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Air classification of forest residue for tissue and ash separation efficiency

December 2022

Changing the World's Energy Future

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Idaho National Laboratory

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RENEWABLE ENERGY

FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

Air classification of forest residue for tissue and ash separation efficiency

DOE/EE-0000 • December 2022

Disclaimer

About the Feedstock-Conversion Interface Consortium

The Feedstock-Conversion Interface Consortium (FCIC) develops first-principles-based knowledge and tools to understand, quantify, and mitigate the effects of feedstock and process variability across the bioenergy value chain, from the field and forest through downstream conversion. The FCIC is a collaborative and coordinated effort involving researchers in many different disciplines. It is led by the U.S. Department of Energy's Bioenergy Technologies Office (BETO) and includes researchers from nine national laboratories: Argonne National Laboratory, Idaho National Laboratory, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, National Energy Technology Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories.

Research within the FCIC focuses on two complementary conversion pathways: (1) the low-temperature conversion of corn stover to fuels and chemicals using deacetylation and mechanical refining, enzymatic hydrolysis, and biological upgrading of the sugar- and lignin-rich streams; and (2) the high-temperature conversion of pine residues to fuels using catalytic fast pyrolysis and hydrotreating. Each pathway covers three sequential process areas—biomass harvest and storage, preprocessing, and conversion.

The FCIC is organized into eight collaborative tasks working in each of these process areas. The Feedstock Variability task investigates biomass attribute variations that originate in the harvest and storage process area; the Preprocessing, Materials Handling, and Materials of Construction tasks investigate the effects of biomass variability in the preprocessing area; and the High-Temperature Conversion and Low-Temperature Conversion tasks investigate the effects of biomass variability in the conversion process area. Two supporting tasks (Crosscutting Analyses and Scientific Data Management) support all FCIC research.

The Feedstock-Conversion Interface Consortium uses first-principles-based science to de-risk biorefinery scale-up and deployment by understanding and mitigating the impacts of feedstock variability on bioenergy conversion processes

energy.gov/fcic

Availability

This report is available electronically at no cost from http://www.osti.gov.

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List of Acronyms

BETO	Bioenergy Technologies Office
CFP	Catalytic Fast Pyrolysis
CMA	Critical Material Attribute
CQA	Critical Quality Attribute
DOE	U.S. Department of Energy
FCIC	Feedstock-Conversion Interface Consortium
gge	Gallons of Gasoline Equivalent
INL	Idaho National Laboratory
MFSP	Minimum Fuel Selling Price
NREL	National Renewable Energy Laboratory
OOE	Overall Operating Effectiveness
PNNL	Pacific Northwest National Laboratory
SOT	State of Technology

Executive Summary

The goal of this Case Study was to evaluate the performance of air classification of logging residues toward meeting conversion CMAs for carbon and ash contents, as compared to the static status quo Base Case system in which the residues are first dried and then ground in a hammer mill with a 6 mm screen and fines < 1.18 mm are removed. Also considered were moisture and ash impacts on throughput and Overall Operating Effectiveness (OOE), as well as delivered feedstock cost and minimum fuel selling price (MFSP). Laboratory data on the impacts of fan speed and moisture content on the separation efficiency of soil ash, needles and bark from white wood were received from FCIC Subtask 5.2: Preprocessing, High Temperature Conversion Preprocessing (Jordan Klinger and Tiasha Bhattacharjee, INL). Average throughput and energy consumption data were obtained from the Bioenergy Feedstock National User Facility (BFNUF) (Neal Yancey, INL) for the same air classifier. These data were utilized to develop the necessary response surface equations to perform throughput analysis using discrete event simulation.

Because the Base Case status quo system utilizes drying prior to grinding, we modeled the Case Study with drying prior to air classification and subsequent grinding of the separated white wood to isolate the individual quality and cost impacts of air classification relative to the Base Case system.

Both cases assumed a nameplate biorefinery design capacity of 2,205 dry tons of feedstock per day, with 350 operating days/year assuming 90% time on-stream over the year which is rounded to 725,000 dry tons/year and is the same as in the High-Temperature Conversion Feedstock 2020 Overall Operating Effectiveness (OOE) State of Technology (SOT) report. Preprocessing Critical Quality Attributes (CQAs), which are equivalent to the Conversion CMAs set by the biorefinery, include an ash content ≤ 1.75 wt% and a carbon content ≥ 50.51 wt%, both on a dry basis. Additional Preprocessing CQAs include a moisture content ≤ 10 wt% on a wet basis and particle size in the range 1-6 mm (fines were assumed to be particles < 1 mm). For both cases, while ash was tracked as a CQA for the quality cost analysis, data on selective ash removal in the fines were not available at the time of the modeling. Data on ash removal in the air classifier lights stream were available, and so that impact was included. Supply Logistics were assumed to be identical to the logging residue supply system design presented in the High-Temperature Conversion Feedstock 2020 OOE SOT. In both cases, a disk screen is inserted after the hammer mill to separate out fines < 1.18 mm (this is the closest screen size to the assumed minimum particle size CQA). In the Case Study, an air classifier was inserted after the dryer to assess the quality and cost impacts of removing soil, needles and bark from the system.

The Case Study had a 6.3% lower throughput capacity than the Base Case due to removal of the air classified lights stream. The production cost (includes, grower payment, harvest and collection, storage, transportation and preprocessing as well as the cost of the lost lights) adjusted for discarded fines were $143.31 and $159.68/dry ton (all costs are reported in 2016$) preprocessed for the Base Case and Case Study, respectively. Energy consumption was similar for the two systems due to drying energy being the dominant input in both cases (about 98% of total energy consumption). Removal of ash in the Base Case significantly reduced the contribution of wear from ash to failures and to downtime. When the compositional CQAs were taken into account (feeding to the reactor throat only preprocessed tons simultaneously meeting all CQAs), the final delivered feedstock costs for the Base Case and Case Study rose to $211.24 and $198.72/dry ton, respectively. FCIC Subtask 8.3: Crosscutting Analysis, High Temperature Conversion (Matt Wiatrowski, NREL) provided us a regression model of MFSP ($/gge) as a function of feedstock cost assuming constant carbon content, which was based on the 2019 SOT for CFP. This equation provides a conservative estimate of potential impact to MFSP, however, it is worth noting that carbon contents of the units fed for the Base Case ranged from 50.51% to 53.24% while for the Case Study it was 50.51% to 53.44%, which provides additional potential for lowering the MFSP due to increased bio-oil yields in both cases. The Base Case mean MFSP estimate was $5.71/gge, while the estimate for the Case Study was $5.50/gge, a decrease of 3.6%. This drop in MFSP highlights the trade-off between adding feedstock preprocessing operations and meeting all of the conversion CMAs 100% of the time, and will be larger when the added yield from the units exceeding the minimum carbon specification are included.

Key takeaways from this Case Study are that air classification improves the quality of the final material, but increases the production cost, especially when lights are disposed; this becomes a tradeoff between increased conversion yield and the extra cost. Removing material should be done as early in the process as possible. Each operation that occurs prior to removing the material increases the cost of the disposed material and leads to wasted energy expenditures. As processes are included or modified, the impact on monetary and energy cost should be included in the decision process. Identifying alternative uses and the associated value for material that is separated from the feedstock stream will have a significant impact on the delivered cost of the material. Although there was an increase in production cost by adding air classification, there was a resulting benefit to the MFSP when meeting or exceeding all of the conversion CMAs; this was an important finding that should be explored further with FCIC Subtask 8.3 and potentially FCIC Task 6: High Temperature Conversion.

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Introduction

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 meeting all conversion Critical Material Attributes (CMAs) at the throat of the reactor. Feedstock logistics can be broken down into subsystems 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 expands 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. Conventional systems tend to be more focused on the feedstock than with a specific conversion process or biorefinery process, which places all burden of adapting to feedstock variability on the biorefinery. Biorefineries, which are constrained by local supply, equipment availability, and permitting requirements, strive to optimize efficiencies and capacities. However, optimizing biorefinery processes is difficult when also faced with feedstock variability.

This Case Study focused on evaluating the performance of air classification of logging residues toward meeting conversion CMAs for carbon and ash contents. Also considered were moisture and ash impacts on throughput and overall operating effectiveness (OOE), and delivered feedstock cost and minimum fuel selling price (MFSP) impacts of not being able to feed residue not meeting all of the conversion CMAs. In this Case Study Summary Report, we compare this Case Study with to the static status quo Base Case that utilizes drying prior to grinding to isolate the individual quality and cost impacts of air classification relative to the Base Case system.

Methods

Both the Base Case and Case Study assumed a nameplate biorefinery design capacity of 2,205 dry tons of feedstock per day, with 350 operating days/year assuming 90% time on-stream over the year which is rounded to 725,000 dry tons/year and is the same as in the High-Temperature Conversion Feedstock 2020 Overall Operating Effectiveness (OOE) State of Technology (SOT) report (Hartley, Griffel and Thompson 2020). Preprocessing Critical Quality Attributes (CQAs), which are equivalent to the Conversion CMAs set by the biorefinery, include an ash content ≤ 1.75 wt% and a carbon content ≥ 50.51 wt%, both on a dry basis. Additional Preprocessing CQAs include a moisture content ≤ 10 wt% on a wet basis and particle size in the range 1-6 mm (greater than 1 mm to eliminate fines). For both cases, while ash was tracked as a CQA for the quality cost analysis, data on selective ash removal in the fines were not available at the time of the modeling. Data on ash removal in the air classifier lights stream were available, and so that impact was included. Flowsheets for the Base Case and Case Study are shown in Figures 1 and 2.

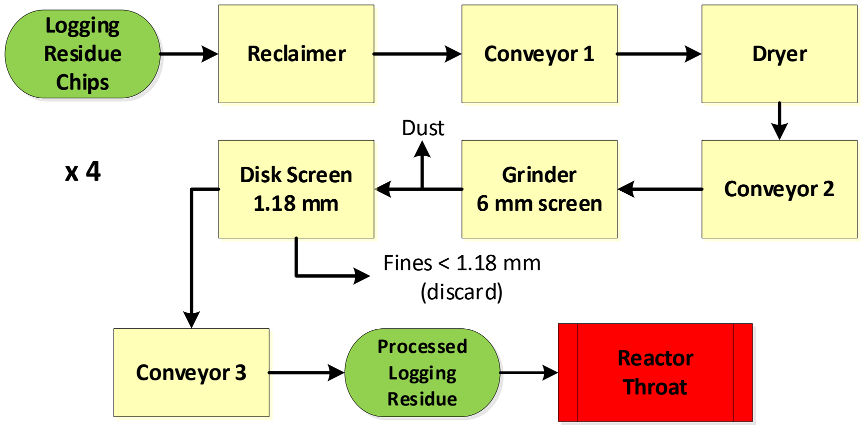

Figure 1. Flowsheet showing preprocessing operations for the Base Case

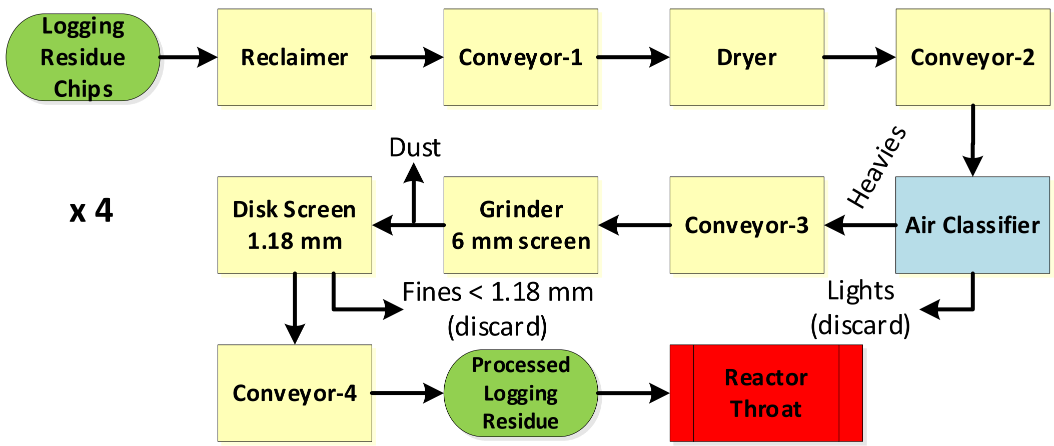

Figure 2. Flowsheet showing preprocessing operations for the Case Study

Supply Logistics were assumed to be identical to the logging residue supply system design presented in the High-Temperature Conversion Feedstock 2020 OOE SOT (Hartley, Griffel and Thompson 2020). In both cases presented here, a disk screen is inserted after the hammer mill to separate out fines < 1.18 mm (this is the closest screen size to the assumed minimum particle size CQA). In the Case Study, an air classifier and an additional conveyor are inserted just downstream of the dryer to assess the quality and cost impacts of reducing ash content by removing the air classifier lights (which contain soil, needles and bark in greater proportion than the heavies).

Laboratory data on the impacts of fan speed and moisture content on the separation efficiency of soil ash, needles and bark from white wood were received from FCIC Subtask 5.2: Preprocessing, High Temperature Conversion Preprocessing (Jordan Klinger and Tiasha Bhattacharjee, INL). Average throughput and energy consumption data were obtained from the Bioenergy Feedstock National User Facility (BFNUF) (Neal Yancey, INL) for the same air classifier. These data were utilized to develop the necessary response surface equations to perform throughput analysis using discrete event simulation. Because the Base Case status quo system utilizes drying prior to grinding, we modeled the Case Study with drying prior to air classification and subsequent grinding of the separated white wood to isolate the individual quality and cost impacts of air classification relative to the Base Case system. The lights fraction from the air classifier was put through proximate and ultimate analyses (Neal Yancey, INL) and were found to have an ash content of 15-18% and 46-47% carbon. Additionally, because the particle size data that we have for the disk screen did not have associated ash contents, we chose to assume that the ash distributed proportionally with total mass into the unders and overs in the disk screen, which is the most conservative assumption for ash in the disk screen.

In the analysis, both systems utilized the same mean times to failure, downtimes and times to repair assumptions as previously described in the High-Temperature Conversion Feedstock 2020 OOE SOT Hartley, Griffel and Thompson 2020). Additionally, the same stochastic composition and moisture generators as used in the High-Temperature Conversion Feedstock 2020 OOE SOT were utilized here; for these analyses we utilized the same feedstock draw order from the compositional and moisture distributions for both cases to allow direct comparison between the cases (eliminates differences due to stochasticity of feedstock properties between the two cases). The reader is referred to the High-Temperature Conversion Feedstock 2020 OOE SOT document Hartley, Griffel and Thompson 2020) for cost details and additional background on the Throughput Factor, Performance Factor and OOE and how they are calculated. Additional details are available in Hartley et al. (2020).

Results and Discussion

Throughput, Mean Production Cost and Downtime

The modeled mean daily production of the Base Case and Case Study preprocessing systems are shown in Figures 3a and 3b. For the Base Case it was approximately 1,219 dry tons of material per day or 55.3% of the daily nameplate capacity (Throughput Factor of 0.5528). The Base Case daily production over the course of the year ranged from 446 dry tons/day (20.2% of the daily nameplate capacity) to 1,251 dry tons (56.7% of the daily nameplate capacity), with an overall standard deviation of 93 dry tons (4.21% of the daily nameplate capacity). For the Case Study,

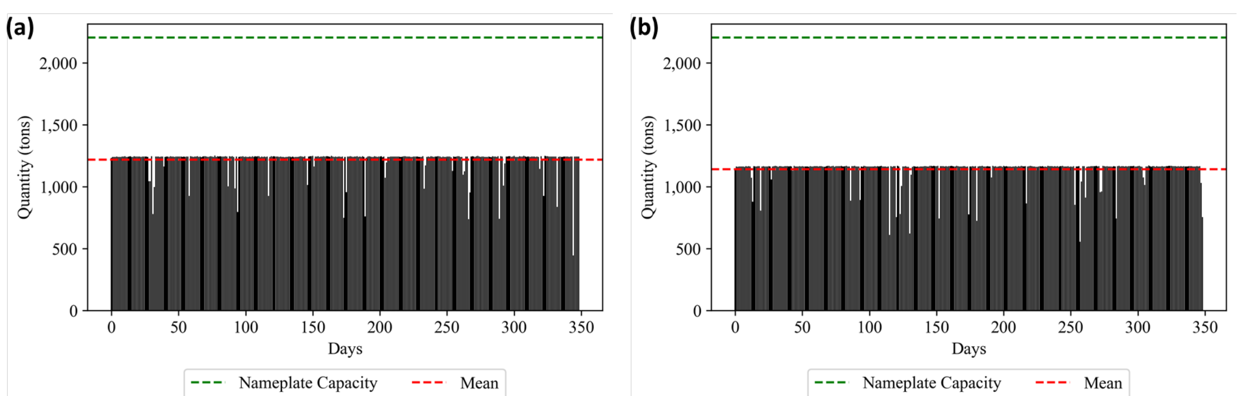

Figure 3. Daily output of the simulated preprocessing systems: (a) Base Case, and (b) Case Study; the green line indicates the daily nameplate capacity while the red line indicates the mean daily production rate for the year

the daily mean production was approximately 1,142 dry tons of material per day or 51.8% of the daily nameplate capacity (Throughput Factor of 0.5177). The Case Study daily production over the course of the year ranged from 556 dry tons/day (25.2% of the daily nameplate capacity) to 1,171 dry tons (53.1% of the daily nameplate capacity), with an overall standard deviation of 90 dry tons (4.06% of the daily nameplate capacity).

The primary reason for the lower throughput achieved in the Case Study is the loss of the lights from the air classification, which amounted to 28,320 dry tons; 429,102 dry tons were processed to the reactor throat in the Base Case (357,935 dry tons of fines discarded) while 399,526 dry tons were processed to the reactor throat in the Case Study (355,701 dry tons of fines discarded).

The modeled energy consumption base production costs (2016$) for the two preprocessing systems are shown in Table 1. The production cost is comprised of grower payment, harvest & collection, storage, transportation & handling and preprocessing, and represents the cost to produce the material at the reactor throat without regard to quality CQAs that define conversion yield. The production cost in the Case Study also includes the cost of the air classifier lights, which is the reason for the slightly increased production cost; the added cost of losing the light material averaged $2.62/dry ton. The reason for the considerably larger added cost due to fines loss in the Case Study is due to fewer tons making it to the reactor throat due to the prior removal of the air classifier lights.

	Base Case	Case Study
Production Cost ($/dry ton)	$74.82	$78.06
Cost with discarded fines ($/dry ton)	$143.31	$159.68
Added cost due to fines ($/dry ton)	$68.49	$81.62

Table 1. Average base production costs and added costs due to discarding fines not meeting the particle size CQA; the added cost does not include disposal costs or tipping fees for landfilling

As the air classifier and added conveyor consume very little energy (0.645 kWh/dry ton and 3.50 kWh/dry ton, respectively) compared to the dryer (2,328 kWh/dry ton), there was little difference in the energy consumption in the two systems. Total modeled energy consumption for preprocessing was 1,966,875 MWh for the Base Case and 1,956,544 MWh for the Case Study, which equate to 2,378 kWh/dry ton and 2,382 kWh/dry ton, respectively. Hence, in the Base Case the rotary dryer accounted for 98.45% of total energy consumption with the remainder of the system accounting for only 1.55% of total energy consumption. For the Case Study, the rotary dryer accounted for 98.32% of total energy consumption while the remainder of the system totaling the hammer mill represented 1.68% of total energy consumption (slightly higher due to the removal of the air classifier lights).

Down events and downtime statistics for the two cases are shown in Table 2. On-stream time results were similar for the two cases, however, the causes of downtime were very different between the two. In the Base Case, two thirds of the failures were due to wear from ash and the remainder were regularly scheduled maintenance (manufacturer-specified mean time to failure). In the Case Study this was reversed, with regularly scheduled maintenance accounting for two-thirds of the failures. While there was 43% more down time in the Case Study, only about 27% of that downtime was due to ash failures whereas about 55% of the downtime was due to ash

	Base Case	Case Study
Total Failures	72	96
Moisture Failures (% of Total)	0.0%	0.0%
Ash (Wear) Failures (% of Total)	66.7%	33.3%
Regular Failures (% of Total)	33.3%	66.7%
Total Operating Time (350 days) (min)	504,000	504,000
Total Downtime (min)	7,056	10,110
Moisture Downtime (% of Total)	0.0%	0.0%
Ash (Wear) Downtime (% of Total)	54.8%	27.3%
Regular Downtime (% of Total)	45.2%	72.7%
Actual time on-stream (350 days) (%)	98.6%	98.0%
Actual time on-stream (365 days) (%)	94.6%	94.0%

Table 2. Modeled failures, downtime and time on-stream for the two cases

failures in the Base Case. The reason for the increase in regular failures for the Case Study is that they occur based on productive time; with more ash failures in the Base Case there was less productive time and thus fewer regular failures.

Quality Assessment and Total Delivered Cost

Beyond throughput impacts on feedstock cost, there are additional CQAs beyond particle size and moisture content that must also be met, including carbon and ash content CQAs (≥ 50.51% and ≤ 1.75%, respectively). Any units processed must also meet those CQAs to be fed to the reactor throat of conversion. Hence, we applied these specifications to the produced units of preprocessed material to determine the actual tons simultaneously meeting all specifications and distributed the cost of the produced tons not meeting all specifications over the tons meeting. Tons of preprocessed residue meeting the carbon specification, the ash specification and both specifications are shown in Figure 4. The percentage meeting both specifications is equivalent to the Quality Performance Factor used to calculate the Overall Operating Effectiveness; for the Base Case it was 0.6818 and it was 0.8078 for the Case Study.

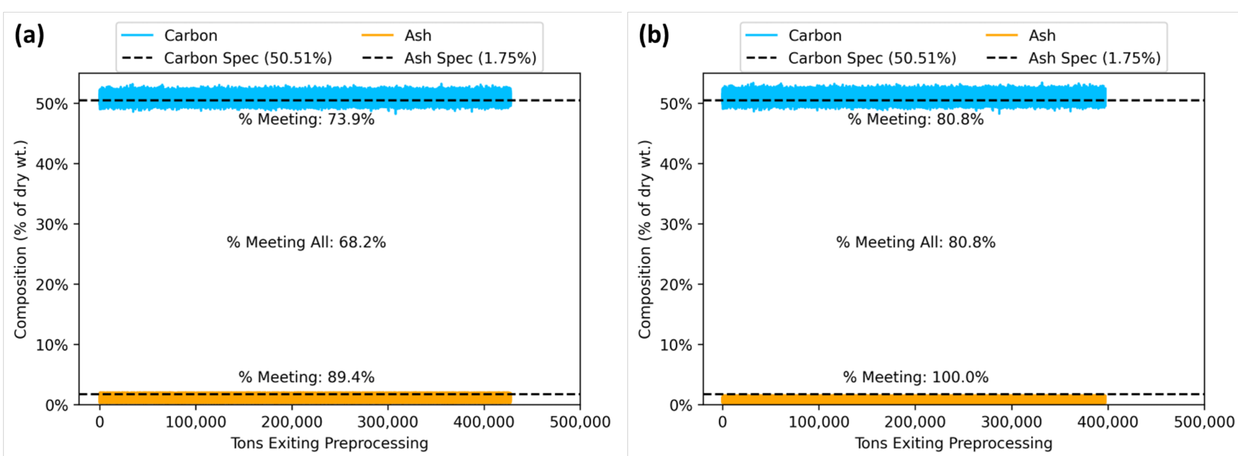

Figure 4. Tons of preprocessed residue meeting the carbon specification, the ash specification and both specifications: (a) Base Case, and (b) Case Study

For the Base Case, 135,302 dry tons of preprocessed material did not meet both specifications and would be discarded or repurposed to another use. For the Case Study, this amounted to 75,616 dry tons of preprocessed material. Hence, for the Base Case there were 293,800 dry tons fed to conversion and for the Case study 323,910 dry tons. The average total carbon delivered for the Base Case was 51.10%, with a standard deviation of 0.39% and a range of 50.51% to 53.24%, while for the Case Study it was 51.18%, with a standard deviation of 0.43% and a range of 50.51% to 53.44%. The average total ash delivered for the Base Case was 1.14%, with a standard deviation of 0.38% and a range of 0.30% to 1.75%, while for the Case Study it was 0.75%, with a standard deviation of 0.35% and a range of 0.30% to 1.60%.

The delivered cost distributions of processed material for the two cases are shown in Figure 5. For the Base Case, the average delivered feedstock cost was \$211.24/dry ton, with a standard deviation of \$11.34/dry ton, a median of \$212.80/dry ton and a range of \$171.11-\$1,094.06/dry ton. This gives a quality cost of discarded units not meeting specifications of \$67.93/dry ton. For the Case Study, the average delivered feedstock cost was \$198.72/dry ton, with a standard deviation of \$13.23/dry ton, a median of \$201.35/dry ton and a range of \$149.93-\$1,199.35/dry ton, giving a quality cost of discarded units not meeting specifications of \$39.04/dry ton.

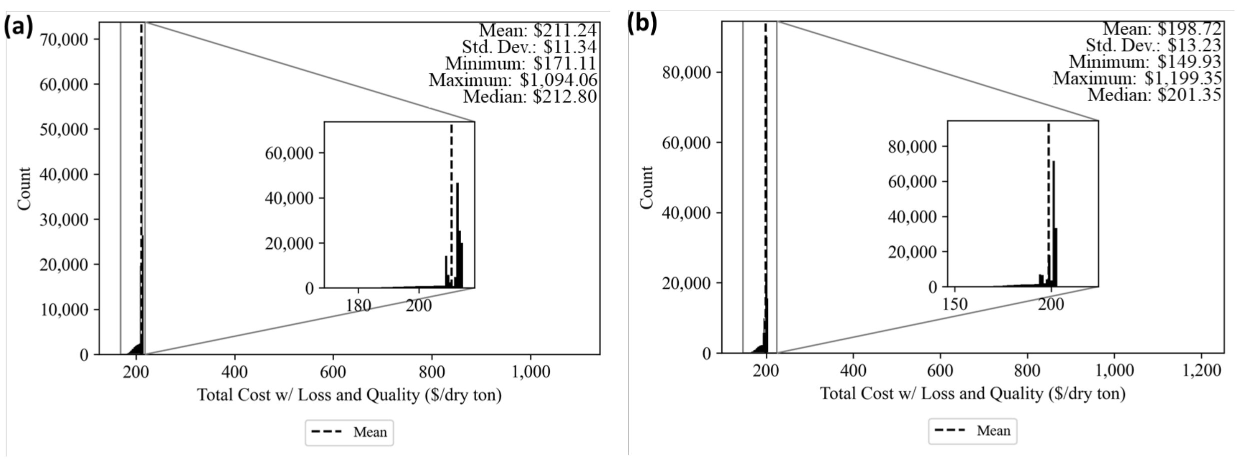

Figure 5. Delivered feedstock cost distributions of processed material for the two cases. (a) Base Case; and (b) Case Study

Overall Operating Effectiveness of the Preprocessing Systems

To maintain comparability of these analyses to the High-Temperature Conversion Feedstock 2020 OOE SOT (Hartley, Griffel and Thompson 2020), we also calculated the Overall Operating Effectiveness for the two systems. *OOE* is defined as the product of the Throughput Factor and the Performance Factor, where the Throughput Factor (*Ff*) is the fraction of nameplate capacity achieved and the Quality Performance Factor (F_B) is the fraction of production delivered meeting all quality specifications (CQAs). For the Base Case this is

$$OOE_{P,Base\ Case} = F_{f,P} \times F_{B,P} \times 100 = 0.5528 \times 0.6818 \times 100 = 37.69\%$$

while for the Case Study it is

$$OOE_{P,Case\ Study} = F_{f,P} \times F_{B,P} \times 100 = 0.5177 \times 0.8078 \times 100 = 41.82\%$$

The primary impacts of the Case Study in comparison to the Base Case are to delivered cost due a significantly increased number of tons meeting both carbon and ash CQAs, with an additional 4.13 percentage point increase in *OOE* (11.0% improvement).

Estimated Impacts to Minimum Fuel Selling Price

Finally, going beyond delivered feedstock cost as a cost metric, it would be instructive to understand how the decrease in feedstock cost and the improved carbon contents fed to conversion (the tons fed to conversion met or exceeded the total carbon CQA of 50.51%) contributed to the Minimum Fuel Selling Price (MFSP). FCIC Subtask 8.3: Crosscutting Analysis, High Temperature Conversion (Matt Wiatrowski, NREL) provided us with a regression model based on the 2019 CFP SOT (Dutta et al. 2020) which estimates MFSP ($/gge) as a function of feedstock cost, assuming that the other CQAs are not impacted (fixed at 50.51% carbon). The equation, shown below, was developed for a feedstock cost range of $50-$200/dry ton

$$MFSP = 0.0169 * (Feedstock\ Cost) + 2.143$$

where the MFSP is in $/gge and the Feedstock Cost is in $/dry ton. For this analysis, we extrapolated the values for MFSP using this equation because the mean, while close to the upper end value was slightly outside the range and we had no reason to expect that the behavior of the data would change beyond the end point of the range. This equation provides a conservative estimate of potential impact to MFSP, however, it is worth noting that carbon contents of the units fed for the Base Case ranged from 50.51% to 53.24% while for the Case Study it was 50.51% to 53.44%, which provides additional potential for lowering the MFSP due to increased bio-oil yields in both cases. The results for the units fed to conversion are shown for the Base Case and Case Study in Figure 6. For the Base Case, the mean MFSP was $5.71/gge, while for the Case Study, the mean MFSP was $5.50/gge. There was thus a $0.21/gge drop in MFSP going from the Base Case to the Case Study, a decrease of 3.6%. This drop in MFSP highlights the trade-off between adding feedstock preprocessing operations and meeting all of the conversion CMAs 100% of the time. If the added yield from the units fed that were higher than the minimum carbon specification was included, the decrease would be larger. We will work with FCIC Subtask 8.3 in the future to also include the higher carbon in the MFSP estimates.

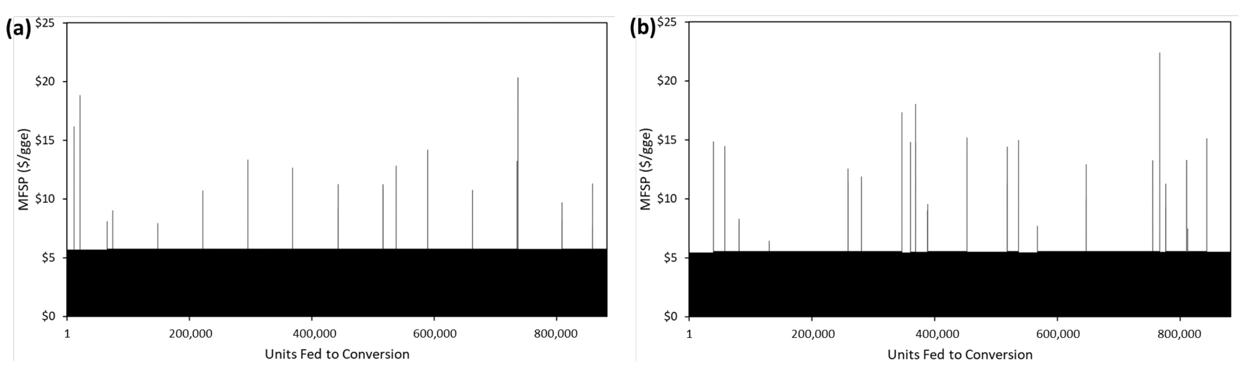

Figure 6. Estimated MFSP for the simulated feedstock units delivered to conversion: (a) Base Case, and (b) Case Study

Conclusion and Next Steps

The goal of this Case Study was to evaluate the performance of air classification of logging residues toward meeting conversion CMAs for carbon and ash contents, as compared to the static status quo Base Case system. Key takeaways from this Case Study are that air classification improves the quality of the final material, but increases the production cost, especially when lights are disposed; this becomes a tradeoff between increased conversion yield and the extra cost. Removing material should be done as early in the process as possible. Each operation that occurs prior to removing the material increases the cost of the disposed material and leads to wasted energy expenditures. As processes are included or modified, the impact on monetary and energy cost should be included in the decision process. Identifying alternative uses and the associated value for material that is separated from the feedstock stream will have a significant impact on the delivered cost of the material. Although there was an increase in production cost by adding air classification, there was a resulting benefit to the MFSP when meeting or exceeding all of the conversion CMAs; this was an important finding that should be explored further with FCIC Subtask 8.3 and potentially FCIC Task 6: High Temperature Conversion.

Next Steps

It is notable that the tons fed to conversion meet or exceed the compositional CQAs, which indicates that with additional infrastructure it would be possible to utilize some of the discarded units through blending. This is a trade-off between adding cost to the feedstock and the value of higher yields to conversion and can be explored in future joint analyses with NREL and PNNL. Other potential next steps may include looking at ash removal in fines, the effect of aspect ratio on drying energy reduction, and benefits that extend beyond the boundaries of preprocessing (i.e., in conversion).

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