥ 59 wt% and lignin specification of ≥ 15.8 wt%. After discussions with NREL analysts, it was decided to remove the lignin specification because they assume that residual sugars as well as protein and extractives are also converted to adipic acid (Davis et al. 2018). Additionally, it was realized that the more appropriate biorefinery-gate specification for total carbohydrates should account for the uneven losses of ash and organics during preprocessing. This leads to a biorefinery gate total carbohydrate specification of ≥ 58.77 wt%, which, together with dropping the lignin specification will increase the number of tons meeting the minimum quality threshold as compared to the 2019 OOE SOT and 2022 OOE Design Case. The total number of tons meeting the minimum quality threshold, $T_{S,N}$ (dry tons) is calculated as

$$T_{S,N} = \sum_{i=1}^{N} T_{S,i,meets\ spec} \tag{10}$$

Then the performance factor is

$$F_{B,S} = \frac{T_{S,N}}{T_{S,delivered}} \tag{11}$$

For the throughput capacity factor, it is important to note that we assume that only enough tons needed for Preprocessing are delivered to the biorefinery, and if the throughput of preprocessing is below design, the design number of tons becomes irrelevant to Supply Logistics. This would logically lead to a fixed $F_{f,S}$ of 1.0 for Supply Logistics, however, this would not account for the dry matter losses incurred during satellite storage and would overestimate the effectiveness of Supply Logistics. Hence, we defined the throughput capacity factor for the Supply Logistics subsystem as

$$F_{f,S} = \frac{T_{S,delivered} * DML_{average}}{T_{S,delivered}} \tag{12}$$

where $DML_{average}$ (%) is the averaged combined dry matter losses incurred over the course of the year of operation.

B.3.2 Preprocessing

If $T_{P,i}$ (dry tons) is the DES-modeled total daily throughput of biomass into the first stage of deconstruction in Conversion on day i, then the modeled annual Preprocessing biomass feedstock capacity $T_{P,fed}$ (dry tons) of the biorefinery is

$$T_{P,fed} = \sum_{i=1}^{N} T_{P,i} \tag{13}$$

If a ton delivered to reactor throat meets the minimum quality threshold equivalent to the conversion-specified carbohydrate content, then that ton is considered to meet the conversion requirement. The total number of tons meeting the minimum quality threshold, $T_{P,N}$ (dry tons) is calculated as

$$T_{P,N} = \sum_{i=1}^{N} T_{P,i,meets\ spec} \tag{14}$$

Then the throughput capacity factor and performance factor are

$$F_{f,P} = \frac{T_{P,fed}}{T_{P,Nameplate}} \tag{15}$$

$$F_{B,P} = \frac{T_{P,N}}{T_{P,fed}} \tag{16}$$

B.3.3 Machine Performance Assumptions

	Conveyor	Destringer	Bale Processor	Air Classifier	Rotary Shear	Densifier
Capacity (tons/hour)	25	25	25	25	25	25
MTTF (minutes)	252,000	120	252,000	262,800	262,800	262,800
TTR (minutes)	480	1	120	120	120	30
TTR_SD (minutes)	90	.25	90	30	30	10
Max_MC (%)	—	—	40	45	45	—
Max_MC_TTR (minutes)	—	—	30	30	30	—
Max_MC_TTR_SD	—	—	15	15	15	—
Max_Ash (U.S. short tons)	—	—	500		100	—
Max_Ash_TTR (minutes)	—	—	360		360	—
Max_Ash_TTR_SD	—	—	120		120	—

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

B.4 References

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