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Herbaceous Feedstock 2019 State of Technology Report

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Milestone Completion Report

HERBACEOUS FEEDSTOCK 2019 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 elsewhere (such as the High-Tonnage Feedstock Logistics projects (Webb et al. 2013a, Webb et al. 2013b, Webb et al. 2013c, Webb and Sokhansanj 2014, Sokhansanj et al. 2014)) 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 improvements to individual supply system unit operations and present the status of feedstock logistics technology development for converting 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 Program Plan.

The 2019 Herbaceous SOT incorporates several technology changes in feedstock preprocessing and introduces opportunities from the integrated landscape management (ILM) strategy and increased grower participation to reduce biomass access costs, while maintaining or improving grower profitability. During FY18 uneven flow from the horizontal bale grinder was identified as a significant issue limiting preprocessing system throughput. Based on FSL-funded research at INL, the 2019 Herbaceous SOT replaces the horizontal bale grinder used in the first

stage size reduction with a bale processor. The improved uniformity of biomass flow entering the PDU eliminated slugging flow from the first stage size reduction and improved the throughput of downstream operations. In order to achieve moisture reduction through frictional heating during grinding (which allowed elimination of the costly rotary drum dryer in previous SOTs), the second stage grinder was changed from a rotary shear, which does not remove moisture, back to a hammer mill. Finally, the 2019 Herbaceous SOT introduces modified three-pass and two-pass corn stover supply curves derived from the BT16 resource assessment, based on FY19 modeling results (WBS 4.2.1.20) quantifying economic benefits of ILM in the supply area, together with modeling results (WBS 1.2.1.5) identifying ILM strategies to increase grower participation.

The 2019 Herbaceous SOT report documents the current modeled cost of an herbaceous feedstock supply system from harvest to the pretreatment reactor throat for hydrocarbon fuel production via biochemical conversion, based on equipment and processes now available or potentially available in the near term. The modeled cost also considers both the required quality and the availability of the biomass resources. The 2019 Herbaceous SOT predicts a modeled delivered feedstock cost of $81.37 /dry ton (2016$); this is a $2.30/dry ton (2016$) decrease from the 2018 Herbaceous SOT. Technology improvements that contributed to this modeled cost reduction include reduced cost for the new preprocessing design and quantification of the opportunities of the integrated landscape management (ILM) strategy and an increased grower participation rate to reduce the grower payment portion of biomass access costs, while maintaining or improving grower profitability. A greenhouse gas emissions (GHG) assessment was completed by Argonne National Laboratory using the 2019 Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model, estimating an increase of 14.89 kg CO_2e/ton from the 2018 SOT (69.27 kg CO_2e/ton in 2018 to 84.16 kg CO_2e/ton in 2019). The increase of energy consumption during preprocessing along with higher transportation distance to access low cost biomass from further distance contributed to the increase of GHG emissions in the 2019 Herbaceous SOT. The reason for the increased transportation distances was the cost tradeoff of going farther from the biorefinery to access the cheaper ILM-derived counties (the cheaper price outweighed the cost of increased supply radius).

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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% operational reliability and field-to-reactor throat delivered cost less than $85.51/dry ton (2016$). As stated by the 2017 Multi-Year Program Plan (USDOE, 2017), the research and development focus of the Terrestrial Feedstock Supply and Logistics (FSL) 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 2016b), FSL 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 2016b).

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 reliability 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. 2014b). 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. 2013b), 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. 2014a) 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.

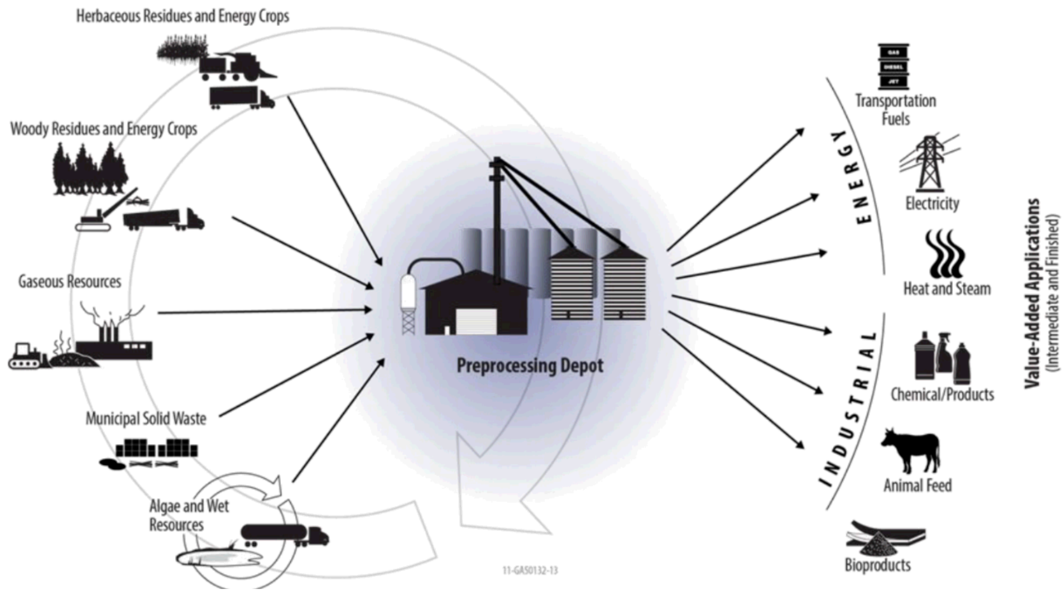

Figure 1. Incorporation of stakeholder feedback has resulted in improvements in advanced feedstock supply system, evolving depots from being standalone/integrated to producing merchandisable intermediates and serving a variety of customers and markets.

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 will also reduce the risk to industry by diversifying reliance on any one feedstock.

The 2019 Herbaceous SOT applies blending of multiple types of herbaceous biomass as a means of increasing access to biomass resources and meeting feedstock quality and cost specifications, which is a critical step toward feedstock commoditization. Blending refers to combining different types of biomass to consistently provide a uniform feedstock of known specifications for a conversion process at the lowest possible cost. This same optimization tool used in the 2018 Herbaceous SOT (Roni et al., 2018) was used in the 2019 Herbaceous SOT to determine the least cost blend and the optimal depot locations and sizes. The 2019 Herbaceous SOT incorporates two depots that are located at a distance from the biorefinery in higher-yielding counties that have significant corn stover available lower on the supply curve.

The 2019 Herbaceous SOT requires 725,000 dry tons feedstock to be delivered to the reactor throat annually. Over the past several years, biomass availability has been estimated solely based on the 2016 Billion-Ton Report (BT16) (DOE 2016a). In the 2019 Herbaceous SOT, biomass availability was estimated by utilizing supply curves from the BT16 report, modified to incorporate new (FY19) models of the impact of implementing the ILM strategy in the supply shed (completed by WBS 4.2.1.20) and of the predicted grower participation rates with the implementation of ILM (completed by WBS 1.2.1.5). The incorporation of ILM practices are shown to provide two benefits in terms of biomass supply and cost. First, low production areas are transitioned to perennial energy crops (i.e. switchgrass), increasing the supply of higher quality material and improving farmer profitability. Second, the cost of corn stover is reduced through reduction of tillage cost as a result of the removal of the crop residue.

2. DELIVERED FEEDSTOCK COST MODELS

The Biomass Logistics Model (BLM) was used to model feedstock logistics cost and energy consumption estimates for the 2019 Herbaceous 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 systems dynamics software package Powersim™. 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, ash content, and dry bulk density) and calculating cost and energy consumption (Cafferty et al. 2013b). 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 2016), to perform a cursory farm gate-to-plant gate life-cycle assessment on GHG emissions (this is completed by colleagues at Argonne National Laboratory for this report).

2.1 Description of Logistic System Designs

The 2019 Herbaceous SOT design assumes annual n^{th}-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. 2013). The shaded rows in Table 1 show the compositional specifications for the feedstock, namely, 59% carbohydrates, ≤ 5 % ash, and 20% moisture. An additional specification is ¼" mean particle size at the pretreatment reactor throat.

Table 1. Delivered feedstock composition assumptions for dilute-acid pretreatment and enzymatic hydrolysis to sugars followed by biological conversion of sugars to hydrocarbons pathway (Humbird et al. 2011, Davis et al. 2013).

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***

The 2019 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 2019 Herbaceous SOT delivers 725,000 dry tons of a 33.33% three-pass corn stover – 66.67% two-pass corn stover blend, utilizing the harvest, collection storage and transportation system described in the 2018 Herbaceous SOT report (Roni et al., 2018) and summarized in Appendix A. The 2019 Herbaceous SOT includes modifications described above and in Appendix A to preprocessing, and to supply curves as described in Appendix B, and predicts a modeled delivered feedstock cost of $81.37/dry ton (2016$); this is a $2.30/dry ton (2016$) decrease from the 2018 Herbaceous SOT.

2.1.1 Resource Availability

The geographic area for the 2019 Herbaceous SOT is northwestern Kansas, with the biorefinery located in Sheridan County, which is unchanged from the 2018 Herbaceous SOT. It was assumed that all the biomass 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. In each of the selected biomass supply counties, the ILM strategy was modeled under WBS 4.2.1.20 to estimate the acreage of high yielding and low yielding areas. Based on modeling by the Resource Mobilization project (WBS 1.2.1.5), a grower participation factor of

44% was applied to the high yielding areas to estimate the potential crop residue areas. Also based on this model, a grower participation factor of 77% was applied to the low yielding areas to estimate the potential acres available for switchgrass. Total dry tons of biomass by county were projected using the estimated acres and yields derived from BT16 data for 2019. Appendix B describes the methodology employed to project modified supply curves from the BT16 resource assessments using the ILM and grower participation modeling results for the supply shed.

2.1.2 Harvest and Collection

Corn stover is the primary feedstock in the 2019 Herbaceous SOT design. It is assumed that corn stover is harvested by both three-pass (conventional) and two-pass methods (advanced). 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 two-pass corn stover harvesting and collection method is an advanced, and more sustainable harvesting method, that eliminates the windrowing step (Birrell et al., 2014). Harvesting yields of three-pass corn stover and two-pass corn stover remain unchanged from the 2018 Herbaceous SOT (Roni et al., 2018), and are referenced from studies conducted by Smith and Bonner (2014).

2.1.3 Storage

In the 2019 Herbaceous SOT design, corn stover storage follows the same practice and assumptions as the 2018 Herbaceous SOT design. The assumed initial moisture content is 30% for corn stover bales. Following field storage, the resulting average moisture content is assumed to be 25% (5% moisture loss) for corn stover. An average field-side stack dry matter loss of 12%/year is assumed for corn stover (Cafferty et al., 2013). Both literature (Shah et al., 2011) and INL laboratory-scale storage experiments indicate that higher initial moisture content leads to greater dry matter loss; losses of individual compositional components of the biomass were estimated based on the results of the INL laboratory storage experiments (see Appendix A).

2.1.4 Preprocessing

Feedstock preprocessing in the 2019 Herbaceous SOT design includes size reduction, grinding and densification. The major update from the 2018 SOT design is the replacement of the stage one grinder (Vermeer BG480E grinder) with an EZ Ration bale processor. The EZ Ration Processor is a horizontal bale processor originally designed for blending cattle feed components such as hay and corn stalks. The new 3-rotating-drum debaling head design of the bale processor (Figure 2) requires lower rpm and energy and eliminates the slugging flow observed in the former first stage hammer mill. Moreover, the EZ Ration bale processor can feed the 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.

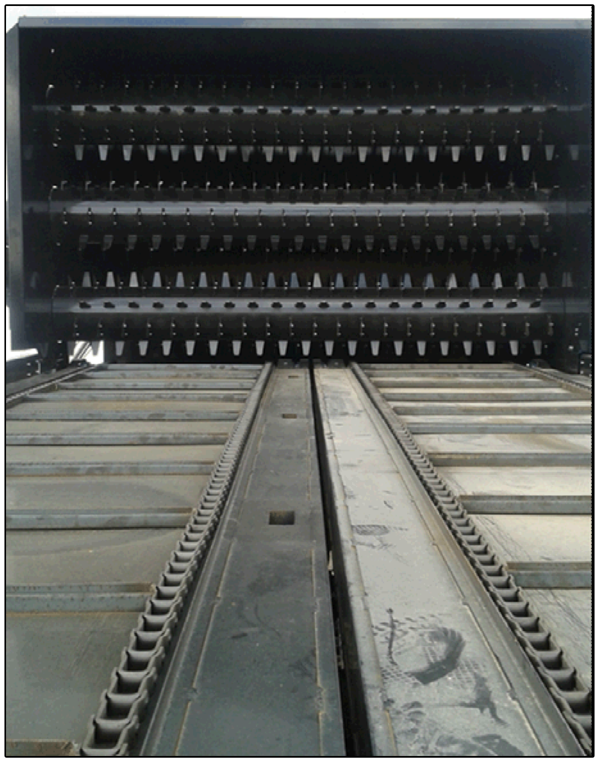

Figure 2. *EZ Ration Debaling System*

Pilot-scale testing was performed during FY19 in the Biomass Feedstock User Facility (BFNUF) at INL (WBS 1.2.3.3) to collect the parametric data for preprocessing. The bale processor greatly improved the uniformity of biomass flow and the throughput compared to the Vermeer grinder used in the 2018 SOT design. Hence, the 2019 Herbaceous SOT replaces the first stage hammer mill with the bale processor. In order to achieve moisture reduction through frictional heating during subsequent grinding (which allowed elimination of the costly rotary drum dryer in previous SOTs), the second stage grinder was also changed from the rotary shear used in the 2018 SOT design, which does not remove moisture, back to a hammer mill.

2.1.5 Transportation and Handling

Transportation and handling includes 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 2019 Herbaceous SOT includes both bale and pellet transportation, which are described in the 2018 Herbaceous SOT (Roni et al., 2018) and shown in Appendix A. In bale transportation, biomass bales are loaded to semi-trucks after the field side storage, transferred and unloaded to the depots. After pelleting, biomass pellets are then load and transfer to the biorefinery.

2.1.6 Cost Summary and Energy Usage

Results of the supply chain analysis are summarized in Table 2, which provides the detailed cost breakdown and greenhouse gas emissions. The greenhouse gas emissions analysis was completed by Argonne National Laboratory (ANL), using energy consumption and transportation distance data from the BLM. ANL employed the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model (GREET®) (Argonne National Laboratory, 2017) to conduct detailed life-cycle analysis of farm gate-to-biorefinery gate GHG emissions of the herbaceous biomass scenarios presented in this report. Table 3 shows the modeled cost estimates for the herbaceous feedstock supply system for the 2018 SOT, 2019 SOT and the 2022 Projection.

Table 2. *The 2019 Herbaceous SOT modeled cost and GHG estimates for an herbaceous feedstock supply system supplying 725,000 dry tons annually in northwestern Kansas. Design details are in Appendix A.*

Cost Element	Cost ($/dry ton) (2016$)			GHG Emissions (kg CO_2e/ton)[a]
	Three-Pass Stover	Two-Pass Stover	Least-Cost Blend[b]	
Blend Ratio	33.33%	66.67%	100.00%	—
Grower payment	$21.42	$20.13	$20.56	—
Harvest and collection	$13.84	$18.79	$17.14	11.38
Storage and queuing	$6.40	$6.53	$6.49	2.43
Transportation and handling	$14.32	$14.98	$14.76	21.00
In-plant receiving and preprocessing	$20.84	$20.84	$20.84	49.35
Dockage	$2.74	$1.01	$1.58	—
Total	$79.56	$82.28	$81.37	84.16

a Pesticide and fertilizer emissions incurred during biomass production were attributed to the biomass growth stage of the life cycle and are not included.
b The blend costs are presented as the weighted average of the blend component costs.

The reduction of $2.98/dry ton in grower payment from the 2018 SOT is a result of incorporation of the supply curves derived from the BT16 resource assessment and modified based on the FY19 WBS 4.1.2.20 and 1.2.1.5 modeling results (see Appendix B), together with optimal selection of biomass resource locations and depot sizes for the blend using the least-cost blend optimization. The $0.46/dry ton increase in harvest and collection costs from 2018 results from the higher harvesting cost of two-pass corn stover, which is the largest component of the blend and is required to meet the carbohydrate specification. There was not a significant

Table 3. *Summary of modeled cost estimates for the herbaceous feedstock supply system for biochemical conversion pathway for the 2018 SOT, 2019 SOT and 2022 Projection.*

	Delivered Cost ($/dry ton) (2016$)		
	2018 SOT	**2019 SOT**	**2022 Projection**
Feedstock	**Blend**	**Blend**	**Blend**
Net delivered cost	**$83.67**	**$81.37**	**$79.07**
Grower payment	$23.54	$20.56	$22.37
Feedstock logistics	$60.13	$60.81	$56.70
Harvest & collection	$16.68	$17.14	$12.79
Storage & queuing	$6.55	$6.49	$8.35
Preprocessing and in-plant receiving	$22.40	$20.84	$21.44
Transportation & handling	$13.23	$14.76	$12.44
Dockage	$1.27	$1.58	$1.68

reduction in feedstock in storage cost in the 2019 SOT. The $1.56/dry ton reduction in preprocessing is a composite result of the use of the bale processor and the hammer mill in the second stage size reduction. The $1.53/dry ton increase in transportation and handling cost resulted from increased transportation distance to access lower cost corn stover from further distance. The increase of $0.31/dry ton in dockage is attributed to the increased amount of high ash three-pass corn stover in the blend (note that dockage is included in the optimization as a cost component). The 2019 Herbaceous SOT showed a net increase in greenhouse gas emissions from 69.27 kg CO_2e/ton in 2018 to 84.16 kg CO_2e/ton in 2019. An increase in energy consumption during preprocessing, as well as increased bale transport distance to the distributed depots and increased transportation distance for pellets to the biorefinery contributed to this 14.89 kg CO_2e/ton net increase of GHG emissions. The reason for the increased transportation distances was the cost trade-off of going farther from the biorefinery to access the cheaper ILM-derived counties (the cheaper price outweighed the cost of increased supply radius).

As stated above, the least-cost blend for this analysis consists of 33.33% three-pass corn stover and 66.67% two-pass stover. The amounts of harvested biomass (prior to storage) required to produce this blend are shown in Table 4, along with their carbohydrate and ash compositions and individual delivered costs. The depot locations, biomass source counties and biorefinery location are listed in Table 5 and Table 6 and are shown pictorially in Figure 3. The least cost supply chain network utilized two distributed depots (Nodes 25 and 27 in Figure 4) for a biorefinery located in Sheridan County, Kansas. The results also show that a biorefinery with a design capacity of 725,000 dry tons/year, would need to procure at least 840,677 dry tons of biomass annually to account for losses in the system.

Table 4. *Delivered (reactor-throat) costs and compositions of the herbaceous biomass sources, the preprocessed blendstocks produced from these biomass sources, and the least-cost blend. The modeled cost estimates are for delivery of 725,000 dry tons/year of blended feedstock at 59.33% carbohydrate, 9.13% ash and 11.19% moisture, and are discussed in detail in Appendix A. An ash dockage of $1.55/dry ton and a moisture dockage of $0.03/dry ton are included in the total delivered blend cost. All costs are in 2016$.*

Biomass Type	Raw Biomass Purchased (dry tons)	Pelleted Blendstocks Produced (dry tons)	Pelleted Blendstocks		
			Total Carbohydrates (wt% db)	Ash (wt% db)	Delivered Cost ($/dry ton)
Three-pass corn stover	280,227	241,668	57.40%	12.20%	$79.56
Two-pass corn stover	560,450	483,332	60.30%	7.60%	$82.28
Totals	840,677	725,000	59.33%	9.13%	$81.37

Table 5. *Node IDs and county names for the biomass source counties for the supply system depicted in Figure 3.*

Node	County	Node	County
-	Sheridan County, KS	16	Hayes County, NE
1	Keith County, NE	17	Frontier County, NE
2	Custer County, NE	18	Gosper County, NE
3	Valley County, NE	19	Phelps County, NE
4	Greeley County, NE	20	Kearney County, NE
5	Nance County, NE	21	Adams County, NE
6	Sherman County, NE	22	Clay County, NE
7	Howard County, NE	23	Fillmore County, NE
8	Merrick County, NE	24	Dundy County, NE
9	Perkins County, NE	25	Red Willow County, NE
10	Dawson County, NE	26	Furnas County, NE
11	Buffalo County, NE	27	Harlan County, NE
12	Hall County, NE	28	Franklin County, NE
13	Hamilton County, NE	29	Webster County, NE
14	York County, NE	30	Nuckolls County, NE
15	Chase County, NE	31	Thayer County, NE

Figure 3. *Supply chain network design for the 2019 Herbaceous SOT. The supply chain has 2 distributed depots (Nodes = 25 and 27) with the biorefinery located in Sheridan County, Kansas. Three-pass corn stover is sourced from Nodes 1, 9, 10, 11, 15, 16, 17, 18, 21, 24, 25, 26 and 29. Two-pass corn stover is sourced from Nodes 2, 3, 4, 5, 6, 7, 8, 12, 13, 14, 19, 20, 22, 23, 27, 28, 30 and 31. County names are shown with their node identifiers in Table 5 and Table 6.*

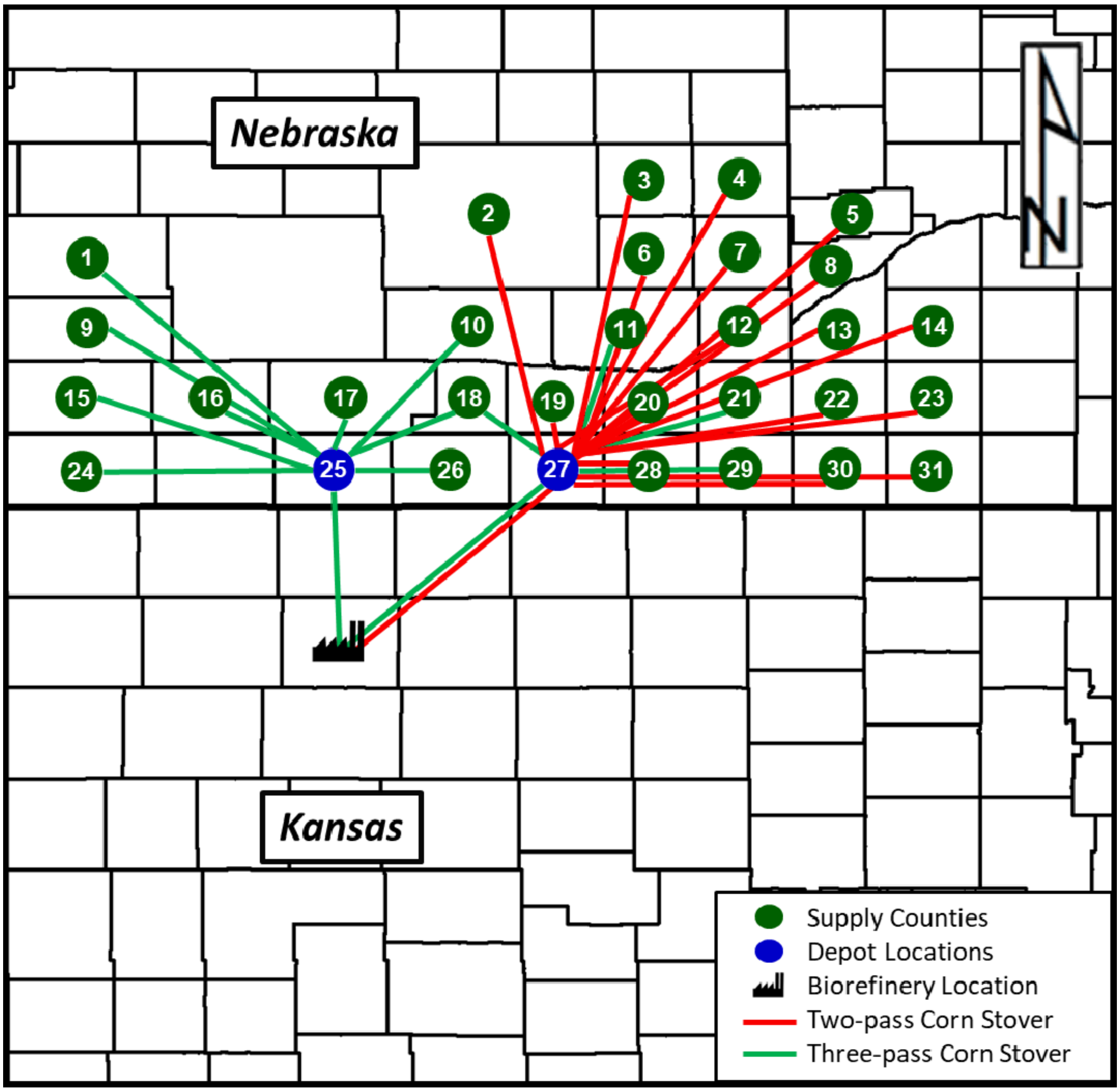

Table 6. *Optimal locations and sizes of distributed depots for least cost delivery of 725,000 dry tons/year of blended feedstock to Sheridan County, KS. Nodes are identified by county name in Table 5 and are shown geographically in Figure 3.*

Node	Identifier	County	Capacity (dry tons/yr)	Biomass Type	Biomass Source Nodes
-	Biorefinery	Sheridan, KS	725,000	Blend	25, 27
25	Depot	Red Willow, NE	200,000	three-pass corn stover	1, 9, 10, 15, 16, 17, 18, 24, 25, 26
27	Depot	Harlan, NE	575,000	three-pass corn stover	11, 18, 21, 29
				two-pass corn stover	2, 3, 4, 5, 6, 7, 8, 12, 13, 14, 19, 20, 22, 23, 27, 28, 30, 31

2.1.7 Sensitivity Analysis of Costs

Sensitivity analysis was performed to determine the impact of uncertainty in values for key operational parameters on the delivered cost for the static nth-plant design presented as the 2019 Herbaceous SOT. Critical process parameters that affect delivered feedstock were investigated to determine the impact of uncertainty in their values on the delivered feedstock cost. The parameters varied in the sensitivity analysis are shown in Table 7.

Table 7. *Model parameters varied for the sensitivity analysis. Each parameter was varied independently based on actual variations observed in experimental and field data.*

Parameter	Units	Biomass Type	Minimum	Average (SOT)	Maximum
Effective windrowing rate[a]	acres/hr	Three-pass corn stover	10.78	11.5	12.51
		Two-pass corn stover	n.a.	n.a.	n.a.
Effective baling rate[b]	dry ton/hr	Three-pass corn stover	16.14	26.18	28.10
		Two-pass corn stover	8.88	14.4	24.7
Field side storage dry matter loss[c]	%	Three-pass corn stover and Two-pass corn stover	8%	12%	20%
Bale transport loading/unloading time[d]	minutes	Three-pass corn stover and Two-pass corn stover	39	42	45

Table 7. *(continued)*

Parameter	Units	Biomass Type	Minimum (SOT)	Average (SOT)	Maximum (SOT)
Bale density[e]	lb/ft^3	Three-pass corn stover and Two-pass corn stover	11	12	13
Hammer mill effective throughput[f]	dry tons/hr/ machine	Three-pass corn stover and Two-pass corn stover	1.43	2.24	4.29
Hammer mill effective energy consumption[f]	kWh/dry ton	Three-pass corn stover and Two-pass corn stover	28.0	35.0	42.0
Bale processor throughput[f]	dry tons/hr/machine	Three-pass corn stover and Two-pass corn stover	5	10	13
Bale processor energy consumption[f]	kWh/dry ton	Three-pass corn stover and Two-pass corn stover	6.5	8.0	11.0
Pelleting throughput[f]	dry tons/hr/ machine	Three-pass corn stover and Two-pass corn stover	3.43	3.62	3.76
Pelleting energy consumption[f]	kWh/dry ton	Three-pass corn stover and Two-pass corn stover	33.79	32.49	34.68
Bypass during fractional milling[g]	%	Three-pass corn stover and Two-pass corn stover	26.0	30.0	32.7
Interest rate[h]	%	Three-pass corn stover and Two-pass corn stover	4.0	8.0	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 and switchgrass. Switchgrass percentage variation of throughput and energy consumption from base case is utilized to estimate the grass clippings variations
g: INL PDU data were utilized to measure the variation in percentage of material by bypassed during second stage grinding under base case process conditions (e.g. moisture, screen size) for corn stover and switchgrass
h: Assumptions based on expected variations

Figure 4 shows the results of the sensitivity analysis; delivered cost was found to vary from $78.35-$86.69/dry ton (2016$). The top five factors impacting uncertainty in the delivered cost included baling rate, hammer mill throughput, storage dry matter loss, interest rate and bale density. Based on the observed variation, baling throughput is a key contributor to uncertainty, with its maximum value reducing the delivered feedstock by $2.98/dry ton, whereas its minimum value would increase the delivered feedstock cost by $5.26/dry ton. Uncertainties in hammer mill throughput led to delivered cost ranges of -$2.86/dry ton to +$3.4/dry ton. Additional parameters that had measurable effects on the uncertainty in delivered feedstock price included bale processor throughput, percentage bypass during fractional milling, and hammer mill energy consumption.

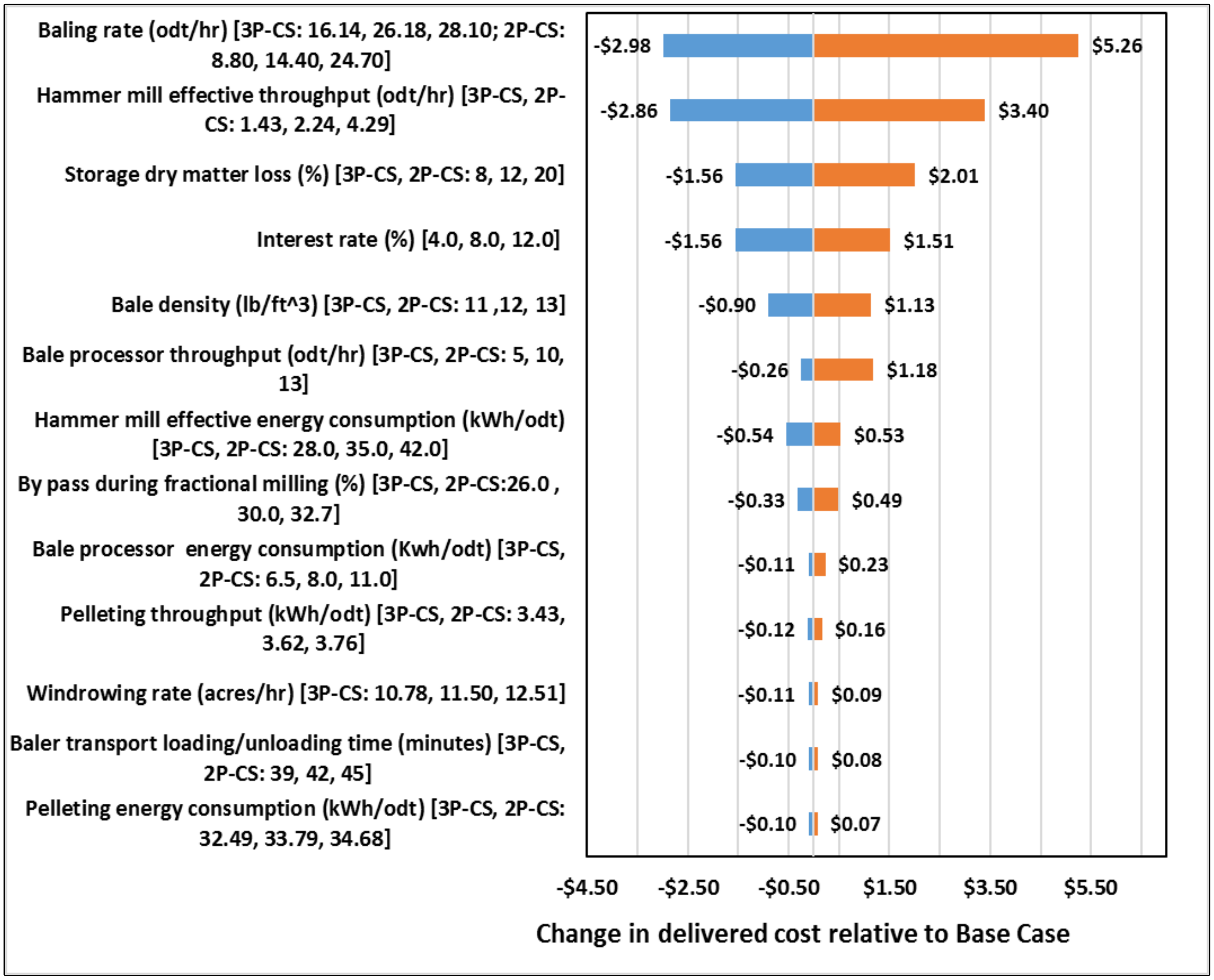

Figure 4. *Tornado chart showing sensitivity of cost to operational parameters used to model the 2019 SOT Design. Values in the parenthesis represent the minimum, SOT and maximum value of each parameter for different biomass.*

3. INDUSTRIAL RELEVANCE OF THE BLENDSTOCKS

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 and two-pass corn stover that can be purchased at average grower payments of $21.42/dry ton and $20.13/dry ton, respectively. The current availability of the blendstocks has been primarily determined through use of the 2016 Billion Ton Report. While BT16 primarily presents projections of how the market will develop based on sustained investment and technology improvement, the 2016 estimates in BT16 represented the currently economically available resources in the calendar year 2016. In 2016 it was estimated that there were 114,072,663 dry tons of corn stover available nationally, with 1,095,021 dry tons of corn stover within 100 miles of the study area. The region of interest for the 2019 herbaceous SOT remains the same as the 2019 SOTs, 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. QUALIFICATION OF THE BLENDSTOCKS FOR RENEWABLE IDENTIFICATION NUMBERS

The Environmental Protection Agency revised the National Renewable Fuel Standard Program to implement the requirements of the Energy Security and Independence Act of 2007 (EISA), in 2010. The revision of the program became known as RFS2 and mandated the use of 36 billion gallons of renewable fuel by 2022. As part of the revised rules, definitions of qualified biofuel feedstocks were outlined; the revised rules stipulated that "renewable fuels" had to be made from materials that qualify as renewable biomass. To be considered renewable biomass the materials must conform to the specified types and land types from where they are harvested as directed by EISA. From the final rule published in Vol 75, No. 58 of the Federal Register on page 14681.

"*The definition includes:*

- *Planted crops and crop residue from agricultural land cleared prior to December 19, 2007 and actively managed or fallow on that date.*
- *Planted trees and tree residue from tree plantations cleared prior to December 19, 2007 and actively managed on that date.*
- *Animal waste material and byproducts.*
- *Slash and pre-commercial thinnings from non-federal forestlands that are neither old-growth nor listed as critically imperiled or rare by a State Natural Heritage program.*

- *Biomass cleared from the vicinity of buildings and other areas at risk of wildfire.*
- *Algae.*
- *Separated yard waste and food waste*."

Biochemical conversion focuses primarily on herbaceous materials. Specifically, the qualification must be examined for the three potential feedstock sources that were considered: corn stover, switchgrass and grass clippings.

Corn stover qualifies as a renewable material under Section II.B.4.a.i on page 14691. This section states that "… planted crops and crop residue harvested from agricultural land cleared or cultivated at any time prior to December 19, 2007, that is either actively managed or fallow, and non-forested." This section goes on to further define both planted crops and crop residue. The definition of planted crops is the following:

> *"All annual or perennial agricultural crops from existing agricultural land that may be used as feedstock for renewable fuel, such as grains, oilseeds, and sugarcane, as well as energy crops, such as switchgrass, prairie grass, duckweed and other species (but not including algae species or planted trees), providing that they were intentionally applied by humans to the ground, a growth medium, or a pond or tank, either by direct application as seed or plant, or through intentional natural seeding or vegetative propagation by mature plants introduced or left undisturbed for that purpose."*

While crop residue is defined as the following:

> *"The biomass left over from the harvesting or processing of planted crops from existing agricultural land and any biomass removed from existing agricultural land that facilitates crop management (including biomass removed from such lands in relation to invasive species control or fire management), whether or not the biomass includes any portion of a crop or crop plant."*

In addition to the definitions of planted crops and crop residue, the qualification as a renewable material stipulates that the biomass must be harvested from "existing agricultural land", which is limited to three land types: cropland, pastureland and Conservation Reserve Program land.

Cropland is defined for the purposes of EISA and RFS2 as, "land used for the production of crops for harvest, including cultivated cropland for row crops or close-grown crops and non-cultivated cropland for horticultural crops". While pastureland is defined as, "land managed primarily for the production of indigenous or introduced forage plants for livestock grazing or hay production, and to prevent succession to other plant types." Another caveat for the qualification of agricultural land is that the land must have been cleared or cultivated prior to December 19, 2007 and actively managed or fallow and non-forested since December 19, 2007. Under normal conditions, both corn stover and switchgrass will meet the conditions necessary to be deemed a renewable material and qualify for RINS.

Ultimately, the qualification of biomass as renewable is subject to verification that the feedstocks meet the requirements specified by EISA. Currently, there are three mechanisms that provide this verification. First, the individual fuel production facilities can perform their own recordkeeping and reporting. Second, renewable fuel producers can form a consortium that funds third-party audit of quality assurance, based on an EPA approved plan. The final method only is only available to producers sourcing their biomass entirely from within the United States. This method uses an aggregate compliance approach using USDA publicly available data about agricultural land to form the basis of determination on feedstock renewability. In the case of non-agricultural products, producers must obtain enough documentation from their suppliers to prove compliance with EISA definitions.

5. SUMMARY

The Terrestrial Feedstock Supply and Logistics 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, experiment-based results and data, and provides a relative comparison to technical targets and costs goals from design cases.

Although CFSS form 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 point 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 2019 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 2019 Herbaceous SOT incorporates several technology changes in feedstock preprocessing and introduces opportunities from the integrated landscape management (ILM) strategy and increased grower participation to reduce biomass access costs, while maintaining or improving grower profitability. During FY18 uneven flow from the horizontal bale grinder was identified as a significant issue limiting preprocessing system throughput. Based on FSL-funded research at INL, the 2019 Herbaceous SOT replaces the horizontal bale grinder used in the first stage size reduction with a bale processor. The improved uniformity of biomass flow entering the PDU eliminated slugging flow from the first stage size reduction and improved the throughput of downstream operations. In order to achieve moisture reduction through frictional heating during grinding (which allowed elimination of the costly rotary drum dryer in previous SOTs), the second stage grinder was changed from a rotary shear, which does not remove moisture, back to a hammer mill. Finally, the 2019 Herbaceous SOT introduces modified three-pass and two-pass corn stover supply curves derived from the BT16 resource assessment, based on FY19 modeling results (WBS 4.2.1.20) quantifying economic benefits of ILM in the supply area, together with modeling results (WBS 1.2.1.5) identifying ILM strategies to increase grower participation.

The 2019 Herbaceous SOT predicts a modeled delivered feedstock cost of $81.37 /dry ton (2016$); this is a $2.30/dry ton (2016$) decrease from the 2018 Herbaceous SOT. Technology improvements that contributed to this modeled cost reduction include reduced cost for the new preprocessing design and quantification of the opportunities of the integrated landscape management (ILM) strategy and an increased grower participation rate to reduce the grower payment portion of biomass access costs, while maintaining or improving grower profitability. Sensitivity analysis on various process parameters that affect delivered feedstock cost in the 2019 Herbaceous SOT shows that the delivered cost could vary from $78.35-$86.69/dry ton. The highest-impacting factors that could lead to uncertainty in delivered cost included effective baling rate, hammer mill throughput, storage dry matter loss, interest rate, and bale density.

The 2019 Herbaceous SOT showed a net increase in greenhouse gas emissions from 69.27 kg CO_2e/ton in 2018 to 84.16 kg CO_2e/ton in 2019. An increase in energy consumption during preprocessing, as well as increased bale transport distance to the distributed depots and increased transportation distance for pellets to the biorefinery contributed to this 14.89 kg CO_2e/ton net increase of GHG emissions. The reason for the increased transportation distances was the cost trade-off of going farther from the biorefinery to access the cheaper ILM-derived counties (the cheaper price outweighed the cost of increased supply radius).

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APPENDIX A – 2019 Herbaceous State of Technology Feedstocks Logistics Design and Assumptions

The 2019 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 an herbaceous biomass blend comprised of 33.33% three-pass stover and 33.67% two-pass stover. The 2019 Herbaceous SOT incorporates two depots (identified as Nodes 25 and 27 in Figure 3 and Table 5 of the main document, and Figure A-1 in this appendix).

The 2019 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 2017 and 2018 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. 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 and also referred to as “multi-pass harvesting systems.” The two-pass corn stover harvesting and collection method modeled is an advanced harvest method that is currently utilized by Poet-DSM to harvest corn stover for its Emmetsburg, IA facility. In this method, the first pass is grain harvest using a combine with header raised to just below the ear on the corn stalks and the spreader turned off, and the second pass is a baler (Birrell et al. 2014; Shinners et al. 2012). This eliminates the windrowing step, which is a significant source of soil entrainment in the baled corn stover. The raised header (higher cut height) leads to a lower harvest yield and is generally a conservative approach to ensure soil sustainability. The three-pass stover and two-pass corn 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 2019 Herbaceous SOT utilizes general purpose depots in the sense that they employ identical preprocessing equipment in each, and can receive any of the sources of agricultural biomass or switchgrass, although the depots in the least-cost scenario receive only a single biomass type (see Table 6 and Figure A-1). The baled biomass delivered from road-side storage at the farm gates of the supplying counties is size reduced using hammer milling/fractional milling followed by rotary shear, 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 (separated by biomass type) when received and blended to the correct ratio immediately prior to feeding to the reactor throat. The silos serve as the metering bin for the conversion process, as the pellets are blended as they are conveyed to the feeding system for the pretreatment reactor.

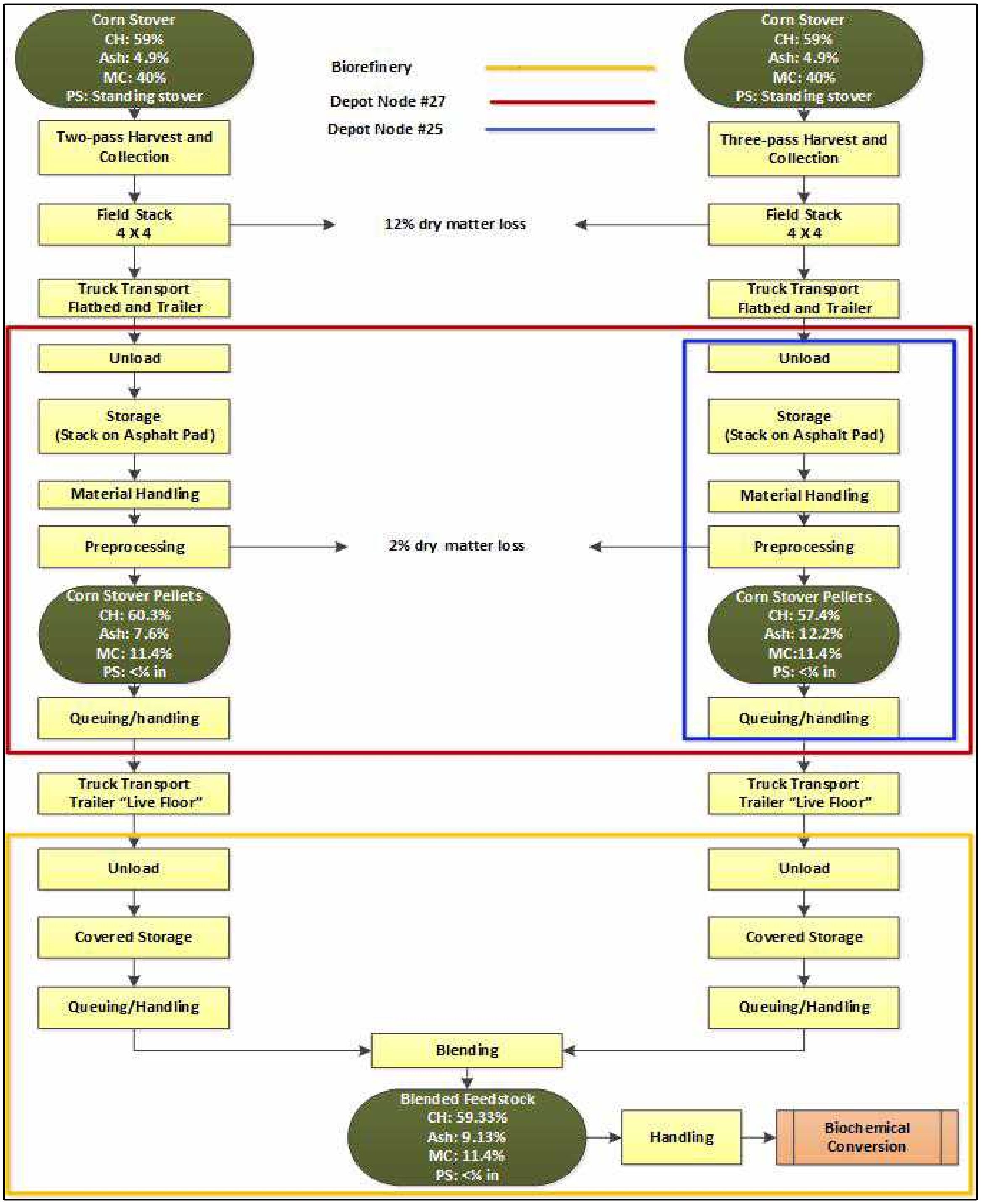

Figure A-1. *The modeled 2019 Herbaceous SOT feedstock supply system. CH=Carbohydrate content, MC = moisture content, PS=Particle size. Depots are identified as nodes 25 and 27. Optimal locations and sizes of these nodes are listed in Figure 3 and Table 5 and 6 of the main body of this report.*

Resource Availability

The geographic area chosen for the 2019 Herbaceous SOT is northwestern Kansas, with the biorefinery located in Sheridan County. It was assumed that all corn stover, switchgrass and grass clippings 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 in 2019 was estimated from the county-level data in the BT16 report (DOE 2016a) and modified through implementation of the ILM strategy (see Appendix B). Corn stover availability in BT16 is representative of conventional three-pass harvesting. We assumed that two-pass harvesting would be limited to high-yielding counties (defined as stover yields ≥ 2.0 dry tons/acre), however, three-pass harvesting could also be utilized in these counties. We further assumed that only three-pass harvest would be used in low-yielding counties (stover yields < 2.0 tons/acre). This was done to maximize yields of corn stover from the low-yielding counties, which are significantly greater in number than high-yielding counties.

Because two-pass harvesting cuts higher on the stalk, less stover is collected by the baler. In a multi-year study, Birrell et al. (2014) showed that two-pass harvest of material other than grain (MOG) reached about 35% of the collection efficiency of conventional three-pass harvest. In another study (Smith et al. 2014), it was observed that the specific two-pass harvest method assumed in this SOT achieved slightly less than half the yield observed for the flail shred three-pass harvest method assumed for this study (Table A-1). Three-pass harvesting with a flail shredder and square bales achieved 1.9-2.0 dry tons/acre, while the two-pass system achieved 0.9-1.0 dry tons per acre. The average ratio of two-pass yield/three-pass yield is then 0.487. Hence, for the high-yielding counties, we adjusted the BT16 three-pass availabilities for corn stover down by a factor of 0.487 to give the two-pass availability numbers for the analysis.

Table A*-1.** *Baled corn stover yield and mean ash contents in three-pass harvesting (Rake, Flail), and two-pass harvesting (MOG) (Smith et al. 2014). We assumed square bales for transportation; relevant treatments in the table are in* ***bolded *text. The flail treatment (ISU '12 3.2) was not used because its low ash content is inconsistent with the other flail treatments.*

Windrow	**Bale Type**	**ID**	**Yield (DMT/acre)**	**Ash** (wt% db)
MOG[a]	Round	MOG-1	0.5	4.9
MOG	Round	MOG-2	0.6	3.8
MOG	Round	MOG-3	0.7	7.6
MOG	Round	MOG-4	0.7	6.8
MOG	Round	MOG-5	0.7	5.6
MOG	Round	MOG-6	0.8	6.3
MOG	**Square**	**MOG-7**	**0.9**	**5.8**
MOG	**Square**	**MOG-8**	**1.0**	**5.3**
Rake	Square	RAKE-1[b]	0.9[b]	8.1
Rake	Square	RAKE-2[b]	1.4[b]	7.6
G-hoff	Square	G-HOF	1.9	8.0
1-P	Square	1-PASS[c]	1.9	5.7
Flail	**Square**	**FLAIL[c]**	**2.0**	**13.9**
Rake	Square	ISU '12 3.1	1.4	14.6
Flail	Square	ISU '12 3.2	1.4	7.6
Rake	Square	ISU '12 3.3	1.9	15.6
Flail	**Square**	**ISU '12 3.4**	**1.9**	**12.1**

a The combine drops the material other than grain (MOG) into a loose windrow, which is followed by a separate baler. Drawbacks to this method are reduced collection efficiency and field "striping" as a result of uneven residue removal.

b Assumed average bale weight from previous co-located studies

c Provided by Matt Darr, Iowa State University

A.1. Process Design and Cost Estimation Details

In this section, the costs of different supply chain operations are described along with assumptions and input parameters. The 2019 Herbaceous SOT uses the same assumptions used for the 2018 Herbaceous SOT as shown in Table A-2.

Table A-2. *Energy prices and interest rates used to model herbaceous feedstock logistics costs for the 2019 Herbaceous SOT.*

Component	2018 Assumptions	2019 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.2.1 Harvest and Collection

The 2019 Herbaceous SOT design utilizes only 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). Two-pass harvesting allows better quality but decreases the harvesting yield. Conventional three-pass systems involve cutting the feedstock, collecting the material into a windrow, and then baling the windrowed material (Figure A-2). The two-pass collection method eliminates the windrowing step and thereby reduces the potential for soil contamination (Shinners et al. 2012, Birrell et al. 2014). In this method, the combine drops the material other than grain (MOG) into a loose windrow, which is followed by a separate baler. The two-pass method assumed here is that utilized by POET-DSM's Advanced Biofuels' Project Liberty. Drawbacks to this method are reduced collection efficiency (due to a higher cut height) and field "striping" (Birrell et al. 2014) as a result of uneven residue removal. Two-pass collection does not increase the required throughput to the combine or hinder its operation but requires some minor operational modifications. Combine operation is altered by disengaging the straw choppers at the rear of the combine to allow the MOG to drop behind the combine into a loose windrow. The combine is modified by adding "stalk-stompers" or by mounting rollers under the header to bend the lower stalk over in the rows on which the MOG will be dropped. These devices are commonly (but not universally) used under the wheel-track rows to reduce the risk of tire punctures. They are optional equipment but are relatively inexpensive.

Because of the higher cutting height in two-pass harvest, the stover yields are limited to the upper stalk, husk, cob, and some leaves, which (stated above) amount to about, or less than, 1 ton/acre. However, it is purported that MOG is lower in moisture and ash content

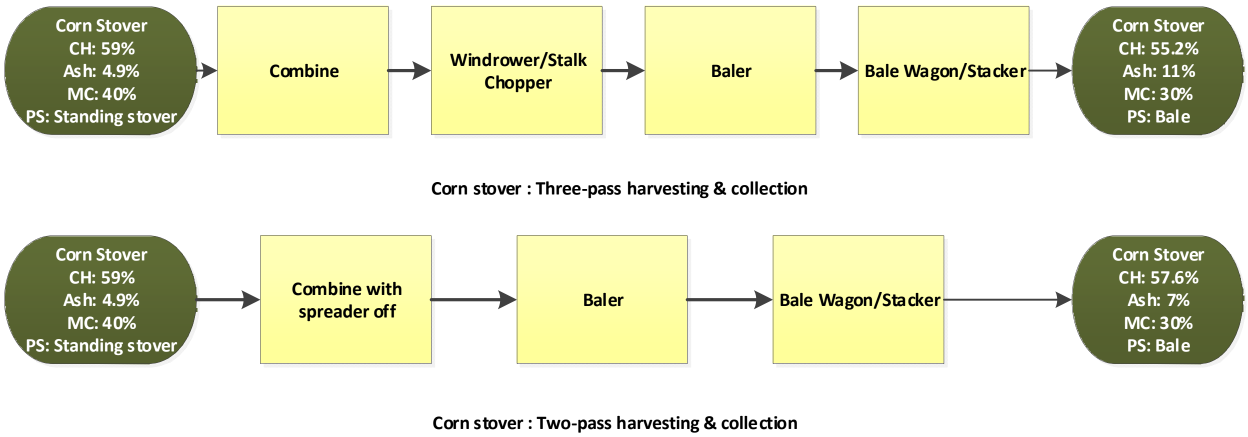

Figure A-2. *The 2019 Herbaceous SOT harvest and collection operations for corn stover. It is assumed that prior to baling there is some amount of field drying to reach 30% moisture for corn stover. CH=Carbohydrate content, MC = moisture content, and PS=Particle size.*

(Hoskinson et al. 2007). Most of the ash variability is introduced from soil during baling. Corn stover yield could be potentially increased in the two-pass harvest and collection method by cutting stover lower in the stalk. This could be accomplished by using a stalk-chopping head, reducing the cutting height. However, with lower stalk comes more moisture and ash and the stalk chopping head requires more power and increases cost.

It was assumed that two-pass harvesting will be limited to high-yielding areas as a result of this stover yield limitation. Our reasoning is as follows: Pordesimo et al. (2005) demonstrated that at grain maturity, the above ground stover mass fraction is approximately equal to the grain mass, in that case 6.7 dry tons/acre and 207 bushels/acre for the stover and the grain, respectively. In a multi-year study (Birrell et al. 2014), two-pass baling resulted in 35% stover yield with 186 bushels/acre grain yield. To recover 0.7 dry tons/acre (the experimentally-validated average two-pass yield used for estimating harvesting costs for two-pass harvest; see Table A-4) or more, it would be necessary to have grain yields of 372 bushels/acre, which is unlikely on low-yielding fields. This represents an average yield in the Corn Belt, meaning that half of the available fields will have yields below this value, thus, corn stover yields less than 0.7 dry tons/acre. Part of the quality benefit from two-pass harvest arises from lower levels of inorganics higher up the stalk. Hoskinson et al. (2007) showed elevated inorganic nutrient and total ash contents in the lower stalk materials relative to the upper stalk. Additionally, an analysis by Birrell et al. (2014) showed that a greater quantity of ash forming minerals (Al, B, Cu, Fe, Mn) were present in multi-pass bales relative to two-pass MOG bales collected from the same experimental plots. Hence, while upper stalk collection via two-pass baling yields less stover, the total ash content of the stover is lower, and there is a sustainability benefit since inorganic nutrient removal from the field is lower as well.

Table A-3 summarizes the harvest and collection design assumptions for the 2019 Herbaceous SOT. The assumed yield, capacity and efficiency of harvest and collections equipment, moisture content, and ash content have been estimated based on published data (Anderson et al. 2013, Lindsey et al. 2013, Bonner et al. 2014b, DOE 2016a, 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].

Table A-3. *Harvest and collection design assumptions in the 2019 Herbaceous SOT for three-pass corn stover and two-pass corn stover.*

Component	Corn stover	
	Three-Pass Harvest	Two-Pass Harvest
Harvest time		
Operational hours	6 weeks/year, 6 days/week, 14 hour/days	6 weeks/year, 6 days/week, 14 hour/days
Combine		
Capacity	41 tons/hour	41 tons/hour
Field efficiency	70%	70%
Collection efficiency	43%	43%
Stalk chopping windrower		
Capacity	11.5 acres/hour	N/A
Efficiency	80%	N/A
Bale wagon/stacker		
Capacity	12 bales/load	12 bales/load
Baler		
Capacity	50 bales/hour	25 bales/hour
Harvest yield	1.2 tons/acre	0.7 tons/acre

a N/A, not applicable.

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

[2] Personal communication from William Smith, INL researcher

A.2.2 Storage

Field storage design assumptions for corn stover are included in the 2019 Herbaceous SOT. The current industry standard for assessing storage performance depends on the measure of dry matter loss. While losses occur during physical handling, such losses are minimized by best practices and are not considered a major factor for improvements within the storage operation. In contrast, dry matter losses via biological decomposition are highly variable, difficult to measure, and difficult to control. 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 substances. The 2019 Herbaceous SOT assumes that 30% moisture content bales in storage for one year will result in an average 12% dry matter loss (Cafferty et al. 2013a), identical to the assumption used for the 2018 Herbaceous SOT for corn stover. In the 2019 Herbaceous SOT, the dry matter losses are partitioned to individual corn stover components using the average losses of individual corn stover components observed in 3-month storage tests (Wendt et al. 2013) in the INL storage simulators at initial moisture contents ranging from 20-52% (Table A-4).

Table A-4. *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%

Additional storage assumptions are shown in Table A-5. The 2019 Herbaceous SOT assumes moisture loss of 5% moisture from 30% moisture corn stover bales during storage, which is a conservative estimate in comparison to the 10-14% moisture losses during bale storage observed in a storage study conducted by Shah et al. (2011). Finally, we assumed the distribution of dry matter losses among compositional components to be identical to that observed for corn stover (Table A-5).

Table A-5. *Field storage design assumptions for the 2019 Herbaceous SOT.*

Component	Corn stover
Storage moisture content	30%
Storage dry matter loss	12%/year
Storage moisture loss	5%/year
Stack configuration	4 x 4 tarped

A.2.3 Preprocessing

The 2019 Herbaceous SOT incorporates several preprocessing technology changes (and improved experimental data) from those used in the 2018 Herbaceous SOT, as well as improved pilot-scale PDU data to guide moisture-loss assumptions during grinding and pelleting. The first-stage grinder was replaced by a bale processor, which provides more uniform biomass flow and has higher throughput with lower energy consumption.

The 2019 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).

The 2019 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.

The 2019 Herbaceous SOT updates the percentage of material bypassed during fractional milling based on the pilot-scale testing performed under INL WBS 1.2.1.2. As shown in Figure A-3, fractional milling inserts a screening operation (disk screen) between the first-stage and second-stage grinding operations (the horizontal grinder and hammer mill, respectively) to

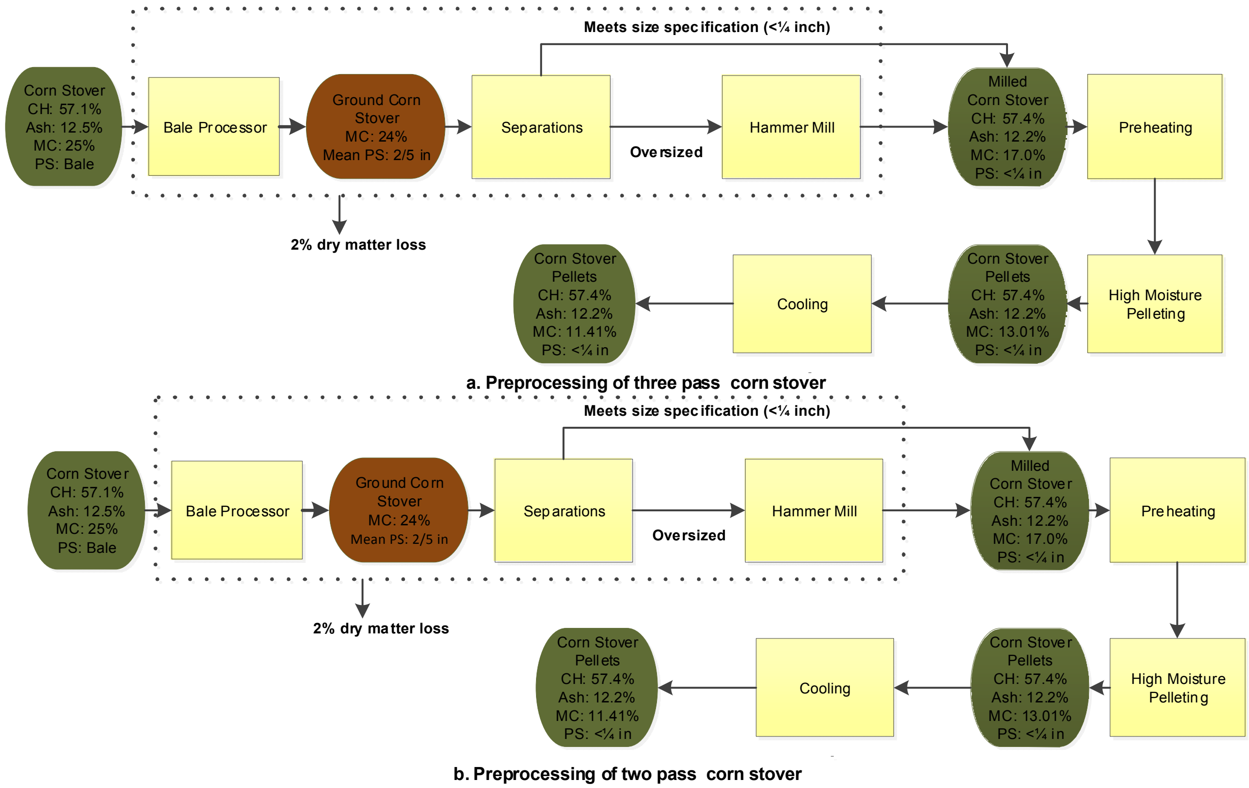

Figure A-3. *2019 Herbaceous SOT preprocessing configurations for corn stover. CH=Carbohydrate content, MC = moisture content, PS = particle size*

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 ground. Hence, a tighter particle size distribution is achieved. Particle size distribution analysis shows that 30.0% 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 2019 Herbaceous SOT design is shown Figure A-3(a)

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

for three-pass corn stover preprocessing, and in Figure A-3(b) for two-pass harvesting. Although the preprocessing operations are identical for both corn stover sources, they have been shown separately because their initial and intermediate moisture contents and compositions are different (these are shown at various stages within the figures). Input parameters (such as throughput and energy consumption) have been updated in Table A-6 for corn stover, based on pilot-scale results (WBS 1.2.1.2).

Table A-6. *Summary of 2019 Herbaceous SOT preprocessing assumptions. The benefit of fractional milling is included by adjusting the throughput and energy consumption of 2nd stage grinding.*

Component	Three-Pass & Two-Pass Corn Stover
Location of operation	Depot Nodes 25 and 27
Stage 1 size reduction	
Grinder type	Bale processor
Screen Size (inch)	NA
Energy (kWh/dry ton)	8
Throughput (dry ton/hour/machine)	10
Operating conditions (moisture %)	25.0%
Separations	
Screen type	Disc Screen
Energy (kWh/dry ton)	Minimal electricity
Throughput (dry ton/hour/machine)	10
Operating conditions (moisture %)	24.0%
Bypass	30%
Stage 2 Grinder	
Comminution method	Hammer mill
Screen Size (inch)	0.25
Energy (kWh/dry ton)	50 (35[a])
Throughput (dry ton/hour/machine)	1.57 (2.24[a])
Operating conditions (moisture %)	22.0%
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	1.70%
Energy (kWh/dry ton)	3.02
Throughput (dry ton/hour/machine)	5

a: The effective energy consumption is reduced because only 70% of the material is processed in Stage 2 due to fractional milling. The effective throughput is improved because only 70% of the material is processed in Stage 2 due to fractional milling

A.2.4 Transportation and Handling

The 2019 Herbaceous SOT incorporates both bale and pellet transportation. Baled biomass is shipped from field side storage to the depots, while pelleted blendstocks 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-7. Transportation and handling comprises 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 2018 Herbaceous SOT, the 2019 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 blended feedstock to the pretreatment reactor. Surge bins, conveyors, and tipper are used in handling operations.

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-6 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 2019 Herbaceous SOT incorporates densification to improve feedstock flowability.

Table A-7. Transportation and handling design assumptions in the 2019 Herbaceous SOT.

Component	Three-pass corn Stover	Two-pass corn Stover
Biomass characteristics during transportation from field to depot		
Format	Bale	Bale
Density	12 lb/ft^3	12 lb/ft^3
Moisture content	25%	25%
Biomass characteristics during transportation from depot to biorefinery		
Format	Bulk pellets	Bulk pellets
Density	39.42 lb/ft^3	39.42 lb/ft^3
Moisture content	11.53%	11.53%
Truck used during both transportation from field to depot and depot to biorefinery		
Speed	50 miles/hour	50 miles/hour
Type	Day cab	Day cab
Trailer used during transportation from field to depot		
Type	53-ft flatbed with ALSS	53-ft flatbed with ALSS
Volume	3,600 ft^3	3,600 ft^3
Trailer used during transportation from depot to biorefinery		
Type	Trailer "Live Floor" 48 feet 2-axle	Trailer "Live Floor" 48 feet 2-axle
Volume	3,600 ft^3	3,600 ft^3
Bale Loader		
Capacity	120 tons/hour	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 2019 SOT (Source: Stinger)*

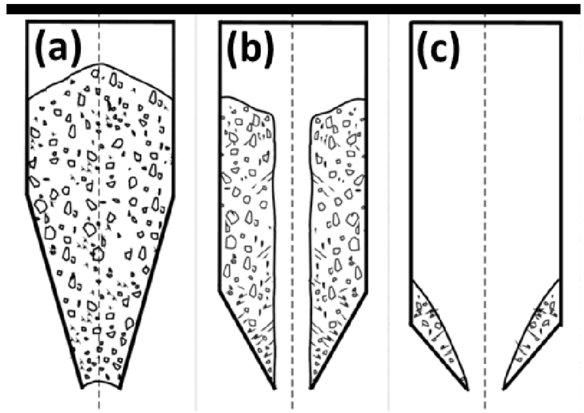

Figure A-5. *Common flow and handling issues encountered when handling biomass. (a) Cohesive arch; (b) Rathole; and (c) Incomplete cleanout. (Source: www.pharmtech.com)*

The 2019 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 blendstock pellet types based on the transportation and handling design assumptions shown above in Table A-8. 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-8.

Once the optimum resource supply, volume and depot locations were determined, an average weighted transportation distance was calculated for the different types of biomass and the pelleted blendstocks. Table A-9 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 2019 Herbaceous SOT. The average weighted transportation distances from field to biorefinery of three-pass corn stover and two-pass corn stover were 105.12 miles and 115.78 miles respectively.

Table A-8. *Total transportation costs for biomass bales and blendstock pellets.*

Distance (mi)	Bale Transportation Costs ($/dry ton)	Pelleted Blendstock Transportation Costs ($/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

Table A-9. *Summary of transported biomass, weighted transportation distance and average transportation cost for various biomass and pellet from field to depot and depot to biorefinery in the 2019 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	280,227	246,600	43.66	$8.37	241,668	61.45	$5.94
Two-pass corn stover	560,450	493,196	36.38	$7.55	483,332	79.40	$7.43
Blended	840,677	739,796	38.81	$7.82	725,000	73.42	$6.94

A.2.5 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 $2.3/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-7.

A.2.6 Blending

Pellets of each individual blendstock are conveyed into separate storage bins upon receipt from the depots. Pellets are blended in the biorefinery just prior to introduction to the pretreatment reactor feeding system and are blended to the desired ratio during conveyance to the feeder. The three-pass corn stover and two-pass corn stover pellets are blended at a ratio of 33.33%/66.67 respectively, and the blend is conveyed to the throat of the pretreatment reactor.

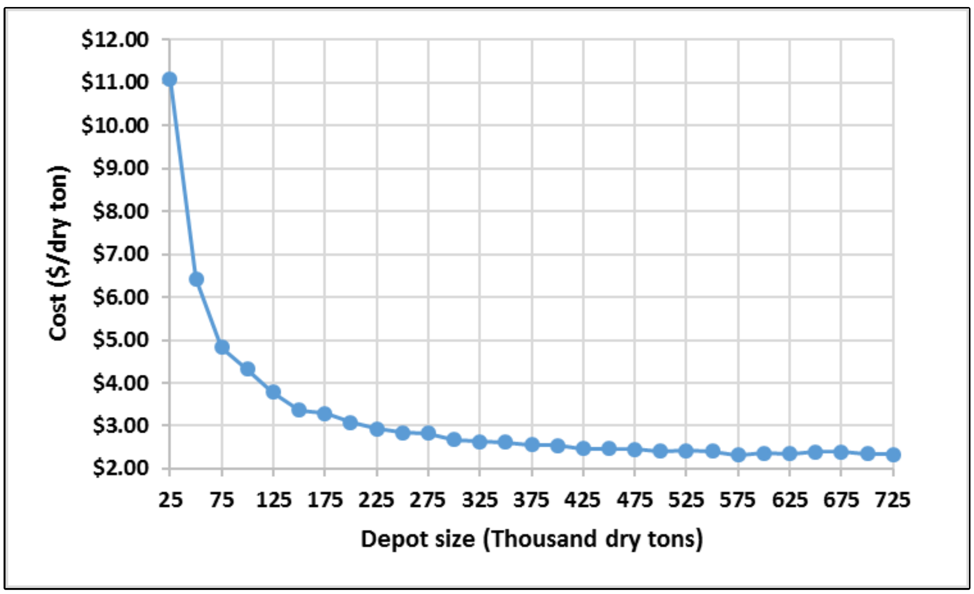

Figure A-7. *Estimated depot construction costs as a function of depot scale.*

A.2.7 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 2019 Herbaceous SOT. Ash disposal costs are assumed to be $37.63/dry ton of ash (Davis et al. 2013). Delivering the feedstock blend 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-11 shows the cost breakdown by operation for the individual blendstocks.

Table A-11. *2019 Herbaceous SOT modeled costs for production of blendstock pellets, by operation.*

Cost Element	**Three-Pass** Corn Stover ($/dry ton)	**Two-Pass** Corn Stover ($/dry ton)
Grower payment	**$21.42**	**$20.13**
Harvest and collection	$13.84	$18.79
Combine	$0.00	$0.00
Shredder	$4.10	-
Baler	$6.29	$15.34
Stacker	$3.45	$3.45
Storage & queuing	**$6.40**	**$6.53**
Field side storage	$3.97	$4.10
Depot storage	$0.88	$0.88
Refinery storage	$0.12	$0.12
Handling and queuing at depot	$1.21	$1.21
Handling and queuing at refinery	$0.22	$0.22
Transportation and handling	**$14.32**	**$14.98**
Transportation from field to depot	$8.37	$7.55
Transportation from depot to refinery	$5.95	$7.43
In-plant receiving and preprocessing	**$20.84**	**$20.84**
Depot construction cost	$2.52	$2.52
Bale processor	$1.80	$1.80
Hammer mill	$8.78	$8.78
Densifier	$5.61	$5.61
Cooling	$0.88	$0.88
Conveyors	$0.16	$0.16
Dust collection	$0.75	$0.75
Surge bin	$0.05	$0.05
Misc. Equipment[a]	$0.22	$0.22
Blending	$0.07	$0.07
Dockage	**$2.74**	**$1.01**
Ash dockage	$2.71	$0.98
Moisture dockage	$0.03	$0.03
Total delivered blendstock cost	**$79.56**	**$82.28**

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

APPENDIX B – Incorporation of ILM Strategies to Reduce Grower Payment and Increase Biomass Availability

ILM considers subfield management strategies to reduce biomass production costs either through gains in operational efficiencies, or through improvement of field-level profitability by maximizing the profitability of both grain production and biomass production. Although seeming contradictory, this provides a mechanism to reduce overall grower payment while either maintaining or improving overall grower profitability.

A technoeconomic analysis (TEA) was conducted to demonstrate how Integrated Landscape Management (ILM) implementation can result in reducing biomass production costs by 20% relative to baseline cost assumptions set by the Herbaceous Feedstock 2017 State of Technology (SOT) Report (Roni et al., 2017). Four specific ILM scenarios were analyzed for years 2015-2017 to demonstrate ILM contributions to reducing biomass production costs by 20% relative to baselines established in the Herbaceous Feedstock 2017 SOT Report (Roni et al., 2017). The majority of the economic results indicate ILM practices improve net field revenue over business as usual (BAU) using reduced biomass production costs (20%) allocated to biomass producers. This was achieved by shifting crop inputs from low-yielding areas, strategically introducing crop residue harvest and collection in the highest yielding areas, reducing tillage practices, and introducing new revenue streams for biomass production.

Additional analysis has shown ILM as a viable strategy to improve the quantity of available biomass. Muth et al. (2012) developed a computational strategy and examined stover removal schemes at a subfield resolution on three fields in Iowa and found that USDA Natural Resources Conservation Service (NRCS) conservation management planning guidelines can exceed sustainable removal thresholds for portions of the field (Muth et al., 2012). Applying this strategy and integrating USDA Revised Universal Soil Loss Equation version 2 (RUSLE2) and Wind Erosion Prediction System (WEPS) models within a computational framework revealed that more than 150 million metric tons of crop residue could be sustainably harvested as a biomass resource (Muth et. al. 2013). Bonner et al. (2016) modeled the integration of switchgrass into a corn-producing field in Iowa and showed significant gains in total biomass availability and soil organic carbon, while reducing total soil erosion resulting in environmental improvements valued at $64 per acre (Bonner et al. 2016).

B.1 Grower participation rate in adopting ILM strategy

Lignocellulosic biomass sources, especially dedicated energy crops, are expected to play an important role the development of supply chains for biofuels and bioproducts into the future (Lee et al., 2018; Langholtz et al., 2016). However, producers must be willing to establish and grow dedicated energy crops. Surveys of farmer willingness to grow dedicated energy crops have been used to try to understand the motivations of growers and have shown an unwillingness to convert productive cropland (Barham et al., 2016).

Willingness of a farmer to adopt has been viewed as purely rational decision, in which the farmer is acting only in his or her own self-interest (Ma et al., 2012; Lopez et al., 1994; Brunstad et al., 1999; Dupraz et al., 2003). However, decisions of this type have been found to be, rarely, purely rational (Simon et al., 1972; Kahneman, 2003), but rather are made intuitively. The decision makers are guided by the information that they have access to, rather than the perfect information needed to make a purely rational decision. In that case, they are acting in "bounded rationality" and are looking only for a satisficing solution, i.e. a solution that meets the needs at the time, rather than the perfect long-term solution.

Agent based modeling and simulation (ABMS) was used in WBS 1.2.1.5 to identify strategies to increase grower participation in establishing and growing energy crops in 50 counties at three states: Nebraska, Kansas and Colorado (Hartley, 2019). ABSM is a stochastic modeling system that utilizes the interactions between agents and their environment to understand the behavior of complex systems (North and Macal, 2007). The purpose is to model a system where the behavior of the agent is not known with complete certainty, but rather behaviors are dictated by probability or random events. ABMS is unlikely to provide a single solution to a problem, but rather identify repeated patterns that provide insight into the agent's behavior. Based on the age profile, risk aversion, land productivity and social structure in the region, the simulation results showed that by the end of the 50-year simulation, approximately 77% of the available low yielding area have been utilized to grow switchgrass, while only approximately 44% of the high yielding acres that could have residue removed had been harvested (Hartley, 2019).

B.2 Approach to Redistributed BT16 Biomass Supply Quantity Using ILM Strategy and Grower Participation Rates

In the Feedstock State of Technology reports through FY18, BT16 estimates served as the only source of feedstock assumed to be available. With the BT16 feedstock assessments it was possible to meet and exceed the $85.51/dry ton (2016$) cost target outlined in the MYPP (DOE, 2016; Roni et al., 2017). However, the location for this facility was situated on the border of high producing corn areas and areas suitable for whole-field monoculture switchgrass production. In order to meet the cost goals going forward, it will be necessary to find alternatives that allow for the crops that are needed to meet the quality requirements at a lower cost.

The geographic area chosen for the 2019 Herbaceous SOT is northwestern Kansas, with the biorefinery located in Sheridan County. It was assumed that all the biomass 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. In each selected biomass supply county, BT16 biomass supply curves for 2019 were redistributed using this ILM strategy along with the modeled grower participation rates from the analyses in WB 1.2.1.5. It is important to note that the overall supply quantity in the redistributed supply curves is the same as the BT16 biomass supply curve for 2019.

The process of redistributing the supply curves is illustrated in Figure B- 1. First, reduced price categories were generated based on the 20% cost reduction assumption in the ILM scenario (Griffel et al., 2018). ILM was then assumed to be adopted to estimate the percentages of high

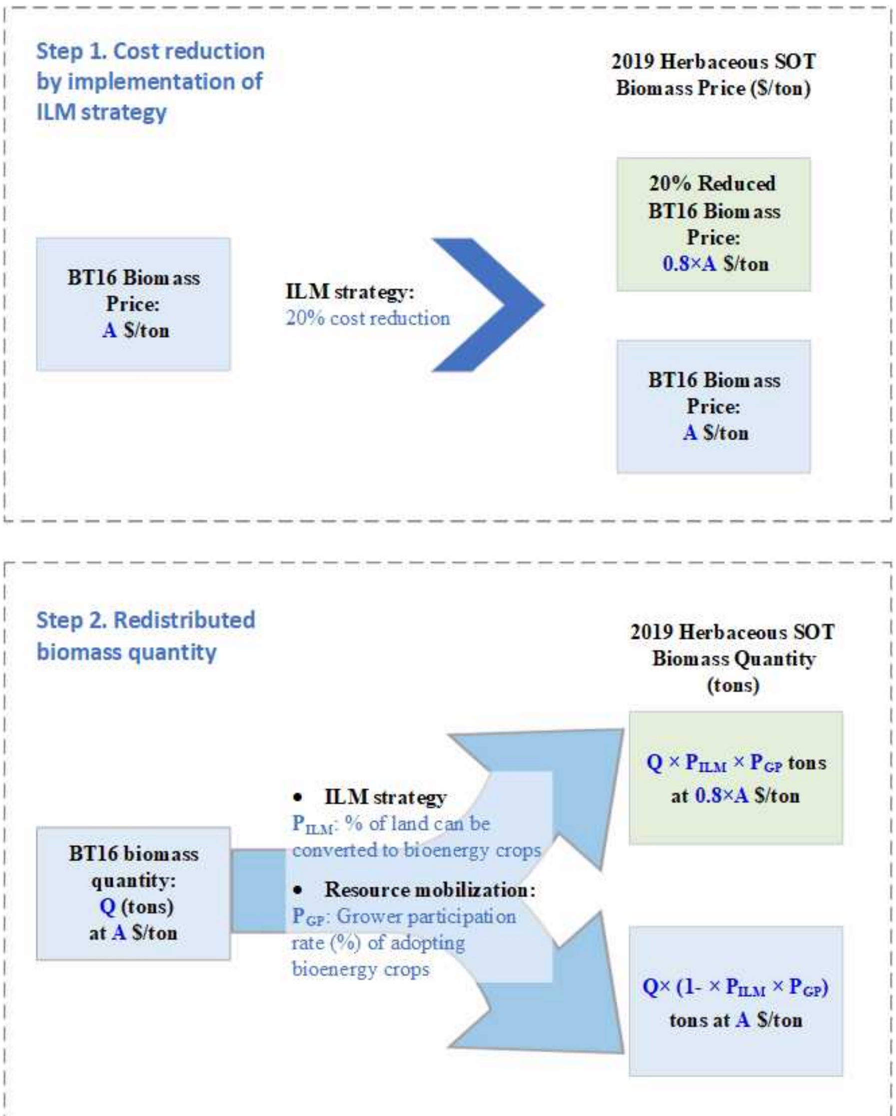

Figure B-1: *Approach to redistributing the BT16 biomass supply curves: Step-1 shows the conversion of BT-16 farmgate price to reflect 20% cost reduction to the applicable area. Step-2 shows conversion of BT-16 supply quantity to generate modified supply curve based on modified farmgate price and grower participation rate.*

yielding and low yielding areas in each county that could be converted to bioenergy crop (switchgrass). Based on the simulation results from WBS 1.2.1.5, a grower participation factor of 44% was applied to the high yielding area to estimate the potential areas that can provide more corn residues (Hartley, 2019). For the low yielding area, a grower participation factor of 77% was applied to estimate the potential acres for switchgrass. The portion of biomass produced in the ILM scenario with a 20% lower production cost was then calculated. The detailed analysis methodology is described in the section below.

Figure B-2 shows an example of the price category calculation. In this example, assuming a portion of land in each county will be converted to bioenergy crop plantation using the ILM strategy and a 20% cost reduction in the farmgate price, a new set of farmgate prices are generated ranging from $32 to $100. The ILM strategy was then adopted to estimate the percent of high yielding and low yielding area in each county that can be converted to bioenergy crop

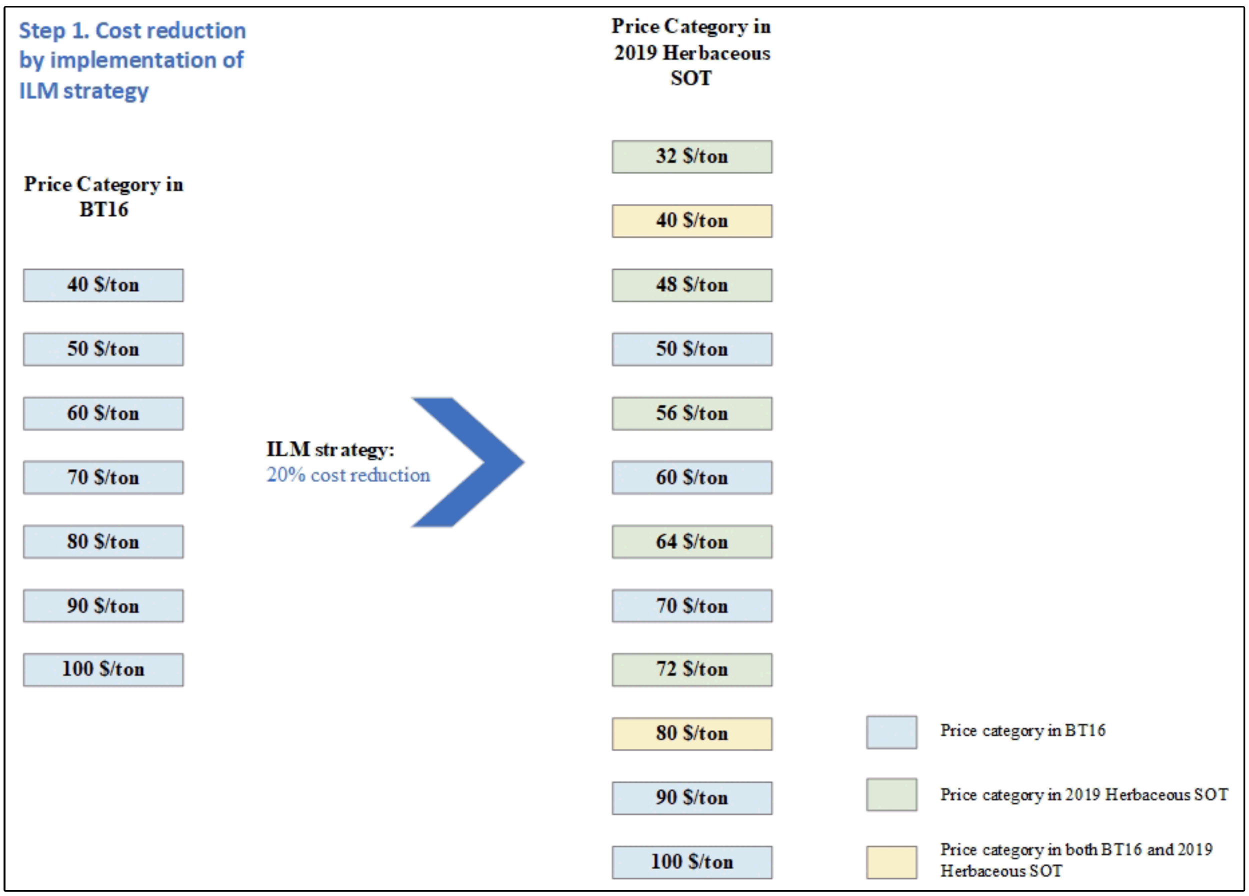

Figure B-2. *Example of the method of modifying BT-16 farmgate prices and generating a new set of farmgate prices for ILM biomass by applying the 20% cost reduction to the applicable area.*

plantation. The possibility for farmers to adopted ILM strategy was estimated based on the simulation results from WB 1.2.1.5. A grower participation factor of 44% was applied to the high yielding area to estimate the potential areas that can provide more corn residues (Hartley, 2019).

Figure B-3 shows an example of the modified supply curve projection based on BT16 resource projection and grower participation to the ILM strategy. Letting *define* the new supply projection at the $32 farmgate price; *define* the BT16 supply projection at the $40 farmgate price; *define* the percentage of land can be converted to bioenergy crops, *define* the grower participation rate (%) adopting bioenergy crops; *define* the new supply projection at the $40 farmgate price; *define* the BT16 supply projection at the $50 farmgate price; *define* the new supply projection at 48$ farmgate price; and *define* the BT16 supply projection at the $60 farmgate price, the new supply projections at $32, $40 and $48 farmgate price are then calculated using equations 1-3 below.

Similarly, the supplies over different ranges of farmgate price from $50-$100/dry ton can be calculated as shown in Figure B-3.

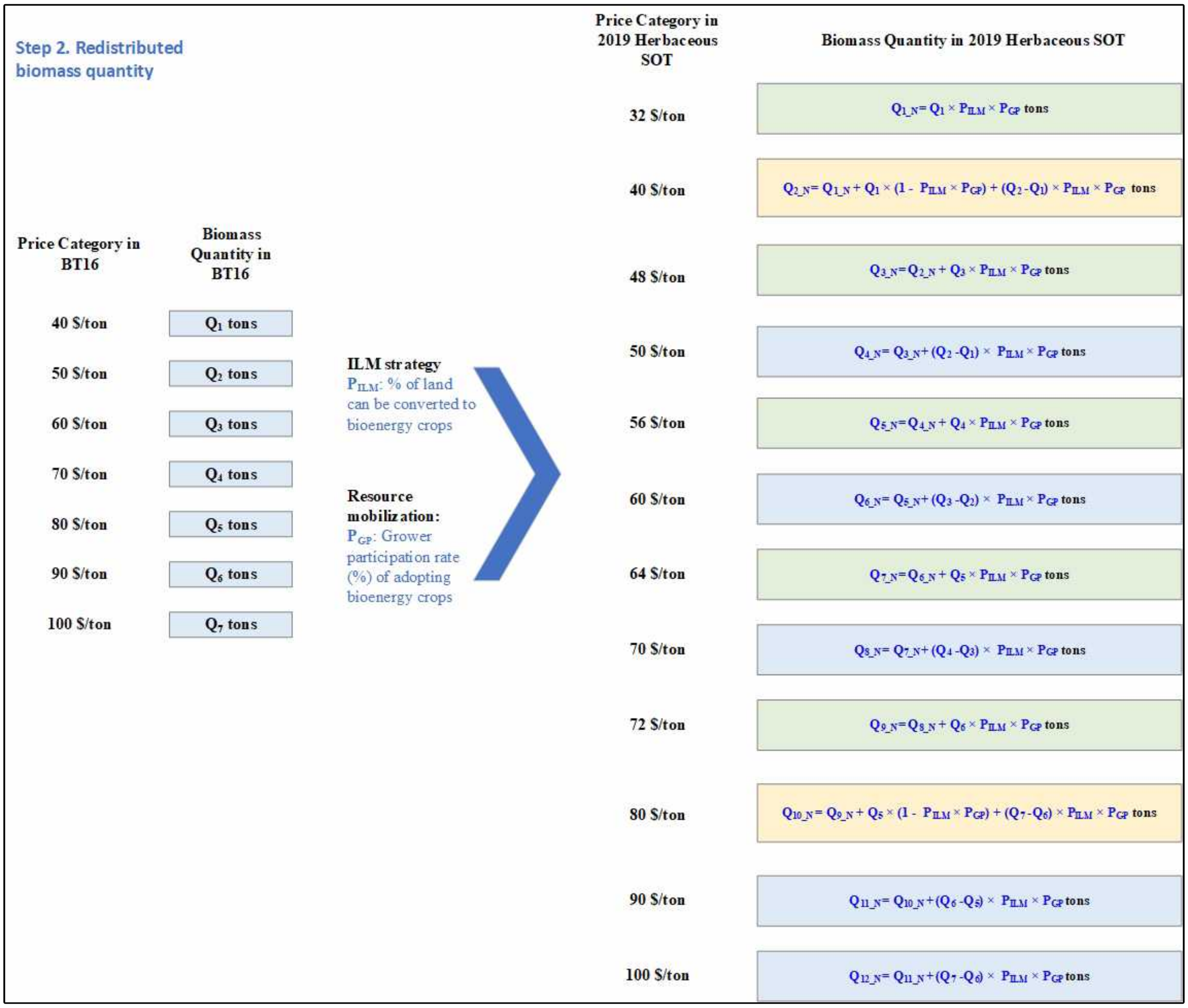

Figure B-3. *Example of biomass supply projection in the 2019 Herbaceous SOT based on the BT16 supply curves, ILM strategy and grower participation rate.*

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