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WOODY FEEDSTOCKS 2022 STATE OF TECHNOLOGY REPORT

September 2024

Changing the World's Energy Future

Pralhad Hanumant Burli, Yingqian Lin, Damon S Hartley, David N Thompson

Idaho National Laboratory

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EXECUTIVE SUMMARY

The U.S. Department of Energy promotes 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 in this mission, Idaho National Laboratory completes an annual SOT report for n^{th}-plant and 1^{st}-plant woody biomass feedstock logistics. The purpose of the SOT is to provide the status of feedstock supply system technology development for woody biomass to biofuels relative to technical targets and cost goals from specific design cases, based on data and experimental results.

Conventional feedstock supply systems need to be modified to meet the demands of conversion pathways, specifically to have the ability to adjust the quality of the raw biomass materials. Advanced systems incorporate innovative methods of material handling, preprocessing and supply chain configuration. In advanced designs, variability of the raw biomass can be reduced to produce feedstocks of a uniform format, moving toward biomass commoditization. Against this backdrop, the 2022 Woody SOT for low-ash woody feedstocks utilizes feedstock fractionation by incorporating technologies that can separate the biomass into its anatomical fractions (wood, bark, needle, and extrinsic ash) to reduce impurities and attempt to maximize the retention of usable fractions that satisfy downstream quality considerations. By using a series of air classification steps, this strategy can reduce the extrinsic ash in forest residues, separate out a majority of the incoming needles (which can be supplied to alternate markets), and maximize the retention of whitewood in the usable fraction. The fractionated forest residues are then mixed with clean-pine chips in a 50-50 blend to prepare the feedstock for the desired conversion pathway.

The n^{th}-plant analysis estimated the delivered cost for the feedstock at $69.23/dry ton (2016$) which represents a $6.64/dry ton decrease compared to the cost estimate of the 2021 Woody SOT supply system for low-ash woody feedstocks. The quality requirements in the 2022 Woody SOT were identical to those of the 2021 Woody SOT at ≤ 1.00 wt % ash and ≥ 50.51 wt% carbon. The cost savings derive primarily from reductions in dry matter losses

during air classification. The GHG emissions for the n^th^-plant analysis were estimated at 178.39 kg CO_2e/dry ton compared to 178.71 kg CO_2e/dry ton in the 2021 Woody SOT, a decrease of 0.32 kg CO_2e/dry ton. The small change stems from an increase in emissions attributed to preprocessing and slightly larger savings in emissions from transportation.

In the 1st-plant analysis of the 2022 Woody SOT system, the average throughput was estimated to be approximately 2,128 dry tons/day or 96.51% of the name plate capacity. During the simulation the daily throughput ranged from 1,090 dry tons/day to 2,200 dry tons/day, or 49.43% to 99.75% of the daily nameplate capacity. After the year of operation 722,403 tons of processed feedstock were produced in total without regard to quality considerations (99.64% of the annual nameplate capacity). The variability in throughput was primarily caused by equipment failures in the system. Regular failures, downtime caused by routine maintenance per manufacturer guidelines, contributed to a majority 62.50% of failures and 62.60% of downtime. Failures due to wear were the other cause of disruption within the system, impacting the rotary shear and orbital screen and accounting for 37.50% of the failures and 37.40% of the total downtime. Ultimately the system was on stream for 87.84% during the simulation period, which is only 2.16 percentage points below the nth-plant assumption for on-stream time. The production cost of the system averaged $71.66/dry ton. The costs ranged from a minimum of $71.23/dry ton to a maximum of $2,115.30/dry ton. When dry matter losses (disposed low-quality fractions as well as other losses such as in grinders) were considered the costs increased to an average of $75.11/dry ton with a minimum of $74.69/dry ton and a maximum of $2,136.86/dry ton.

When compared to the ideal nth-plant cost, the average cost from the first plant analysis is $5.88/dry ton greater than the nth-plant estimate. While the nth-plant analysis assumed a constant average quality feedstock, the 1st-plant analysis utilized stochastic variability in the material to assess its impact. In the 1st-plant analysis, it was assumed that any material that does not meet the base quality specifications of ≥ 50.51 wt% carbon and ≤ 1.0 wt% ash would be discarded. From this simulation, 97.90% of the material met the defined quality specifications, requiring the disposal of 2.10% of the preprocessed biomass. The material discarded due to quality represents an additional cost that must be accounted for in the total cost of the material. When the cost is fully burdened, considering system disruptions, material lost during operation, and material removed for quality considerations, the average delivered cost per ton of biomass was $76.75/dry ton, with a range from $76.32/dry ton to $2,138.50/dry ton. The resulting Overall Operating Effectiveness (OOE) for the system was found to be 97.55%.

Improvements in the preprocessing system (air classification unit), resulting in lower dry matter losses and elimination of soil contamination, contributed to cost savings and reduced ash-related downtime over a year of operation as simulated in the 1st-plant analysis. These changes narrowed the cost difference between the nth-plant and 1st-plant analyses. Yet, the higher delivered cost in the 1st-plant analysis suggests that additional technology development is needed to further address the variability of quality within the feedstock and improvements in the operational performance preprocessing of materials to attain cost parity with the nth-plant analysis.

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1. BACKGROUND

The U.S. Department of Energy (DOE) promotes production of advanced liquid transportation fuels from lignocellulosic biomass by funding fundamental and applied research that advances the state of technology (SOT) to transform renewable biomass into commercially viable biofuels. To gauge progress toward DOE objectives, the Bioenergy Technologies Office (BETO) sets cost and technology targets, and an annual SOT report provides the status of technology relative to these goals with data and experimental results. The BETO Renewable Carbon Resources (RCR) Platform develops performance targets that are directed at mobilizing large amounts of biomass. One target is to validate feedstock supply and logistics systems that can deliver feedstock at or below $85.51/dry ton (2016$), including both grower payment and logistics costs through to the in-feed of the conversion reactor (USDOE 2017).

Feedstocks are essential to achieving BETO goals because the cost, quality, and quantity of feedstock available and accessible at any given time limits the maximum volume of biofuels that can be produced. The 2016 U.S. Billion Ton report (USDOE 2016) provided several biomass supply scenarios that show potential biomass resources that could be developed under different sets of assumptions regarding yield improvements over time. Some of these scenarios lead to a sustainable national supply of more than 1 billion tons of biomass per year by the year 2030.

In accordance with the 2017 Multi-Year Program Plan (USDOE 2017), terrestrial feedstock supply and logistics 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 verifying efficient and economical integrated systems for harvest and collection, storage, handling, transport, and preprocessing raw biomass from a variety of sources 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 (USDOE 2015).

Progression of Feedstock Supply System Designs

Feedstock supply systems are highly complex organizations of operations required to move and transform biomass from a raw form at the point of production into a formatted, on-spec feedstock at the throat of the reactor. Feedstock logistics can be broken down into unit operations, including 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 to growth of the bioenergy industry.

Research on feedstock supply systems aims to reduce delivered cost, improve or 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. Conventional feedstock supply system designs rely on existing technology and systems to supply feedstock to biorefineries (Figure 1). Conventional designs tend to be vertically integrated with a specific conversion process or biorefinery; they also place all burden of adapting to feedstock variability on the biorefinery. Within the constraints of local supply, equipment availability, and permitting requirements, biorefineries strive to optimize efficiencies and capacities. However, this approach makes the system vulnerable to feedstock variability.

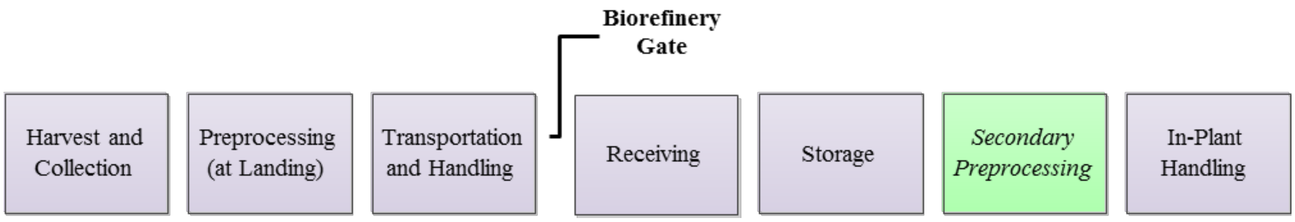

Figure 1. *Conventional feedstock supply system designs rely on existing technologies and biomass to supply biorefineries, but they require biorefineries to adapt to the variability of feedstock.*

Conventional designs are currently the backbone of the emerging biofuels industry. However, conventional feedstock supply systems have limitations that restrict widespread implementation on a national scale (Hess et al. 2009, Searcy and Hess 2010). The original expectation was that conventional supply system designs could be successful in geographical areas that have a concentrated supply of easily accessible and low-cost biomass resources (such as corn stover in the Midwestern United States and pine in the southeastern United States). Moving outside these select regions, the feedstock supply system must be adapted to accommodate changing cost, quality, and conversion facility size constraints.

Conventional systems can only address feedstock quality indirectly through passive controls such as resource selection or best management practices. An example of this is the high-capacity grapple used in the DOE-funded Auburn High Tonnage Biomass Logistics Demonstration Project (Sokhansanj et al. 2014), which prevented woody material from being dragged along the ground during skidding and preventing soil ash entrainment. When positioned in a highly productive single resource area, biorefineries can be selective in contracting only those feedstocks that meet their specifications. However, biomass quality (e.g., ash and moisture content) is highly variable both spatially and temporally (Kenney et al. 2013), and in any given year passive controls may not provide sufficient quality control for the delivered feedstock to meet desired in-feed characteristics. Therefore, biorefineries that rely on conventional designs are constrained to local resources and are limited in the expansion of the collection radius, which limits plant size (Graham et al. 2013).

Several analyses have shown that as the biofuels industry expands past highly productive regions, conventional supply systems will fail to meet supply requirements (Argo et al. 2013, Bonner et al. 2014, Hess et al. 2009, Lamers et al. 2015, Muth et al.

2014). To meet the demands of future industry, feedstock supply systems will be required to expand beyond conventional systems in certain areas, to what has been termed "advanced" feedstock supply systems (AFSS) (Hess et al. 2009, Searcy and Hess 2010, Jacobson et al. 2014). Advanced systems incorporate innovative methods of material handling, preprocessing and supply chain configurations.

The 2022 Woody SOT presents current supply chain designs for delivering a woody feedstock that meets the quality requirements of ≤ 1 wt% ash and ≥ 50.51 wt% total carbon. The 2022 Woody SOT utilizes a 50% clean pine - 50% forest residue blend as the model feedstock, to remain in alignment with the feedstocks that are being tested by conversion for the 2022 verification. The choice to utilize a blend of biomass sources relaxes the constraint that the facility be located in an area with large inventories of available Renewable Identification Number (RIN)-qualified pine and lessens net transport distances. For this case, as in 2020, the location of the biorefinery is in the Piedmont Region on the South Carolina/Georgia border.

2. 2022 WOODY FEEDSTOCK SOT

The Biomass Logistics Model (BLM) (Cafferty et al. 2013a) was used to model feedstock logistics cost and energy consumption for the 2022 Woody SOT for low-ash woody feedstocks. The BLM incorporates information from a collection of databases that provide (1) engineering performance data for hundreds of equipment systems; (2) spatially explicit labor cost data sets; and (3) local tax and regulation data. The BLM's analytic engine is built in the system dynamics software package Powersim™. 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.

2.1 Description of Logistics System Design

The 2022 SOT for low-ash Woody feedstocks is reported in 2016 dollars (2016$) and includes both grower payment and logistics costs to reflect a total delivered feedstock supply cost. The logistics system delivers 725,000 dry tons annually of a 50% clean pine - 50% logging residue blend, utilizing the systems described in the 2018-2021 Woody SOT reports (Hartley et al. 2018, Hartley et al. 2020, Hartley et al. 2021) for clean pine and logging residue, respectively. For the clean pine, the system harvests plantation grown pine and natural forest thinning material using a mechanized harvest system. Trees are moved to the landing where they are topped and debranched. Logs are sent to the processing facility where they are size reduced before feeding into the conversion process. The tops and branches are available for use as logging residue, with their harvest and collection costs attributed to the harvest of the clean pine logs. Additionally, logging residue is available from the landing at sites where pine logs are harvested for other products. Residues are chipped at the landing and transported by truck to the biorefinery. The 2022 analysis assumes annual delivery of 725,000 dry tons of woody feedstock, with total ash ≤ 1.00 wt%, total carbon ≥ 50.51wt%, moisture content ≤ 10% (wet basis), and a particle size of ¼-in. minus (Table 1).

Table 1. *Delivered feedstock composition assumptions for low-ash Woody Feedstocks.*

Component	Composition (dry wt%)
Carbon	50.51
Hydrogen	5.99
Nitrogen	0.17
Sulfur	0.03
Oxygen	41.55
Ash	≤ 1.00
Heating Value (Btu/lb)	8,601 HHV 7,996 LHV
Moisture (Bulk Wt. %)	10.0
Particle Size (inches)	≤ 0.08

2.1.1 Resource Availability and Transportation

The geographic region for the 2022 Woody SOT is located in the Piedmont region, drawing resources from both South Carolina and Georgia. In FY21 Q3, a joint analysis was performed by INL and ORNL to examine the availability of woody biomass as the industry and supply chains mature. The analysis focused on two separate aspects, the long-term availability of forestland biomass (i.e., pine logs and logging residue) and the ability of short rotation woody crops to augment the supply on the edges of forested areas and increase the number of facilities that can be supported. Due to the structure of the forest products industry and the growth characteristics of forest, it was found that there is little to no perceivable difference between the currently available supply of forestland biomass and the availability of the same materials into the future. The only reason to expect that the availability would change would be a shift in the structure of the forest products industry, which is the main driver of material availability.

Due to the stability of the biomass supply, it is expected that the biomass supplied in this SOT case will remain as it has been modeled previously. Figure 2 depicts the sources of biomass delivered to a biorefinery located in Warren County, GA. In all there were 11 source counties for clean pine and 105 counties supply logging residue. The maximum distance that clean pine is transported is 41.81 miles, while logging residue is transported from as far away as 125.87 miles.

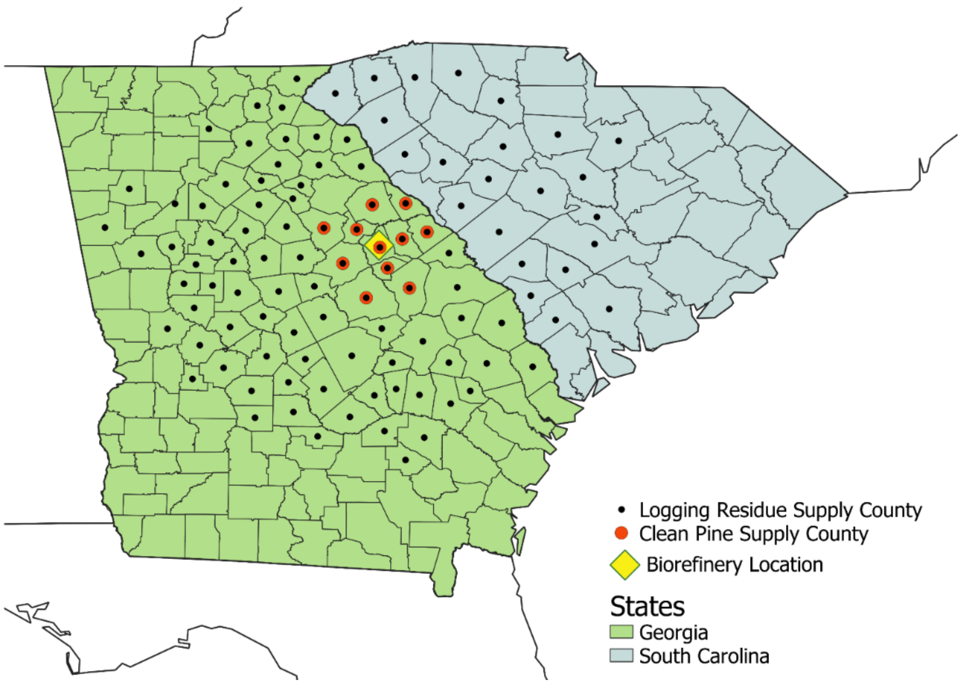

Figure 2. *Supply Chain for the 2022 Woody SOT. The supply chain delivers clean pine and logging residue to a centralized biorefinery.*

2.1.2 Grower Payment

Grower payment represents the stumpage price paid to the landowner to secure permission to harvest the material. The grower payment was calculated using the size class stumpage values reported in the 2016 Billion Ton Report (BT16; USDOE 2016). BT16 provides values of $32.40/dry ton, $16.20/dry ton and $8.10/dry ton (all in 2016$), for both planted and natural softwood stands of size classes 1, 2 and 3, respectively, in the Southern Region. The calculation of forest residue grower payment utilizes the residue ratios from the USDA Forest Service Forest Inventory and Analysis Database (USDA Forest Service 2017), to determine the proportion of the value of the whole tree stumpage that remains as residue after the harvest. Based on the assumed harvest region, the size class distribution of delivered material and the residue ratio, the weighted average grower payment of forest residue is $3.75/dry ton. The aggregate grower payment for the blended material is $9.74/dry ton.

2.1.3 Field-side Operations

2022 field-side operations for logging residue are identical to those presented in the 2018, 2019 & 2020 SOTs for CFP (Hartley et al. 2018, Hartley et al. 2020, Hartley et al. 2021). As before, it is assumed that the forest residue is brought to the landing as part of the primary harvest operation and as such does not incur harvest or collection costs. Instead, the supply chain starts with size reduction of material that has been field dried to 30% moisture content. Size reduction is performed with a mobile chipper, and the operational characteristics of the equipment are based on descriptions resulting from the High Tonnage project completed by Auburn University (Sokhansanj et al. 2014). The chips are blown directly into a truck for transport, eliminating the need for additional loading equipment. For clean pine the field-side operations are the same as those presented in the 2018 SOT for CFP (Hartley et al. 2018). Felling is completed using a feller-buncher, and a grapple skidder is utilized. Operational characteristics of both pieces of equipment are based on descriptions resulting from the High Tonnage project (Sokhansanj et al. 2014). The logs are delimbed using a gate delimber at the landing and stacked into a storage pile awaiting transportation to the biorefinery.

2.1.4 Preprocessing Operations

The forest residue chips are delivered to the refinery by truck, where they are offloaded using a truck tipper with a hopper. The forest residue chips are conveyed from their storage piles into the facility where they undergo multi-stage air classification to remove needles and soil as well as some of the bark fraction. The objective of the air classification is to maximize the retention of whitewood fractions in the outgoing stream that will be blended with clean pine chips. The air classification process also separates a needle-rich fraction that can be supplied into an alternate market to produce specialized products, for example, essential oils. The clean pine chips are generated from the clean pine logs. The clean pine logs are unloaded from the trucks using a high-lift loader and placed into storage piles. To initiate preprocessing, logs are delivered by loader to a rotary head debarker, and the debarked logs are conveyed to a 25 ton/hr disk chipper to produce an approximate 2-in nominal chip.

The chips from both materials are blended 1:1 as they are conveyed to secondary size reduction by a rotary shear and then dried using a rotary dryer. After the blended chips are rotary sheared and dried to 10% moisture content, they are held in covered storage until feeding to the conversion process. Work completed at Forest Concepts in conjunction with INL during 2019 has shown that there is a reduction in drying energy needed to dry rotary sheared material as compared to chips. The results of the Forest Concepts study showed that the energy was reduced by approximately 47%, however, because we assume that the material starts at a lower moisture content and exits the system at a higher moisture content than the study, the assumption for modeling purposes is that the reduction in energy is 25%.

2.1.5 Processing Depot Construction Cost

Construction and infrastructure costs were estimated as follows. Hu et al. (2017) utilized installation factors ranging from 1.43-1.7 to estimate the capital layout for construction and infrastructure for individual preprocessing equipment similar to the equipment in this design. For our calculations, we used the higher value of 1.7 for all preprocessing equipment to provide the more conservative estimate. Hence, the total capital layout for construction and infrastructure was estimated using an installation factor of 1.7 together with the installed capital cost of all preprocessing, handling and storage equipment; the estimate includes site preparation, construction, engineering and contingency (Hu et al. 2017). Land cost was calculated assuming 160 acres per depot at a cost of $500/acre and was added to the capital cost to determine the loan amount. 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 $2.96/dry ton.

2.2 2022 n^{th}-Plant Woody Feedstock SOT Analysis

The Biomass Logistics Model (BLM) (Cafferty et al. 2013a) was used to model feedstock logistics cost and energy consumption for the 2022 Woody SOT for low-ash woody feedstocks. The BLM incorporates information from a collection of databases that provide (1) engineering performance data for hundreds of equipment systems; (2) spatially explicit labor cost data sets; and (3) local tax and regulation data. The BLM's analytic engine is built in the system dynamics software package Powersim™. 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.

2.2.1 Cost Summary and GHG Emissions

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 scaling emissions data from the 2020 Woody SOT for CFP, which was derived from 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-reactor throat GHG emissions of the woody biomass scenarios.

Table 2. *Summary of modeled cost estimates for the woody feedstock supply systems for low-ash woody feedstocks.*

	Cost ($/dry ton) (2016$)			
	Clean Pine	**Logging Residue**	**Total[a]**	**GHG Emissions (kg CO_2e/dry ton)**
Grower Payment	$15.73	$3.75	$9.74	
Harvest & Collection	$9.88	$0.00	$4.94	6.74
Field-side Preprocessing	$4.73	$12.09	$8.41	10.04
Transportation	$7.67	$14.02	$10.84	10.22
Preprocessing	$27.32	$30.69	$29.00	149.68
Storage	$0.68	$0.68	$0.68	0.90
Handling	$2.65	$2.65	$2.65	0.81
Preprocessing Construction	$2.96	$2.96	$2.96	
Grand Total	**$71.62**	**$66.84**	**$69.23**	**178.39**

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

Energy consumption and transportation distance data from the BLM were used as inputs to update the model. Table 3 shows the modeled cost estimates for the woody feedstock supply system providing feedstocks to CFP for the 2019, 2020, 2021 and 2022 SOTs for low-ash woody feedstocks.

2.2.2 Sensitivity Analysis of Costs

Sensitivity analysis was performed to determine the impact that uncertainty in key operational parameters would have on the delivered cost presented as the 2022 SOT Design for low-ash woody feedstocks. Model parameters were chosen that could be variable or could cause variability in the preprocessing operations and ultimately cost. Each of the equipment parameters were varied based on variation seen in the processes, based on literature, from the values that were used in the final model run (Cao et al. 2007, Spinelli et al. 2012, Thompson et al. 2013). The values used are presented in Table 4.

Table 3. *Summary of modeled cost estimates for the woody feedstock supply system providing CFP for the 2019, 2020, 2021 and 2022 SOTs for low-ash woody feedstocks.*

	Cost Summary ($/Dry Ton) (2016$)			
	CFP 2019 SOT	**CFP 2020 SOT**	**2021 SOT[b]**	**2022 SOT[c]**
Grower Payment	$9.74	$9.74	$9.74	$9.74
Harvest & Collection	$4.94	$4.94	$4.94	$4.94
Field-side Preprocessing	$8.41	$8.41	$8.41	$8.41
Transportation	$12.22	$12.22	$12.22	$10.84
Preprocessing	$28.55	$25.43	$34.27	$29.00
Storage	$0.68	$0.68	$0.68	$0.68
Handling	$2.65	$2.65	$2.65	$2.65
Preprocessing Construction	$2.96	$2.96	$2.96	$2.96
Quality Dockage	$0.00[a]	$0.00	$0.00	$0.00
Grand Total	**$70.15**	**$67.03**	**$75.87**	**$69.23**

a The conversion process model has been updated with conversion data for this blend which accounts for yield changes, hence, dockage is not added for ash content exceeding the specification.

b The 2021 cost represents meeting the ash specification of <1% instead of <1.75% as in previous years, disposing of below quality material

Figure 3 presents the results of the sensitivity analysis on the cost of the blended feedstock. Factors that are prior or current RCR-funded R&D topics are indicated with red boxes. The delivered cost is most sensitive to the dry matter losses that occur in the air classifier units in the system. The air-classification having the largest impact underscores that finding alternative uses for the discarded material and reducing the quantity of material that escapes the system should be an important focus. After the air classifiers, the energy consumption of the field-side chipper used for the residue, followed by the capacity of the centralized chipper, have the next largest impacts. The impact of energy consumption on the field-side chipper is because of the wider range of uncertainty that is observed in experimental data for field-side chipping. The impact of throughput has to do with distributing the cost of the piece of equipment over the amount of material that is processed. When the throughput is decreased the cost increases, while when throughput increases the cost decreases.

Table 4. *Sensitivity parameters for the 2022 SOT feedstock supply for low-ash woody feedstocks. The unit abbreviation "odt" stands for "oven dried tons."*

	Minimum	**Mean (SOT)**	**Maximum**
Dryer Capacity	1.52 odt/hr	1.55 odt/hr	1.58 odt/hr
Dryer Energy	244.6 kWh/t	263.0 kWh/t	281.4 kWh/t
Field-side Chipper Capacity	61.94 odt/hr	65.20odt/hr	68.46 odt/hr
Field-side Chipper Energy	27.97 kWh/t	37.30 kWh/t	46.62 kWh/t
Centralized Chipper Capacity	16.66 odt/hr	23.80 odt/hr	30.94 odt/hr
Centralized Chipper Energy	20.32 kWh/t	25.40 kWh/t	30.48 kWh/t
Rotary Shear Capacity	5.40 odt/hr	5.68 odt/hr	4.96 odt/hr
Rotary Shear Energy	18.99 kWh/t	20.20 kWh/t	21.42 kWh/t
Air Classifier Unit DML	14.92%	19.90%	24.87%
Air Classifier Unit Capacity	6.75 odt/hr	7.5 odt/hr	8.25 odt/hr
Air Classifier Unit Energy	11.97 kWh/t	13.30 kWh/t	14.63 kWh/t

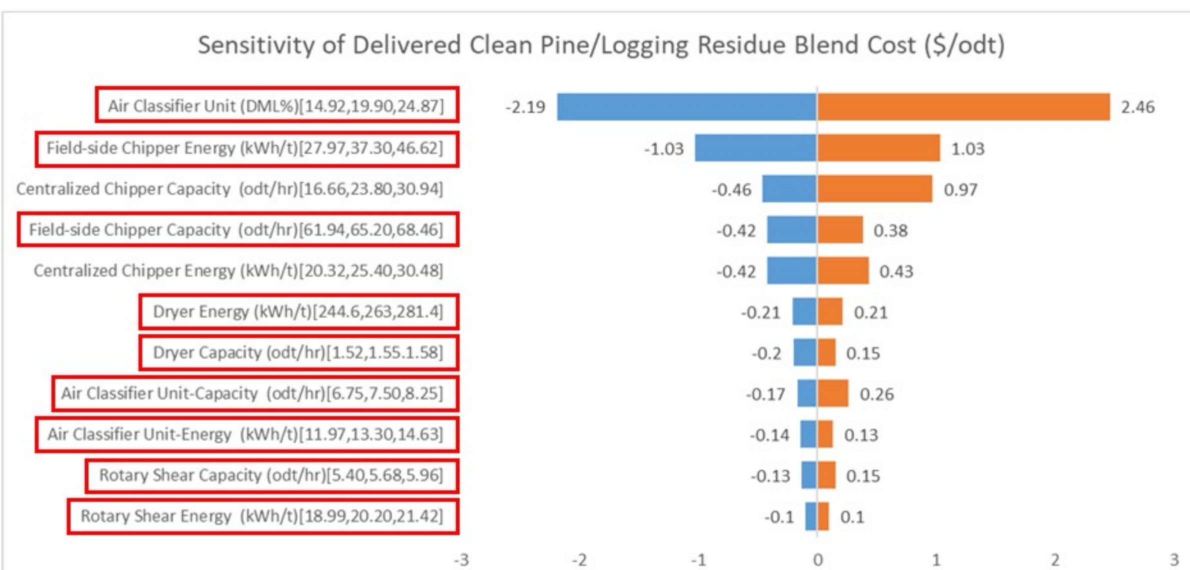

Figure 3. *Tornado chart showing sensitivity of cost to operational parameters used to model the 2022 SOT Case for low-ash woody feedstocks for CFP.*

Figure 4 presents the results of a sensitivity analysis on GHG emissions to the same operational parameters from the sensitivity analysis for cost. Factors that are prior or current RCR-funded R&D topics are indicated with red boxes. Some of the operational parameters had no impact on GHG emissions and thus are not included in the figure. The sensitivity of GHG emissions returned similar estimates (± 4.56 kgCO_2e/dry ton) for the centralized chipper and the dryer, however, the energy consumption was varied around 20% from the base case for the centralized chipper while only 7% in the case of the dryer which indicates that the GHG emissions are most sensitive to dryer energy. This is not surprising, as dryer energy consumption dominates energy consumption for the preprocessing system. Energy consumption for the field-side chipper and the air classifier had the next highest impact on GHG emissions at (± 3.29 kgCO_2e/dry ton) and (± 1.19 kgCO_2e/dry ton) respectively.

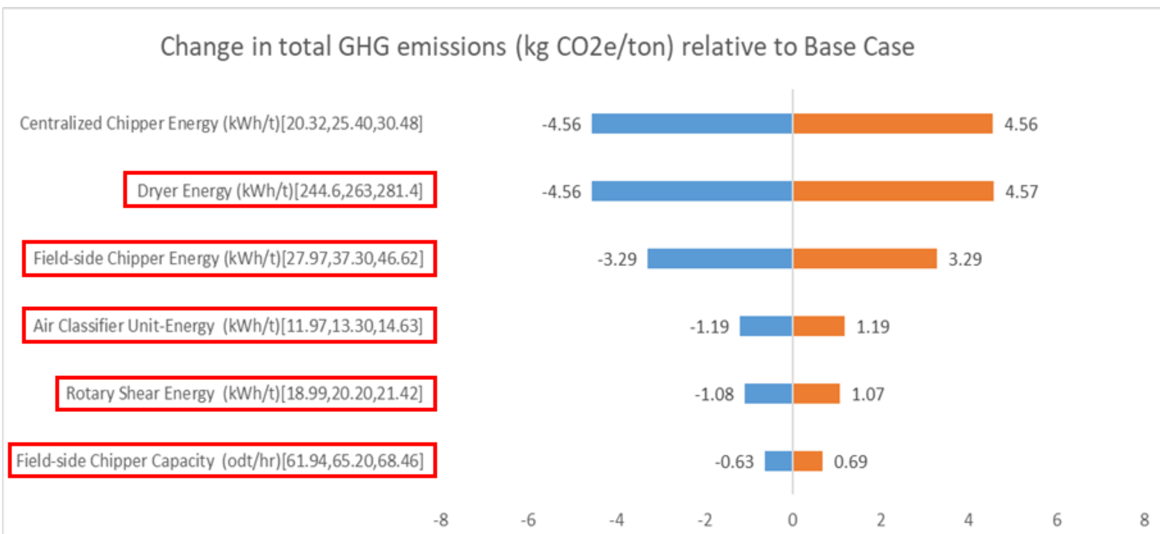

Figure 4. *Tornado chart showing sensitivity of GHG emissions to operational parameters used to model the 2022 SOT Case for low-ash woody feedstocks.*

2.2.3 Enriched material for mid-stream markets

The preprocessing design adopted in the 2022 Woody SOT for low-ash feedstocks includes an air classification step that maximizes the proportion of white-wood material in the output sent downstream for conversion. Moreover, it also produces a needle-enriched stream that can be supplied to an alternate mid-stream market, for example production of essential oils. Essential oils are volatile aromatic oils, which are terpenes and oxygenated derivatives, produced by steam or hydro distillation. These "oils" are present at concentrations of 1–2% by weight, with higher concentrations in needles, twigs, and buds (Kelkar et al., 2006). Essential oils possess various biological attributes such as antiviral, antimicrobial, antioxidant, antiparasitic, and insecticidal effects. They have been widely utilized in perfume and makeup products and in the food industry as generally recognized as safe substances (Zeng et al., 2012). The market for essential oils, however, is characterized by high value for the product albeit at relatively low market volumes. Furthermore, specifics around feedstock cost and volume are difficult to obtain. Soh et al. (2021) presented a technoeconomic and profitability analysis of extraction of patchouli oil wherein the cost of dry patchouli leaves is estimated at between $300-350/tonne ($272-$318/ton), while the consumption of patchouli oil is estimated at 1,100 tons per year (ETC Group, 2014).

Figure 5 shows the relationship between the wholesale price of needles in a mid-stream market and its influence on the weighted delivered feedstock cost for the biorefinery assuming a range of price premiums over the cost of production for the needle fraction. Based on the 2022 Woody SOT, the cost of the enriched needle fraction is estimated at $41.12/dry ton (2016$) with a corresponding cost of the delivered feedstock at $69.15/dry ton (2016$). If the wholesale price of the needles in the midstream market is 5.0% higher than the cost of producing the needles, $43.17/dry ton (2016$), it results in 0.11% cost savings in the delivered feedstock costs. Similarly, a wholesale market price for the needles at $55.50/dry ton, a premium of approximately 34.8% over production cost, corresponds to a 0.75% reduction in the cost of delivered feedstock for the biorefinery. Hence, because the mass of needles relative to the mass of the whole biomass is very small (5.7%), the value in a midstream market does not significantly affect the delivered cost of the enriched whitewood. Benefits of removing them on the conversion side (potentially increased bio-oil yield and improved finished fuel quality) may need to be the driving force for their removal rather than delivered feedstock cost.

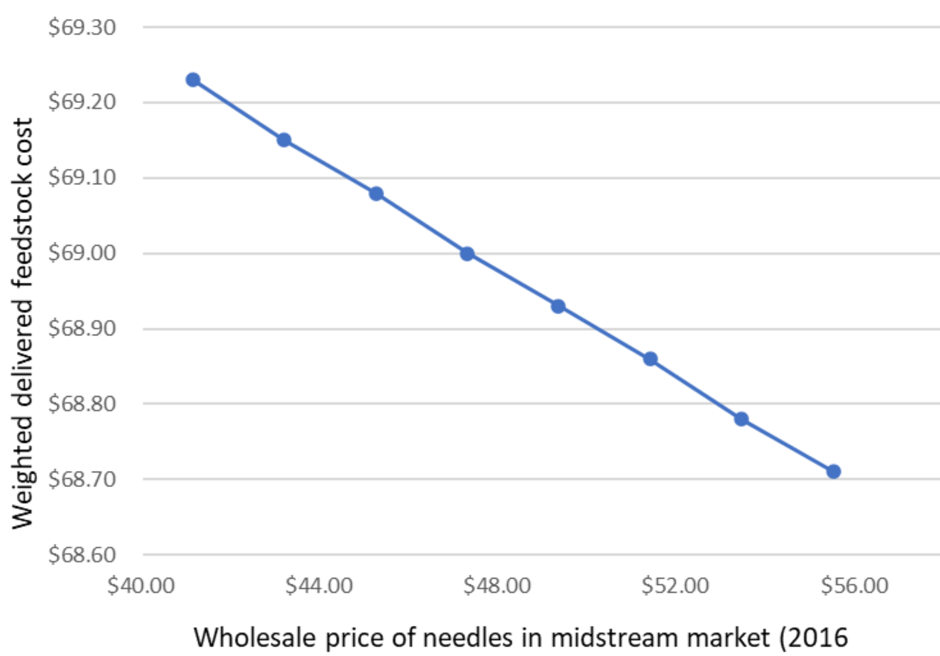

Figure 5. *Relationship between wholesale price of needles in midstream market and delivered*

feedstock cost for the biorefinery.

2.3 2022 1st-Plant Woody Feedstock SOT Analysis

2.3.1 Operational Efficiency Analysis and Approach

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

A traditional nth-plant design assumes a fixed average feedstock quality (moisture, ash, composition) together with experimentally determined average rates, titers and yields of products to develop steady state process simulations. An on-stream time lower than the full calendar year is generally assumed to account for routine maintenance (for example, 90% on-stream, or 328 days/year, 24 hours/day). Process simulations deterministically estimate average plant throughputs of feedstock, intermediates and products, and thereby equipment size requirements and capital costs (CAPEX), and the average energy and chemical usage are estimated to determine operational costs (OPEX). For nth-plant designs, both the CAPEX (i.e., plant size) and OPEX are allowed to vary to define the "optimal" design, and sensitivity analysis is performed within the expected bounds of uncertainty around key parameters, to understand the variation in plant size requirements that would occur within the bounds of known variability. In contrast, a significant issue with 1st-plant designs especially for biomass conversion, is that they are often developed from incomplete or missing data on the expected operational impacts of physical properties of the feedstock on the plant equipment.

Additionally, feedstock preprocessing is rarely piloted in an integrated fashion with the conversion process. Commercial handling, grinding and feeding equipment designed for different types of biomass (i.e., woody materials) are commonly assumed to perform similarly regardless of the biomass feedstock type. Hence, there is substantial need for analysis to predict *dynamic* plant throughput and operational efficiency outcomes to achieve n^{th}-plant design capacities and economics.

2.3.1.1 Simulation Approach and Assumptions

To conduct the throughput analyses performed for this report, Discrete Event Simulation (DES) was employed to model the interactions of storage and preprocessing equipment throughput and performance. The discrete event model begins with generating one dry ton (2,000 dry lb) of simulated feedstock of each type of material (logging residue and clean pine). The materials are generated with random compositions of white wood, bark, needles and soil. The ranges for white wood, bark and needles are based on Lacey *et al*. (2015). Values for the individual fractions of the biomass were drawn from the following distributions: white wood, N(91,2.4); bark, Gamma(126.56, 0.0004, 0); and needles, Gamma(42.75,0.0003, 0). Moisture and soil ash compositions were developed to match the quality specifications used in the 2020 Woody SOT for CFP (Hartley et al. 2021). For logging residue, the moisture content for each unit of feedstock was drawn randomly from a Normal distribution N(30,2.84), values for which ranged from 20.16% to 39.50% wb (wet basis), representing observed values from previous studies (Afzal et al. 2010, Greene et al. 2014, Lin and Pan 2015). The extrinsic ash content of the material was drawn from a Gamma distribution (0.75, 0.0183, 0.0038), representing values ranging from 0.38 wt% to 12.5 wt% db (dry basis) and a mean value of 1.77 wt%. These values also encompass observed ash content in logging residues from earlier studies (Acquah, 2016, Lacey et al. 2015). In the case that a sampled material is generated that has a composition greater than 100% the values of each component are normalized to create a material that has a sum of compositional components equaling 100%.

As done for logging residue, the simulated feedstock generator for clean pine is set to generate one dry ton units of material with randomized moisture and ash contents, as well as randomized elemental compositions for the processing model run. The moisture content for each unit of feedstock is drawn randomly from a Normal distribution N(30,2.84), values for which ranged from 18% to 42% wb, representing observed values from previous studies (Afzal et al. 2010, Greene et al. 2014, Lin and Pan 2015). The ash content of the material is drawn from a Gamma distribution (0.4, 0.005, 0.003), representing values ranging between 0.3% to 2.7% db and a mean value of 0.5%. These values also encompass observed ash content in clean pine across earlier studies.

2.3.2 Throughput Analysis

The n^{th}-plant preprocessing system consists of 4 processing lines that process logging residue and clean pine. The nameplate biorefinery design capacity of each of the lines preprocessing both logging residue and clean pine is 551.25 dry tons/day (22.969 dry tons/hr), totaling 2,205 dry tons/day for the system. During FY18, through discussions with the Industry Advisory Board for the Feedstock-Conversion Interface Consortium (FCIC) we learned that a common practice in industry is to set nameplate biorefinery design capacity at the value necessary to be profitable, but to size plant equipment at a higher capacity to account for unexpected operational issues. Hence, for this analysis we sized the preprocessing lines at 25 dry tons/hr (about 9% higher throughput capacity).

2.3.2.1 Daily Production

The modeled mean daily production of the preprocessing system, shown in Figure 6, was approximately 2,101 dry tons of material per day or 95.3% of the daily nameplate capacity. The daily production varied over the course of the year, ranging from 1,146 dry tons/day (52.0% of the daily nameplate capacity) to 2,163 dry tons (98.1% of the daily nameplate capacity), with an overall standard deviation of 165.3 dry tons (7.5% of the daily nameplate capacity).

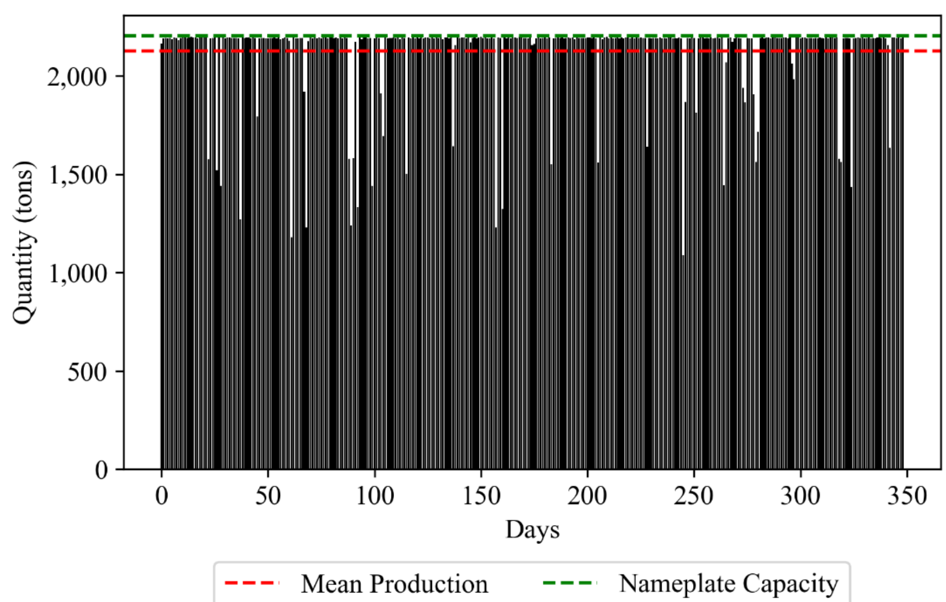

Figure 6. *Daily output of the simulated preprocessing system. The green line indicates the daily nameplate capacity, while the red line indicates the mean daily production rate for the year.*

Beginning with the 2020 SOT we aligned to the 90% on-stream time assumptions used in the nth-plant feedstock and conversion SOTs represented in the BETO Multi-Year Plan and State of Technology Report, leading to an annual nameplate capacity of 725,000 dry tons/year. A result of this is that if the modeled on-stream time exceeded the assumed 90% time on-stream, the average annual throughput capacity factor $F_{f,P}$ can exceed 100% if the daily throughput is high throughout the year—even if it does not exceed the daily nameplate capacity on any day during the year (this is also due to the oversizing of the equipment). The modeled time on-stream for the preprocessing system in the 2022 1st-plant Woody SOT for feedstock supply to CFP was 87.84%, leading to an annual throughput factor $F_{f,P}$ of 0.9964 (99.64% of the annual nameplate capacity) or a modeled annual capacity of 722,403 dry tons.

2.3.2.2 Shutdowns (Time Off-stream)

During the simulation, equipment failures were tracked to compare the relative impacts of individual pieces of equipment on downtime. The downtime associated with failures was also tracked to determine the importance of the reliability of individual pieces of equipment. Table 5 provides a breakdown by occurrence of failure and the accumulated downtime of the resulting failures by equipment type and the breakdown by occurrence of failure and the downtime by underlying cause. It is observed that the majority of the equipment failures are experienced by the rotary shear and orbital screen. The rotary shear and screen accounted for 42.50% of the shutdown events over the course of the year, with over 88% of those caused by ash related wear. As a proportion of total down time, its share is 43.77%. The other equipment in the preprocessing system did not experience failures due to ash wear. Reductions in extrinsic ash by air classification have provided a benefit to system performance as these failures take on average 6 hours to repair and bring the equipment back online. On the other hand, regular failures contributed to the majority of the down events, 62.50% and downtime, 62.60%. Conveyors accounted for approximately 48% of the down events caused by regular failures, while their contribution to overall downtime was 66.16%.

2.3.3 Quality and Cost Analysis

2.3.3.1 Cost Assumptions

The nth-plant cost assumptions are retained from the 2020 Woody SOT Report (Hartley et al. 2021) for the case of delivering logging residues and clean pine to a centralized thermochemical biorefinery. Costs for areas other than preprocessing were not adjusted for the small operational differences as they represent the best cost estimates that we currently have. The costs shown for preprocessing were based on the nth-plant cost developed for 2022 SOT for low-ash woody feedstocks in section 2.2 above and were converted from a cost per ton to a cost per minute for use in the analysis. The per minute costs were applied to the processing time per unit throughput to arrive at the estimated processing cost in the simulation model. Finally, estimates for other costs were assumed to

Table 5: *Summary of failure events and downtime and time on-stream. In the labels, "Regular" refers to downtime caused by manufacturer-specified mean time to failure (the expected time between recommended maintenance).*

	2022 SOT
Total Failures	**160**
Moisture Failures (% of Total)	0%
Ash (Wear) Failures (% of Total)	37.5 %
Regular Failures (% of Total)	62.5%
Total Operating Time (350 days) (min)	**504,000**
Total Downtime (min)	**61,307**
Moisture Downtime (% of Total)	0%
Ash (Wear) Downtime (% of Total)	37.4%
Regular Downtime (% of Total)	62.6%
Actual time-onstream (350 days) (%)	**87.84%**
Actual time-onstream (365 days) (%)	**84.23%**

remain similar to those for the n^{th}-plant assumptions. These costs were added to the processing cost per unit to arrive at the total costs which are compared to the target of $86/ton.

Additionally, we sized the preprocessing lines in a manner utilized in industry to better approximate engineering design and equipment sizing practices. Hence, the n^{th}-plant cost estimates correspond to equipment with operational capacity at 22.969 tons/hour, therefore processing costs were adjusted to accurately reflect cost estimates for the 25 tons/hour system design in the 2022 1^{st}-plant woody SOT for low-ash woody feedstocks and were scaled using the following equation.

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

2.3.3.2 Annual Units Meeting both Cost and Quality Requirements

Supply Logistics

For woody materials the throughput factor for supply logistics ($F_{f,S}$) will always be equal to 1.0 because there are no dry matter losses during storage and only enough tons needed for Preprocessing are delivered to the biorefinery. Furthermore, if the throughput of preprocessing is below design, the design number of tons becomes irrelevant to Supply Logistics. Additionally, the quality requirement for the material is slightly different than the final requirements for conversion as the material is changed in preprocessing and the relative changes among components are not homogeneous. After accounting for the changes in material that occur in preprocessing, the ash requirement at the biorefinery gate is ≤ 1.00 wt% and the carbon requirement is ≥ 50.51 wt%. An evaluation of the incoming material from supply logistics revealed that for logging residue 16.70% of the material met the preprocessing quality requirement of total ash and 15.49% met the carbon requirement (adjusted for losses in preprocessing), with 14.09% meeting both requirements simultaneously. For the clean pine 82.31% of the material met the total ash specification and 50.90% met the carbon specification, for a combined 50.90% meeting both. This results in a weighted quality performance factor ($F_{B,S}$) for Supply Logistics (tons delivered to the biorefinery gate meeting quality divided by the total tons delivered to the biorefinery gate) of 0.3250.

The percentages meeting the carbon requirement for both materials are markedly lower than reported in the 2021 Woody SOT (which were 92.49% and 99.99% for the residues and clean pine, respectively). In investigating why this occurred, we discovered that the carbon content being output was prior to normalization for soil addition when the feedstock units were being generated, hence, in prior 1^{st}-plant Woody SOTs we overestimated the number of units exiting Supply Logistics that met the carbon requirement and thus overestimated the quality performance factor $F_{B,S}$ and OOE_S for supply logistics. This did not impact those metrics for preprocessing, however, as the numbers adjusted for soil addition were used in the preprocessing simulation.

Preprocessing

In the preprocessing system the cost of an aliquot of material exiting the system is dependent on the amount of time that the aliquot resides in the preprocessing system. If the dynamic throughput of a given unit operation were to decrease or if the unit operation failed completely, the cost for all aliquots of material in the system will increase. Hence, variable throughput makes the costs become more variable, and the mean cost increases. Figure 7 shows the cost distribution of delivered feedstock units that leave the preprocessing system over the course of a year of operation, accounting only for delays in the processing system. The production cost of the system averages $71.66/dry ton (2016$) (3.51% higher than the $69.23/dry ton n^{th}-plant cost). The stochastic costs ranged from a minimum of $71.23/dry ton to a maximum of $2,115.30/dry ton, with a standard deviation of $12.19/dry ton. Under this scenario, 722,403 tons of feedstock are simulated to be delivered at a cost of less than $86/dry ton.

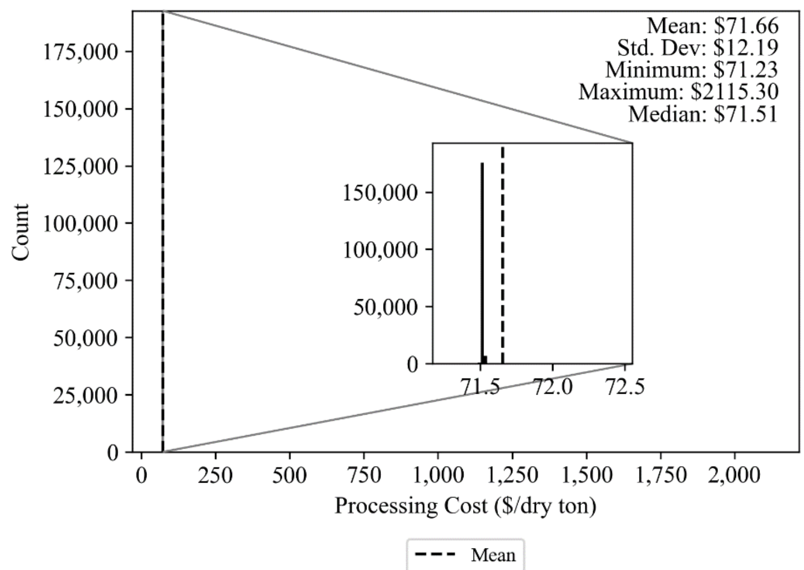

***Figure** 7. Distribution of cost of processed feedstock units accounting only for delays in the processing system.*

During the processing of biomass, inevitably material is lost from the system either from dry matter losses such as in grinders or from discarded material (from the air classifier) that has properties that lead to failures. When these losses are accounted for the costs increase to an average of $75.11/dry ton (8.49% higher than the n^{th}-plant cost) with a minimum of $74.69/dry ton, a maximum of $2,136.86/dry ton and a standard deviation of $12.30/dry ton (Figure 8).

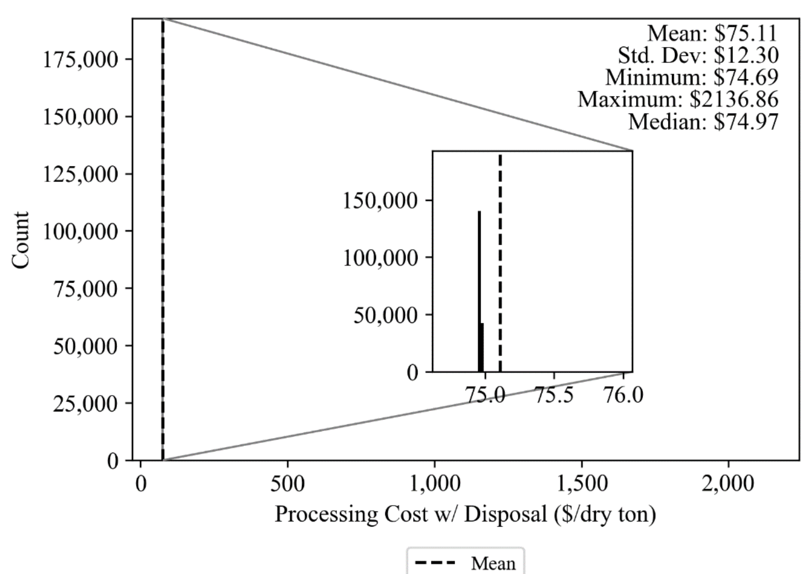

Figure 8. *Distribution of cost when considering system dry matter losses.*

The yield potential (quality) of the material that leaves preprocessing is critical to the performance of the conversion process, and directly affects the performance factor $F_{f,B}$. The requirements of the feedstock entering conversion that directly impact conversion yield are a carbon content ≥ 50.51 wt% and an ash content ≤ 1.00 wt%. Figure 9 shows the distribution of the units meeting the quality specifications for total ash and total carbon in the processed materials leaving the preprocessing system. Ultimately, all of the units exiting the system met the ash requirement of ≤ 1.00 wt% while 97.9% of the units exiting preprocessing met the carbon requirement of ≥ 50.51 wt%. Ultimately, the amount of material that met both requirements was 97.9% of the units exiting storage. This quantity of material meeting specifications represents an increase of 21.18 percentage points compared to the previous year's SOT. This resulted in preprocessing quality performance factor ($F_{B,P}$) of 0.9790.

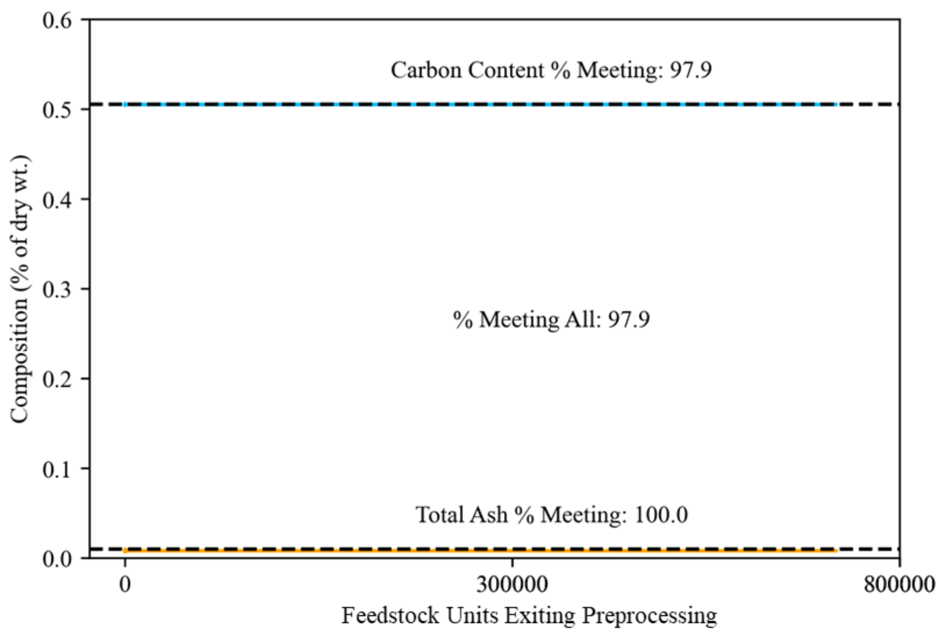

Figure 9. *Distribution of ash and carbon content of feedstock leaving the preprocessing system for the 2022 SOT requirements.*

The disposal of material due to quality requirements has an associated cost impact. When the cost is fully burdened for the system disruptions, material lost during operation, as well as material removed for not meeting the required quality specifications, the average cost per ton is $76.75/dry ton (10.86% higher than the n^{th}-plant case), with a minimum cost of $76.32/dry ton, a maximum cost of $2,138.50/dry ton and a standard deviation of $12.25/dry ton (Figure 10). Compositional variability continues to present a challenge from a preprocessing perspective, but improvements to the system resulting in lower dry matter losses and separation efficiencies have contributed to cost reductions compared to the 2021 SOT.

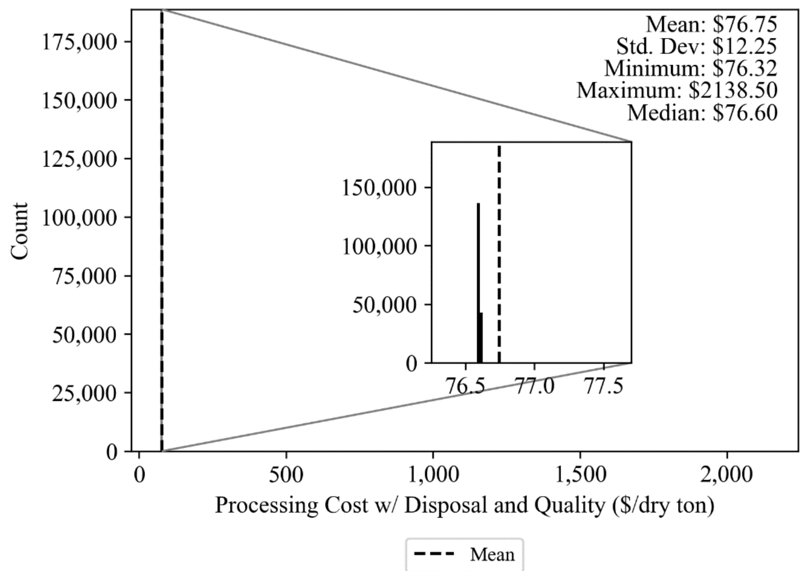

Figure 10. *Distribution of total cost of processed materials considering quality.*

2.3.4 Overall Operating Effectiveness for the 2022 Woody SOT

The results of this analysis indicate modeled Supply Logistics throughput capacity utilization factor and performance factors of 1.000 and 0.3250, respectively. For preprocessing, the utilization and performance factors were found to be 0.9964 and 0.9790, respectively. This resulted in an OOE of 97.55% for preprocessing and represents an increase of 21.40 percentage points over the previous SOT. The calculation of overall operating effectiveness for each subsystem is show below:

$$Supply\ Logistics: \qquad OOE_S = F_{f,S} \times F_{B,S} = 1.000 \times 0.3250 = 0.3250\ (32.50\%)$$

$$Preprocessing: \qquad OOE_P = F_{f,P} \times F_{B,P} = 0.9964 \times 0.9790 = 0.9755\ (97.55\%)$$

Improvements in the preprocessing system (air classification unit), resulting in lower dry matter losses and elimination of soil contamination, contribute to cost savings and reduced ash-related downtime over a year of operations as simulated in the 1st-plant analysis. These changes narrow the cost difference between the nth-plant and 1st-plant analyses. Yet, the higher delivered cost in the 1st-plant analysis suggest that additional technology development is needed to further address the variability of quality within the feedstock and improvements in the preprocessing of materials to attain cost parity with the nth-plant analysis.

3. INDUSTRIAL RELEVANCE OF THE BLENDSTOCKS

Currently, it is estimated that there are 21,218,792 dry tons of pine feedstocks available nationally, with 11,804,620 dry tons of planted pine and 9,414,172 dry tons of pine forest residues (BT16; USDOE 2016). The use of plantation grown pine and forest residue is qualified by EPA to be eligible for RINs (USEPA, 2010). Analysis completed in the third quarter of FY21, jointly with ORNL, shows that through blending clean pine with logging residue that it is possible to access 48.25 million dry tons of woody feedstocks at an average price of $50 or less at the roadside. However, if a 50/50 blend is required the quantity available would be 11.4 million dry tons.

4. SUMMARY

The Renewable Carbon Resources 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 their bioenergy production goals, INL completes annual SOT reports for herbaceous and woody biomass feedstock logistics, which provides the status of technology development of feedstock logistics for biomass to biofuels given actual data and experimental results, relative to technical target and cost goals from design cases.

To meet the demands of the conversion pathway, the preprocessing system for the 2022 Woody SOT for low-ash woody feedstocks utilized feedstock fractionation by incorporating technologies that can separate the biomass by its fractions (wood, bark, needle, and extrinsic ash) to reduce impurities and attempt to maximize the retention of usable biomaterials that satisfy the quality considerations. The n^{th}-plant analysis estimated the delivered cost for the feedstock at $69.23/dry ton (2016$) which represents a $6.64/dry ton decrease compared to the n^{th}-plant cost estimate of the 2021 Woody SOT supply system for low-ash woody feedstocks. The quality requirements in the 2022 Woody SOT were identical to those of the 2021 Woody SOT at ≤ 1.00 wt% ash and ≥ 50.51 wt% carbon. The cost savings derive primarily from reductions in dry matter losses during air classification.

In the 1^{st}-plant analysis of the 2022 Woody SOT system, the average throughput was approximately 2,128 dry tons/day or 96.51% of the name plate capacity. During the simulation the daily throughput ranged from 1,090 dry tons/day to 2,200 dry tons/day, or 49.43% to 99.75% of the daily nameplate capacity. After the year of operation 722,403 tons (99.64% of yearly nameplate) of processed feedstock were produced in total without regard to quality considerations. The variability in throughput was primarily caused by equipment failures in the system. Regular failures, downtime caused by routine maintenance per manufacturer guidelines, contribute to a majority 62.50% of failures and 62.60% of the downtime. In addition, failures due to wear were the other cause of disruption within the system, impacting the rotary shear, accounting for 37.50% of the failures and 37.40% of the total downtime. Ultimately the system was on stream for 87.84% during the simulation period, which is only 2.16 percentage points below the n^{th}-plant assumption for time on-stream. The production cost of the system averaged $71.66/dry ton. The costs ranged from a minimum of $71.23/dry ton to a maximum of $2,115.30/dry ton. When dry matter losses (disposed low-quality fractions as well as other losses such as in grinders) are considered the costs increase to an average of $75.11/dry ton with a minimum of $74.69/dry ton and a maximum of $2,136.86 dry ton.

When compared to the ideal nth-plant cost, the average cost from the first plant analysis is $5.88/dry ton greater than the nth-plant estimate. While the nth-plant analysis assumes a constant average quality feedstock, the 1st-plant analysis utilizes stochastic variability in the material to assess the impact. In the 1st-plant analysis, it is assumed that any material that does not meet the base quality specifications of ≥ 50.51 wt% carbon and ≤ 1.0 wt% ash is discarded. From this simulation, only 97.90% of the material met the defined quality specification, requiring the disposal of 2.10% of the biomass. The material that is discarded due to quality represents an additional cost that must be accounted for in the total cost of the material. When the cost is fully burdened considering system disruptions, material lost during operation, as well as material removed for quality considerations the average delivered cost per ton of biomass was $76.75/dry ton, with a range from $76.32/dry ton to $2,138.50/dry ton. A feedstock quality performance factor of 97.90% and a fully burdened cost that is $7.60/dry ton higher than the estimated nth-plant cost were observed. The resulting Overall Operating Effectiveness (OOE) for the system, from the simulation, was found to be 97.55%.

Improvements in the preprocessing system (air classification unit), resulting in lower dry matter losses and elimination of soil contamination, contribute to cost savings and reduced ash-related downtime over a year of operations as simulated in the 1st-plant analysis. These changes narrow the cost difference between the nth-plant and 1st-plant analyses. Yet, the higher delivered cost in the 1st-plant analysis suggest that additional technology development is needed to further address the variability of quality within the feedstock and improvements in the preprocessing of materials to attain cost parity with the nth-plant analysis.

5. REFERENCES

Ackerman, P., B. Talbot, and B. Dahlin, 2014, “Biomass Harvesting and Logistics,” In: T. Seifert (ed.), *Bioenergy from Wood*, Springer, Netherlands.

Argo, A. M., E. C. D. Tan, D. Inman, M. H. Langholtz, L. M. Eaton, J. J. Jacobson, C. T. Wright, D. J. Muth, M. M. Wu, Y.-W. Chiu, and R. L. Graham, 2013, “Investigation of biochemical biorefinery sizing and environmental sustainability impacts for conventional bale system and advanced uniform biomass logistics designs,” *Biofuels Bioprod. Bior.* 7: 282–302

Argonne National Laboratory. 2018, Summary of Expansions, Updates, and Results in GREET® 2016 Suite of Models. Technical Report, ANL/ESD-16/21, https://greet.es.anl.gov.

Bonner, I., D. Muth, J. Koch, and D. Karlen, 2014, “Modeled impacts of cover crops and vegetative barriers on corn stover availability and soil quality,” *Bio Energy Res.* 7: 576-589.

Cafferty, K.G., Muth, D.J., Jacobson, J.J., Bryden, K.M, 2013a, Model Based Biomass System Design of Feedstock Supply Systems for Bioenergy Production. In: *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, August 4–7, Portland, OR, USA. ASME. pp. V02BT02A023.

Cafferty, K, J. Jacobson, and K. Kenney, 2013b, “Woody/Pyrolysis Feedstock 2013 State of Technology Report,” Milestone Completion Report, Idaho National Laboratory.

Cafferty, K. G and D. S. Hartley, 2015, *Woody Feedstock 2014 State of Technology Report*, INL\LTD-15- 34165.

Cao, C.W., D. Y. Yang & Q. Liu, 2007, Research on Modeling and Simulation of Mixed Flow Grain Dryer, Drying Technology, 25:4, 681-687, DOI: 10.1080/07373930701290951

Carolan, J., S. Joshi, and B. E. Dale, 2007, “Technical and Financial Feasibility Analysis of Distributed Bioprocessing Using Regional Biomass Pre-Processing Centers,” *Journal of Agricultural & Food Industrial Organization* 5(2): 1203-1230.

Coyle, D. R., Coleman, M. D., Durant, J. A. and Newman, L. A., 2006, “Survival and growth of 31 Populus clones in South Carolina,” *Biomass and Bioenergy* 30(8):750-758.

Dutta, A., M. Talmadge, J. Hensley, M. Worley, D. Dudgeon, D. Barton, P. Groenendijk, D. Ferrari, B. Stears, E. Searcy, C. Wright, and J. Hess, 2011, *Process Design and Economics for Conversion of Lignocellulosic Biomass to Ethanol - Thermochemical Pathway by Indirect Gasification and Mixed Alcohol Synthesis*, NREL/TP-5100-51400, May 2011.

EC-DG-ENV, 2015, Environmental Implications of Increased Reliance of the EU on Biomass from the South East US. B. Kittler, A. S. Olesen, W. Price, F. Aguilar and S. L. Bager. Brussels, Belgium, Pinchot Institute for Conservation & COWI for the European Commission Directorate-General for Environment. ENV.B.1/ETU/2014/0043. Retrieved from http://www.aebiom.org/wp- content/uploads/2016/08/DG-ENVI-study-imports-from-US-Final-report-July-2016.pdf.

Emerson, R., T. Westover, D. Carpenter, B. Evans, and D. Howe, 2014, “Thermochemical Conversion Feedstock Interface, Combined Milestone Completion Report: INL, NREL and PNNL,” Idaho National Laboratory.

Erber, G., J. Routa, M. Kolstrom, C. Kanzian, L. Sikanen, and K. Stampfer, 2014, “Comparing Two Different Approaches in Modeling Small Diameter Energy Wood Drying in Logwood Piles,” *Croatian Journal of Forest Engineering* 35: 15-22.

ETC Group, 2014, Case Study: Patchouli and Synthetic Biology. https://www.etcgroup.org/content/case-study-patchouli-and-synthetic-biology. (Accessed 09.23.2022).

Fisher, R. F. and D. Binkley, 2000, *Ecology and management of forest soils*, John Wiley and Sons, Inc., New York.

Forest2Market, 2015, Wood Supply Market Trends in the US South: 1995 - 2015. Charlotte, NC, USA, Forest2Market analysis for National Alliance of Forest Owners, US Endowment for Forestry and Communities, US Industrial Pellet Association. Retrieved from http://www.nafoalliance.org/images/pellets/Forest2Market_USSouthWoodSupplyTrends.pdf [November 22, 2015].

FORISK, 2011, "Woody Biomass as a Forest Product - Wood Supply and Market Implications," B. Mendell, A. H. Lang, and T. Sydor, Forisk Consulting and National Alliance of Forest Owners, http://nafoalliance.org/wp-content/uploads/NAFO-US-Wood-Markets-Report-102411.pdf, accessed August 13, 2015.

Gan, J. and C. T. Smith, 2007, "Co-benefits of utilizing Forest residues for bioenergy production: The case for East Texas, USA," *Biomass and Bioenergy* 31(9): 623-630.

Graham, R., M. Langholtz, L. Eaton, J. Jacobson, C. Wright, M. Muth, D. Inman, E. Tan, M. Wu, Y. W. Chiu, S. Jones, L. Snowden-Swan, and A. Argo, 2013, "Investigation of Biochemical Biorefinery Sizing and Environmental Sustainability Impacts for Conventional Bale System and Advanced Uniform Biomass Logistics Designs," *Biofuels, Bioproducts and BioPower*.

Greene, W., J. Cutshall, C. Dukes, and S. Baker, 2014, "Improving Woody Biomass Feedstock Logistics by Reducing Ash and Moisture Content," *Bioenergy Res* 7(3): 816-823.

Grigal, D. F., 2000, "Effects of extensive forest management on soil productivity," *For. Ecol. Manag.* 138(1–3): 167–185.

Hansen, J., J. Jacobson, and M. Roni, 2015, "Quantifying Supply Risk at a Cellulosic Biorefinery," In K. Chichakly and K. Saeed (eds.), *Proceedings from the 33rd International Conference of the System Dynamics Society*, Albany, New York: System Dynamics Society.

Harris, R. A. and D. R. Phillips, 1986, "Density of Selected Wood Fuels," Georgia Forestry Commission, Georgia Forest Research Paper 61: 6.

Hartley, D., D. Jones, M. Langholtz, M.Davis, C. Brandt, M. Griffel, Y. Lin, P. Burli, D Thompson, 2019, Q3 Quarterly Progress Milestone: Development of nth-plant modeling assumptions for grower payment, harvest & collection for herbaceous and woody feedstocks. Idaho National Laboratory, Idaho Falls, ID.

Hartley, D., M. Roni, E. Searcy and P. Lamers, 2015, Woody/Pyrolysis Feedstock 2015 State of Technology Report, INL/LTD-15-36596, September 2015.

Hartley, Damon S., Thompson, David N., Hu, Hongqiang, and Cai, Hao, 2018, Woody Feedstock 2018 State of Technology Report. United States: N. p., 2018. Web. doi:10.2172/1606238.

Hartley, Damon S., Thompson, David N., and Cai, Hao. Woody Feedstocks 2019 State of Technology Report. United States: N. p., 2020. Web. doi:10.2172/1607741.

Hartley, Damon S., Thompson, David N., and Cai, Hao, 2020, Woody Feedstocks 2020 State of Technology Report. United States: N. p., 2021. Web. doi:10.2172/1782211.

Hess, J. R., K. L. Kenney, L. P. Ovard, E. M. Searcy, and C. T. Wright, 2009, *Commodity-Scale Production of an Infrastructure-Compatible Bulk Solid from Herbaceous Lignocellulosic Biomass. Uniform-Format Bioenergy Feedstock Supply System Design Report Series*, INL/EXT-09-17527, April 2009.

Hill, L. D., 1990, *Grain grades and standards: Historical issues shaping the future,* Chicago, IL, USA, University of Illinois Press.

Hodges, D. G., A. J. Hartsell, C. Brandeis, T. J. Brandeis, and J. W. Bentley, 2012, "Recession Effects on the Forests and Forest Products Industries of the South," *Forest Products Journal* 61(8): 614-624.

Howe, D, T. Westover, D. Carpenter, D. Santosa, R. Emerson, S. Deutch, A. Starace, I. Kutnyakov, and Lukins, 2015, "Field-to-Fuel Performance Testing of Lignocellulosic Feedstocks: An Integrated Study of the Fast Pyrolysis-Hydrotreating Pathway," *Energy and Fuels* 29(5): 3188-3197.

Humbird, D., R. Davis, L. Tao, C. Kinchin, D. Hsu, A. Aden, P. Schoen, J. Lukas, B. Olthof, M. Worley, D. Sexton, and D. Dudgeon, 2011, *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover*, NREL/TP-5100-47764, http://www.nrel.gov/biomass/pdfs/47764.pdf, accessed June 30, 2014.

IBSS, 2014, "Wood energy: understanding the forest connection," R. E. Bardon and D. W. Hazel, Southeastern Partnership for Integrated Biomass Supply Systems, http://www.se-ibss.org/publications-and-patents/extension-and-outreach-publications/wood-energy-understanding- the-forest-connection/at_download/file, accessed August 13, 2015.

Jacobson, J., P. Lamers, M. Roni, K. Cafferty, K. Kenney, B. Heath, J. Hansen, and J. Tumuluru, 2014, *Techno-economic analysis of a biomass depot*, INL/EXT-14-33225, September 30, 2014.

Janowiak, M. K. and C. R. Webster, 2010, "Promoting Ecological Sustainability in Woody Biomass Harvesting," *Journal of Forestry* 108(1): 16-23.

Jernigan, M. O., 2012, "High tonnage harvesting and skidding for loblolly pine energy plantations," M.Sc. Thesis, Auburn University, Alabama

Johnson, L. R., D. Page-Dumroese, and H-S. Han, 2007, "Effects of machine traffic on the physical properties of ash cap soils," In D. Page-Dumroese, R. Miller, J. Mital, P. McDaniel, D. Miller (eds.) *Proceedings of conference on Volcanic-ash-derived forest soils of the Inland Northwest: properties and implications for management and restoration*, Proc. RMRS-P-44, Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 69-82.

Jones, S, E. Tan, J. Jacobson, A. Meyer, A. Dutta, and L. Snowden-Swan, 2013, *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels: Fast Pyrolysis and Hydrotreating Bio-oil Pathway*, Pacific Northwest National Laboratory, DRAFT Technical Report to the Bioenergy Technologies Office.

Kaczmarek, D. J., D. R. Coyle, and M. D. Coleman, 2013, "Survival and growth of a range of Populus clones in central South Carolina USA through age ten: Do early assessments reflect longer-term survival and growth trends?," *Biomass and Bioenergy* 49: 260-272

Kelkar, V.M., Geils, B.W., Becker, D.R., Overby, S.T., Neary, D.G. 2006, How to recover more value from small pine trees: Essential oils and resins. *Biomass and Bioenergy* 30:316-320. https://www.fs.fed.us/rm/pubs_other/rmrs_2006_kelkar_v001.pdf

Kenney, K. L., W. A. Smith, G. L. Gresham, and T. L. Westover, 2013, "Understanding biomass feedstock variability," *Biofuels* 4: 111–127.

Klockow, P. A., A. W. D'Amato, and J. B. Bradford, 2013, "Impacts of post-harvest slash and live-tree retention on biomass and nutrient stocks in Populus tremuloides Michx.-dominated forests, northern Minnesota, USA," *Forest Ecology and Management* 291: 278-288.

Lacey, J. A., J. E. Aston, T. L. Westover, R. R. S. Cherry, and D. N. Thompson, 2015, "Removal of introduced inorganic content from chipped forest residues via air classification," *Fuel* 160: 265-273.

Lamers, P. and D. Hartley, 2016, Domestic feedstock use patterns to identify market linkages. Idaho Falls, ID, USA, Idaho National Laboratory.

Lamers, P., M. S. Roni, J. S. Tumuluru, J. J. Jacobson, K. G. Cafferty, J. K. Hansen, K. Kenney, F. Teymouri, and B. Bals, 2015a, "Techno-economic analysis of decentralized biomass processing depots," *Bioresource Technology* 194: 205-213.

Langholtz, M, 2013, ORNL personal communication, December 2013.

Langholtz, M, 2014, ORNL personal communication, December 2014.

Lanning, D. N., J. H. Dooley, and C. J. Lanning, 2012, "Shear processing of wood chips into feedstock particles," in *2012 ASABE Annual International Meeting, Dallas, Texas, July 29-August 1, 2012,* American Society of Agricultural and Biological Engineers.

Muth, D. J., M. H. Langholtz, E. C. D. Tan, J. J. Jacobson, A. Schwab, M. M. Wu, A. Argo, C. C. Brandt, K. G. Cafferty, Y. W. Chiu, A. Dutta, L. M. Eaton, and E. M. Searcy, 2014, "Investigation of thermochemical biorefinery sizing and environmental sustainability impacts for conventional supply system and distributed pre-processing supply system designs," *Biofuels Bioprod. Bior* 8: 545-567.

Nurmi, J., 2007, "Recovery of Forest residues for energy from spruce (Pices abies) dominated stands," *Biomass and Bioenergy* 31(6): 375-380.

Nurmi, J., 2014, "Changes in volumetric energy densities during storage of whole-tree feed stocks from silvicultural thinnings," *Biomass and Bioenergy* 61: 114-120.

Owens, V. N., D. L. Karlen, and J. A. Lacey et al., 2016, Regional Feedstock Partnership Report: Enabling the Billion-Ton Vision. U.S. Department of Energy and Idaho National Laboratory. INL/EXT-15-37477.

Pace, D. P and N. A. Yancey, 2013, *Biomass Feedstock PDU Project: Biomass Comminution Study*, INL/EXT-14-31058.

Pearson, C.H., Halvorson, A.D., Moench, R.D. and Hammon, R.W., 2010, Production of hybrid poplar under short-term, intensive culture in Western Colorado. *Industrial Crops and Products*, *31*(3), pp.492-498.

Ponder, F., R. L. Fleming, S. Berch, M. D. Busse, J. D. Elioff, P. W. Hazlett, and R. A. Voldseth, 2012, "Effects of organic matter removal, soil compaction and vegetation control on 10th year biomass and foliar nutrition: LTSP continent-wide comparisons," *Forest Ecology and Management* 278: 35-54.

Ralevic, P., M. Ryans, and D. Cormier, 2010, "Assessing forest biomass for bioenergy: operational challenges and cost considerations," *The Forestry Chronicle* 86(1): 43-50.

Reddy, D. V. and N. Krishna, 2009, "Precision animal nutrition: A tool for economic and eco-friendly animal production in ruminants," *Livestock Research for Rural Development* 21(3).

Roise, J. P., G. Catts, D. Hazel, A. Hobbs, and C. Hopkins, 2013, *Balancing biomass harvesting and drying tactics with delivered payment practice*, Technical Report-not held in TRLN member libraries, Greenville, SC: U.S. Endowment for Forestry and Community.

Sami, M., K. Annamalai, and M. Wooldridge, 2001, "Co-firing of coal and biomass fuel blends," *Progress in Energy and Combustion Science* 27(2): 171-214.

Searcy, E. and J. R. Hess, 2010, *Uniform-Format Feedstock Supply System: A Commodity-Scale Design to Produce an Infrastructure-Compatible Biocrude from Lignocellulosic Biomass*, INL/EXT-10-2037.

Searcy E. M, C. T. Wright, J. R. Hess, and T. Westover, 2012, "Logistics Costs for the 2012 Conventional Woody Biomass Feedstock Supply for Thermochemical Conversion," Idaho National Laboratory Technical Report to Office of Biomass Program, U.S. Department of Energy, January 2012.

Shepard, J. P., 2006, "Water quality protection in bioenergy production: the U.S. system of forestry Best Management Practices," *Biomass and Bioenergy* 30(4): 378-384.

Shih, J.-S. and H. C. Frey, 1995, "Coal blending optimization under uncertainty," *European Journal of Operational Research* 83(3): 452-465.

Skog, K. E. and R. J. Barbour, 2006, "Estimating woody biomass supply from thinning treatments to reduce fire hazard in the U.S. West," In P. L. Andrews and B. W. Butler (compilers), *Conference proceedings RMRS-P-41—Fuels management: How to measure success*, Ft. Collins, CO: USDA Forest Service Rocky Mountain Research

Station: 657-672.

Soh, S. H., Jain, A., Lee, L. Y., Chin, S. K., Yin, C. Y., & Jayaraman, S., (2021), Techno-economic and profitability analysis of extraction of patchouli oil using supercritical carbon dioxide. *Journal of Cleaner Production*, 297, 126661.

Sokhansanj, S., A. Turhollow, and E. Webb, 2014, *Simulation of the DOE High-Tonnage Biomass Logistics Demonstration Projects-Auburn University*, ORNL/TM-2014/505.

Spinelli, R., Cavallo, E., Facello, A., Magagnotti, N., Nati, C. and Paletto, G., 2012, Performance and energy efficiency of alternative comminution principles: chipping versus grinding. *Scandinavian Journal of Forest Research*, *27*(4), pp.393-400.

Stokes B., T. McDonald, and T. Kelly, 1993, *Transpirational drying and costs for transporting woody biomass a preliminary review*, Auburn, AL: USDA forest service, southern forest experiment station.

Thompson, J. and W. Sprinkle, 2013, Production, cost and chip characteristics of in-woods Microchipping. Council on Forest Engineering Annual Meeting, Auburn, AL (2013)

Thompson, V., J. Aston, J. Lacey and D. Thompson, 2016, *Develop feedstock blends using combined chemical and mechanical separations along with formulation techniques to reduce feedstock costs and risks in the supply chain,* 1.2.2.1 Milestone Completion Report.

Townsend, P. A., S. P. Kar, and R. O Miller, 2014, "Popular (Populus spp.) Trees for Biofuel Production," accessed 9-6-2016: http://articles.extension.org/pages/70456/poplar-populus-spp-trees- for-biofuel-production.

Tumuluru, J.S., 2016, Specific energy consumption and quality of wood pellets produced using high-moisture lodgepole pine grind in a flat die pellet mill. Chemical Engineering Research and Design. 110(2016) 82-97.

U.S. Department of Energy, 2016a, *2016 Billion Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*, M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160, Oak Ridge National Laboratory, Oak Ridge, TN: 448.

U.S. Department of Energy, 2016b, *Bioenergy Technologies Office Multi-Year Program Plan*, DOE/EE-1385, March 2016, http://www.energy.gov/sites/prod/files/2016/07/f33/mypp_march2016.pdf.

U.S. Department of Energy, 2011, U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN. 227p.

U.S. Department of Energy, Bioenergy Technologies Office, 2015, "Accomplishments and Successes," http://www.energy.gov/eere/bioenergy/accomplishments-and-successes#2014, accessed July 2015.

U.S. Energy Information Administration, 2015a, "Electric Power Monthly: Table 5.6.A Average Retail Price of Electricity to Ultimate Customers by End-Use Sector," accessed 9/1/15: http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a.

U.S. Energy Information Administration, 2015b, "Gasoline and Diesel Fuel Update," accessed 9/1/15: http://www.eia.gov/petroleum/gasdiesel/.

U.S. Energy Information Administration, 2015c, "Natural Gas: Henry Hub Natural Gas Spot Price-Annual History," accessed 9/1/15: http://www.eia.gov/dnav/ng/hist/rngwhhdA.htm.

U.S Energy Information Administration, 2013, Manufacturing Energy Consumption Survey (MECS). Washington DC, USA, US Energy Information Administration (EIA). Retrieved from https://www.eia.gov/consumption/manufacturing/, accessed February 2016.

U.S. Forest Service, 2012, Future of America's Forest and Rangelands: Forest Service 2010 Resources Planning Act Assessment. Washington, DC, USA, United States Forest Service. Retrieved from http://www.treesearch.fs.fed.us/pubs/41976/, accessed February 2016.

Vakkilainen, E., K, Kuparinen and J. Heinimö, 2013, Large Indusrial Users of Energy Biomass. IEA Bioenergy, Task 40: Sustainable International Bioenergy Trade. pp 75.

Vance, E. D., W. M. Aust, B. D. Strahm, R. E. Froese, R. B. Harrison, and L. A. Morris, 2014, "Biomass Harvesting and Soil Productivity: Is the Science Meeting our Policy Needs?," *Soil Science Society of America Journal* 78(S1): S95-S104.

Wang, J., D. S. Hartley, and W. Liu, 2013, "Biomass Harvesting Systems and Analysis," In: M. Jacobson and D. Ciolkosz (eds.), *Wood Based Energy in the Northern Forests*: 101-120, New York: Springer.

Webb, E., S. Sokhansanj, and A. Turhollow, 2013a, *Simulation of the DOE High-Tonnage Biomass Logistics Demonstration Projects-AGCO Corporation* ORNL/TM-2013/323.

Webb, E., S. Sokhansanj, and A. Turhollow, 2013b, *Simulation of the DOE High-Tonnage Biomass Logistics Demonstration Projects-FDC Enterprises,* ORNL/TM-2013/338.

Webb, E., S. Sokhansanj, and A. Turhollow, 2013c, *Simulation of the DOE High-Tonnage Biomass Logistics Demonstration Projects-State University of New York College of Environmental Science and Forestry* ORNL/TM-2013/376.

Webb, E., S. Sokhansanj, and A. Turhollow, 2013d, *Simulation of the DOE High-Tonnage Biomass Logistics Demonstration Projects-TennEra LLC,* ORNL/TM-2013/375.

Wright, J., 2013, "Advances in Hardwood Plantation Systems Implications for Bio-energy feedstock," In: *2013 SWST International Convention*, Austin, TX. June 9-11, 2013.

Yancey, N. A., C.T. Wright, C.C. Connor and J.R. Hess, 2009, "Preprocessing moist lignocellulosic biomass for biorefinery feedstocks," *Proceedings of the ASABE Annual Meeting,* Reno, Nevada.

Zeng, W.C., Zhang, Z., Gao, H., Jia, L.R., He, Qiang, 2012, Chemical Composition, Antioxidant, and Antimicrobial Activities of Essential Oil from Pine Needle (Cedrus deodara). *Journal of Food Science* 77: 824-829.

APPENDIX A – 2022 State of Technology Feedstock Logistics Design and Assumptions for Low-Ash Woody Feedstock Supply to CFP

The 2022 woody SOT for low-ash woody feedstocks case (Figure A-1) consists of 50% clean pine and 50% air classified forest residue and supplies 725,000 dry tons of biomass annually to the throat of the conversion reactor. The clean pine is harvested and preprocessed using a modified ground-based mechanized chip production system that is based on the system that was studied by Auburn University during their High Tonnage Logistics Demonstration Project. The forest residues are preprocessed at the roadside using a system that is based on the chip processing system that was also studied by Auburn University during their High Tonnage Logistics Demonstration Project. The processed forest residues are transported from their aggregation points after preprocessing. The materials are delivered directly to the biorefinery, where they are further preprocessed, ground and dried before being delivered to the throat of the reactor.

The model relies on assumptions about exogenous factors such as interest rates, energy prices, and land rents. The prices for electricity, natural gas, and off-road diesel are identical to those used in the 2020 SOT for CFP. Table A-1 shows the values that were used.

Table A-1. *Energy prices and interest rates used to model feedstock logistics costs for the 2022 woody SOT for low-ash woody feedstocks.*

Component	2021 Assumptions	2022 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	$2.01/gal[d]	$2.01/gal[d]

[a]Jones et al. 2013.
[b]EIA 2017

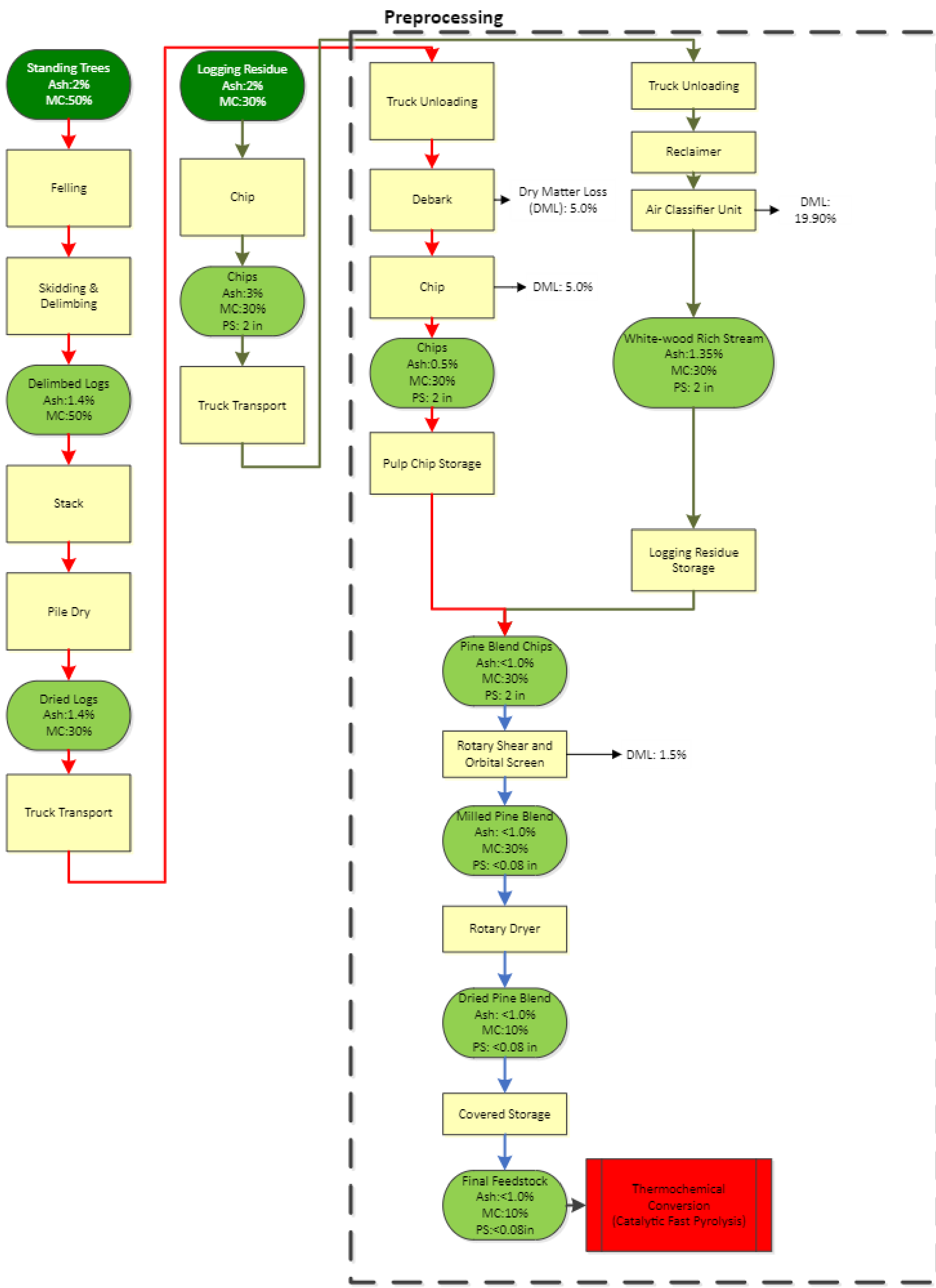

Figure A-1. *2022 woody SOT feedstock supply system design for low-ash woody feedstocks.*

A.1 Harvest and Collection

The 2022 woody SOT for low-ash woody feedstocks utilizes both clean pine and forest residues. The harvest of clean pine for energy is similar to harvest of materials for the production of paper or lumber, using integrated activities to prepare the raw material for transport from the field to the processing facility (Wang et al. 2013). The 2022 woody SOT for low-ash woody feedstocks maintains the same type of system for clean pine harvest and collection that was used in the 2018 SOT for CFP and is based on the system studied in the DOE High-Tonnage Biomass Logistics Demonstration Project carried out by Auburn University. The system uses a tracked feller buncher with a high-speed shear for felling the clean pine sized material. Collection and primary transportation are completed using a grapple skidder with an oversized grapple to increase payload. Felling production using the feller buncher is 49 dry tons per hour (Cafferty and Hartley 2015, Sokhansanj et al. 2014, Jernigan 2012). Collection of the material is completed through use of a grapple skidder with a capacity of 40 dry tons per hour (Cafferty and Hartley 2015, Sokhansanj et al. 2014, Jernigan 2012).

Forest residues are materials, in the form of limbs, tops, cutoffs, and/or culled material that originate from the harvest of saw log material. This material is accumulated at the landing as saw logs are processed and stored in piles. Because the material is a byproduct of saw log processing, the cost of harvest and collection are not attributed to the material. Key harvest and collection assumptions for the 2022 woody SOT for low-ash woody feedstocks are shown in Table A-2.

Table A-2. *Key harvest and collection assumptions for the 2022 woody SOT for low-ash woody feedstocks.*

Component	Clean Pine	Forest Residue
Harvest Machine		
Type	Feller-buncher	N/A
Rated Capacity (ton/hour)	75.38	N/A
Utilization (%)	65	N/A
Collection Machine		
Type	Grapple skidder	N/A
Rated Capacity (ton/hour)	62	N/A
Utilization (%)	65	N/A
Average Extraction Distance (feet)	1,500	N/A
Initial Moisture Content	50%	50%
Field Dry Moisture Content	30%	30%
Operation Hours	50 weeks/year, 5 days/week, 8 hours/day	50 weeks/year, 5 days/week, 8 hours/day

A.2 Storage

Storage involves stockpiling material to provide an adequate lead time for downstream processes and accumulating material quantities for economical transportation. Woody biomass is subject to degradation by fungi, yeast, and bacteria that alter the feedstock's composition. Degradation is a more prevalent problem in comminuted biomass, which has a higher surface area exposed and accessible to the damaging agents. Conversely, if the woody biomass is stored as uncomminuted material, the material is stable and can be kept for periods greater than a year without experiencing a reduction in quality (Nurmi 2014, Erber et al. 2014, Ackerman et al. 2014). The additional benefit of storage in the field is that the material dries during that time, reducing the moisture content before transportation (Stokes et al. 1993).

Field drying during storage (first included in the 2014 woody SOT and also a key component of Auburn's High Tonnage Logistics Demonstration Project (Cafferty and Hartley 2015, Sokhansanj et al. 2014)) is included in the 2022 woody SOT for low-ash woody feedstocks. A variety of data show the effectiveness of field drying, which is highly variable by region, species, age, and methodology. A study conducted by North Carolina State University showed that by allowing logs to dry on the landing for a period of 330 to 360 days, the moisture content can be reduced from 50% to approximately 18%, independent of time of harvest or tree type (i.e., hardwood or softwood) (Roise et al. 2013). Because the study was completed in the same region as the defined study area, we can assume that similar results are likely and an assumption of a moisture reduction of 20% (from 50% down to 30%) in both clean pine and forest residue is conservative. Similar studies in other areas have shown greater moisture reductions in less time (Stokes et al. 1993, Greene et al. 2014).

When the materials reach the biorefinery they are stored in uncovered piles to await drying. The storage requirements at the conversion facility are assumed to be enough material to sustain the operation for 1 week. This quantity of material is assumed to be adequate to sustain operations during periods of time when material is not supplied due to weather or other disruptions, while also not being so great that storage losses will be large due to degradation (Table A-3).

Table 1. *Key storage assumptions for the 2022 woody SOT for low-ash woody feedstocks.*

Component	Clean Pine	Forest Residue
Field-side		
Type	Log Pile	Uncovered pile
Ground Cover	None	None
Material Loss (%)	<1%	<1%
Biorefinery		
Type	Uncovered pile	Uncovered pile
Ground Cover	Asphalt pad	Asphalt pad
Material Loss (%)	2%	2%
Days of Supply	6	6

A.3 Transportation and Handling

Transportation includes all processes involved in movement of material to a centralized location (such as a preprocessing facility or to the biorefinery). Transportation includes processes such as loading, trucking, rail transport, and unloading. Beyond transportation, additional handling is required to transfer and queue biomass to the conversion facility. Surge bins, conveyors, dust collection, and miscellaneous equipment are used in handling operations. Handling operations depend on many factors, including biomass moisture content, bulk density, and particle size and shape distribution. Lignocellulosic feedstock inherently possesses characteristics that inhibit handling (e.g., high cohesivity, low density, high compressibility, and high variability in particle size and shape uniformity) (Kenney et al. 2013). For this reason, lignocellulosic feedstock handling operations are typically designed at 150% of design capacity in order to accommodate variability in biomass handling properties.

The 2022 woody SOT for low-ash woody feedstocks uses truck transportation to the depot/biorefinery (Table A-4). The clean pine material is transported as logs on log trailers with a capacity of 3,600 ft^3. The forest residues are blown from the chipper into possum belly open back trailers with a capacity of 4,000 ft^3. The clean pine logs are assumed to have a bulk density of 16 lb/ft^3, while the forest residue chips are assumed to have a dry bulk density of 11 lb/ft^3 (Harris and Phillips 1986) and the assumed moisture content at transportation is 30% (wet basis) (Greene et al, 2014). This resulted in a calculated weight-limited payload of 17.68 dry tons/load for the forest residue material. The draw radius for the clean pine was 41.81 miles while for the forest residue the draw radius was 125.87 miles, based on material availability.

Table A-4. *Key transportation and handling assumptions for the 2022 woody SOT for low-ash woody feedstocks.*

Component	Clean Pine	Forest Residue
Truck		
Type	Day Cab	Day Cab
Transportation Distance (mi)	51	104
Speed (mph)	50	50
Trailer		
Type	Log Trailers	Open back possum belly
Volume	3,600 ft^3	4,000 ft^3
Dry Bulk Density	16 lb/ft^3	11 lb/ft^3
Moisture Content	30%	30%

A.4 Landing Preprocessing

The landing is the location where forest materials are initially aggregated, stored, and processed for transport and sale after harvest. Landing preprocessing is used to improve the transportation and handling characteristics of the biomass feedstocks. Landing processing is designed to increase the bulk density and/or remove materials that will be considered waste further along the supply chain. Through both increasing density and removing waste materials, transportation cost for the material is reduced and subsequent processing is made more efficient.

With clean pine the only processing operation at the landing is delimbing, Delimbing is accomplished just prior to stacking for storage using a delimbing gate. It is worth noting that use of the delimbing gate resulted in reduced productivity of the grapple skidder, since the stems are manually forced through a metal grid by the skidder to remove the branches.

Landing preprocessing for the forest residues included in the 2022 woody SOT for low-ash woody feedstocks blend begins before transportation to the depot. In this design the only preprocessing at the landing is chipping. The forest residues are chipped to a 2-in. chip using a mobile disk chipper. Production and fuel consumption for the chipper were taken from the DOE High-Tonnage Biomass Logistics Demonstration Project that was carried out by Auburn University. The chips are then loaded into the chip trailer by blowing the chips from the outfeed (Table A-5).

Table A-5. *Key landing preprocessing assumptions for the 2022 woody SOT for low-ash woody feedstocks.*

Component	Clean Pine	Forest Residue
Loader		
Type	Knuckle boom	Knuckle boom
Capacity (ton/hr)	75.6	75.6
Delimbing		
Type	Gate	N/A
Capacity (ton/hr)	50	N/A
Dry Matter Loss (%)	5	N/A
Size Reduction		
Type	N/A	Chipper
Capacity (ton/hour)	N/A	65.2
Dry Matter Loss (%)	N/A	5
Particle Size	Logs	2 in.
Moisture Content	30%	30%

A.5 Refinery Operations

The forest residue chips are delivered to the refinery by truck, where they are offloaded using a truck tipper with a hopper. The clean pine logs are unloaded from the trucks using a high-lift loader and placed into storage piles. To initiate preprocessing, logs are delivered by loader to a rotary head debarker, and the debarked logs are conveyed to a 25 ton/hr disk chipper to produce approximate 2-in nominal chips and are held in storage piles until they can be conveyed for preprocessing. The residue chips are subjected to a sequential air classification to remove needles for a midstream market to offset some of the preprocessing cost. Some of the loose bark is also removed, producing an enriched whitewood fraction.

Data for the sequential air classification were received from a competitive BETO-funded Directed Funding Opportunity project for a method they developed, comprised of four sequential Key Technologies air classification stages. As the project team plans to publish the flowsheet and separation efficiencies, we modeled the system for this SOT as a single air classification unit so that the information is not publicly available before they publish it (this SOT will be available on OSTI after review).

The air classified logging residue chips are then blended with clean pine chips into a 50/50 stream as they are fed to the rotary shear. Owing to the design capacity for the rotary shear and orbital screen we assumed that a combined piece of equipment with a processing capacity of 5 tons/hour was used in the system. To match the processing capacity of the other equipment, multiple units (5) of the rotary shear-orbital screen combination were included in the model. After the blended chips are rotary sheared and dried to 10% moisture content, they are held in covered storage until feeding to the conversion process (Table A-6).

Table A-6. *Assumptions for key depot operations in the 2022 woody SOT for low-ash woody feedstocks.*

Component	Clean Pine	Forest Residue
Reclaimer		
Energy	N/A	2.21 kWh
Capacity	N/A	100 ton/hour
Drag Chain Conveyor		
Energy	3.73 kWh	3.73 kWh
Capacity	100 ton/hour	100 ton/hour
Loader		
Capacity	120 ton/hour	120 ton/hour
Debarker		
Horsepower	50	N/A
Capacity	80 ton/hour	N/A
Dry Matter Loss	3%	N/A
Chipper		
Energy	25.4 kWh	N/A
Capacity	23.8 ton/hour	N/A
Air Classifier Unit		
Capacity	N/A	7.5 ton/hour
Energy	N/A	13.3 kWh/ton
Operating Conditions	N/A	30% moisture
Dry Matter Loss	N/A	19.90%
Rotary Shear and Orbital Screen		
Capacity	5.68 ton/hour	5.68 ton/hour
Energy	20.2 kWh/ton	20.2 kWh/ton
Screen Size	1/4-in	1/4-in
Operating Conditions	30% moisture	30% moisture
Dry Matter Loss	1.5%	1.5%

Component	Clean Pine	Forest Residue
Dryer		
Capacity	1.55 ton/hour	1.55 ton/hour
Energy	263 kWh/ton	263 kWh/ton
Waste Heat	0%	0%
Moisture Reduction	20%	20%

APPENDIX B – Overall Operating Effectiveness

B.1 Definition of the Overall Operating Effectiveness of a System

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

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

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

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

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

$$OEE\ (\%) = A \times PR\ \times QR \times 100 \quad (3)$$

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

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

$$OEE(\%) = (A \times PR) \times QR \times 100 \quad (4)$$

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

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

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

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

$$OOE(\%) = F_f \times F_B \times 100 \quad (6)$$

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

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

B.2 OOE in the 2022 Woody Feedstock Supply Chain

The woody feedstock field to biofuel system consists of three subsystems, (1) Supply Logistics; (2) Preprocessing; and (3) High-Temperature Conversion. The conversion process consists of *ex situ* catalytic fast pyrolysis followed by hydrotreating (Dutta et al. 2018). Woody biomass sources are best suited for this process, and while the best studied biomass feedstocks are oak whitewood and clean pine, these feedstocks are too costly and so there is a desire to utilize logging residues (which are less costly, but also of lower quality). The feedstock mix utilized mirrors the feedstocks used in the nth-plant 2020 Woody SOT for Catalytic Fast Pyrolysis (Hartley et al., 2021), using both clean pine and logging residues. The clean pine is harvested, delimbed and delivered to the biorefinery as logs. At the biorefinery the logs are debarked and chipped. Supply Logistics for logging residue consists of chipping of the residues at the landing, transportation to the biorefinery and storage of a 2-week supply in a chip pile. The logging residue chips are reclaimed from the pile when needed, air classified in a series of steps and blended with the clean pine chips to be brought to a set of conversion specifications.

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

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

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

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

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

B.3 Discrete Event Simulation Approach

Supply Logistics consists of the operations from harvest to the biorefinery gate. Harvest, collection and transportation of logging residue chips to the biorefinery occur year-round on a 1-year timeframe. Preprocessing and Conversion also both occur on a 1-year timeframe. As only a 2-week supply of chips are stored at the biorefinery, dry matter losses and other changes to the logging residue are expected to occur prior to chipping (during field drying while stored as intact logging residues at the landing). Transportation of the chips to the biorefinery is not expected to cause any significant changes to the compositional or physical properties of the logging residues. Hence, for Supply Logistics the only contribution to the throughput analysis was to define the distributions of compositional and physical properties at the biorefinery gate (see below).

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

To conduct the throughput analyses performed for this report, Discrete Event Simulation (DES) was employed from the landing through to the conversion reactor throat to model the interactions of supply logistics and preprocessing equipment throughput and performance. The discrete event models began with the introduction of one dry ton of feedstock into the chipper at the landing. The moisture, ash and organic elemental content (C, H, O and N) contents were randomly sampled from distributions developed from various INL and public data sources. Details on the individual data sources and distribution generation methods for the various distributions are provided in the main body of this report.

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

$$Preprocessing\ Equipment\ or\ Subsystem\ Throughput = f_1(moisture\ content, ash\ content) \tag{12}$$

$$Convertible\ Composition\ Exiting\ Preprocessing\ Equipment\ orSubsystem = f_2(moisture\ content, ash\ content) \tag{13}$$

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

B.3.1 Supply Logistics

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

$$T_{S,delivered} = \sum_{i=1}^{N} T_{S,i} \tag{14}$$

If a ton delivered to biorefinery gate meets the minimum quality threshold equivalent to the conversion-specified ash and carbon contents (adjusted for losses in preprocessing), then that ton is considered to meet the conversion requirement. The total number of tons meeting the minimum quality threshold, $T_{S,N}$ (dry tons) is calculated as

$$T_{S,N} = \sum_{i=1}^{N} T_{S,i,meets\ spec} \tag{15}$$

Then the throughput capacity factor and performance factor are

$$F_{f,S} = \frac{T_{S,delivered}}{T_{S,delivered}} = 1.0 \tag{16}$$

$$F_{B,S} = \frac{T_{S,N}}{T_{S,delivered}} \tag{17}$$

Note that $F_{f,S}$ will always be equal to 1.0 because there are no dry matter losses during storage and only enough tons needed for Preprocessing are delivered to the biorefinery, and if the throughput of preprocessing is below design, the design number of tons becomes irrelevant to Supply Logistics.

B.3.2 Preprocessing

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

$$T_{P,fed} = \sum_{i=1}^{N} T_{P,i} \tag{18}$$

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

$$T_{P,N} = \sum_{i=1}^{N} T_{P,i,meets\,spec} \tag{19}$$

Then the throughput capacity factor and performance factor are

$$F_{f,P} = \frac{T_{P,fed}}{T_{P,Nameplate}} \tag{20}$$

$$F_{B,P} = \frac{T_{P,N}}{T_{P,fed}} \tag{21}$$

B.3.3 Machine Performance Assumptions

	Reclaimer	Conveyor	Debarker	Chipper	Air Classifier Unit	Rotary Shear+ Orbital Screen	Dryer
Capacity	25	25	25	25	25	25	25
MTTF (minutes)	262,800	252,000	262,800	262,800	252,00	262,800	252,00
TTR (minutes)	740	480	120	30	480	480	740
TTR_SD (minutes)	120	90	60	15	90	90	120
Max_MC (%)	—	—	—	—	—	45	—
Max_MC_TTR (minutes)	—	—	—	—	—	30	—
Max_MC_TTR_SD (minutes)	—	—	—	—	—	15	—
Max_Ash (U.S. short tons)	—	—	300	215	—	100	—
Max_Ash_TTR (minutes)	—	—	45	15	—	360	—
Max_Ash_TTR_SD (minutes)	—	—	20	5	—	120	—

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

B.4 References

American Society for Quality (ASQ), 2011, Glossary: Reliability. Accessed on September 26, 2019. Available at http://asq.org/glossary/r.html.

da Costa, S. G.; de Lima, E. P., 2002, In Uses and misuses of the overall equipment effectiveness' for production management, IEEE International Engineering Management Conference, IEEE, pp 816-820.

Dutta, A., K. Iisa, C. Mukarakate, M. Griffin, E.C.D. Tan, J. Schaidle, D. Humbird, H. Wang, D. Hartley, D. Thompson, and H. Cai, 2018, "*Ex Situ* Catalytic Fast Pyrolysis of Lignocellulosic Biomass to Hydrocarbon Fuels: 2018 State of Technology and Future Research." NREL Technical Report, NREL/TP-5100-71954, October 2018.

Hartley, Damon S, Thompson, David N, and Cai, Hao, 2021, Woody Feedstocks 2020 State of Technology Report. United States: N. p., 2021. Web. doi:10.2172/1782211.

Miyata, E.S. and H.M. Steinhilb, 1981, "Logging System Cost Analysis: Comparison of Methods Used." USDA Forest Service, North Central Forest Experiment Station, Research Paper NC-208.

Muchiri, P.; Pintelon, L., 2008, Performance measurement using overall equipment effectiveness (OEE): literature review and practical application discussion. International journal of production research. 46 (13), 3517-3535. DOI:10.1080/00207540601142645

SEBoK contributors, 2019, "Reliability, Availability, and Maintainability," In *Guide to the Systems Engineering Body of Knowledge (SEBoK)*, Accessed on September 26, 2019. Available at https://www.sebokwiki.org/w/index.php?title=Reliability,_Availability,_and_Maintainability&oldid=55829.

Zammori, F.; Braglia, M.; Frosolini, M., 2011, Stochastic overall equipment effectiveness. International Journal of Production Research, 49 (21), 6469-6490. DOI: 10.1080/00207543.2010.519358