U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

# FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

## Particle Scale Impacts on Deconstruction Energy of Pine Residues

DOE/EE-2733 • July 2023

## 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 quantify the impacts of variable moisture and ash on hammer mill throughput and energy consumption and on generation of fines that are not able to be fed to conversion, as compared to a status quo Base Case system. Also considered was convertible carbon content (minimum carbon specification) and maximum ash content and the delivered feedstock cost impacts of not being able to feed residue not meeting both specifications to the conversion reactor. Laboratory data on the impacts of input particle size and moisture content on the exit particle size were received from FCIC Subtask 5.2: Preprocessing, High Temperature Conversion Preprocessing from their single particle impact population balance modeling study (Tiasha Bhattacharjee, INL). Additional throughput and energy consumption data were obtained from FCIC Subtask 5.2 (Jordan Klinger, INL) for the same grinder with a 6 mm screen in place. These data were utilized to develop the necessary response surface equations to perform throughput analysis using discrete event simulation. Because the ash contents in the separated

fines had not been analyzed in the laboratory at the time of the model runs, we chose to assume that the ash distributed proportionally with total mass into the overs and unders in the disk screen following grinding.

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. 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, the rotary drum dryer is moved downstream of the disk screen in order to assess the cost impacts of reducing loss of fines (grinding drier material produces more fines) and more efficient drying (smaller particles dry more efficiently due to improved heat and mass transfer).

The Case Study achieved 27.6% higher throughput capacity than the Base Case due to the generation of fewer fines during wet versus dry grinding; the production cost (includes grower payment, harvest and collection, storage, transportation and preprocessing) adjusted for discarded fines were $137.46 and $72.04/dry ton (all costs are reported in 2016$) preprocessed for the Base Case and Case Study, respectively. Grinder energy consumption more than doubled for wet grinding versus dry grinding (26.2 kWh/dry ton for grinding dry material to 59.9 kWh/dry ton for grinding wet material). However, drying energy savings from the more efficient drying of smaller particles following wet grinding far outstripped that increase (2,328 kWh/dry ton for drying wet chips to 1,238 kWh/dry ton for drying hammer milled residue). When the compositional CQAs were considered (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 $154.56 and $81.13/dry ton, respectively. FCIC Subtask 8.3: Crosscutting Analysis, High Temperature Conversion (Matt Wiatrowski, NREL) provided us with a regression model of MFSP ($/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 content in the units fed for the Base Case ranged from 50.51% to 54.30% while for the Case Study it ranged from 50.51% to 54.42%, which provides additional potential for lowering the MFSP due to increased bio-oil yields in both cases. The Base Case mean MFSP estimate was $4.75/gge, while the estimate for the Case Study was $3.51/gge. This is a significant drop in MFSP and will be larger when the added yield from the units exceeding the minimum carbon specification is included.

Key takeaways from this Case Study are that it is significantly more cost effective to hammer mill the residue prior to drying, even though the grinder throughput is lower and energy consumption is higher versus drying first before grinding. An effect of dry grinding versus high moisture grinding is the production of higher amounts of fines during dry grinding, leading to significantly more of the ground feedstock being rejected by conversion for being below a minimum particle size. With wet grinding the system is still able to produce more preprocessed feedstock meeting the minimum particle size specification even though the instantaneous throughput is lower than for the case of grinding dry feedstock. Additionally, even without the higher fines production from dry grinding, the status quo would still be more costly than wet grinding because the material is rejected after the drying energy has already been input for the dry grinding case. Finally, significant reductions in drying energy are obtained by drying after grinding, and those reductions are of far greater magnitude than the grinding energy increase. 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.

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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 the feedstock preprocessing production cost impacts of variable moisture and ash on hammer mill throughput and energy consumption and on generation of fines that are not able to be fed to conversion because they cause the feeder to fail. Also considered was convertible carbon content (minimum carbon specification) and maximum ash content and the delivered feedstock cost impacts of not being able to feed residue not meeting both specifications to the conversion reactor. In this Case Study Summary Report, we compare this Case Study with a Base Case that represents the status quo.

# 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 $\leq$ 1.75 wt% and a carbon content $\geq$ 50.51 wt%, both on a dry basis. Additional Preprocessing CQAs include a moisture content $\leq$ 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. Flowsheets for the Base Case and Case Study are shown in Figures 1 and 2.

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

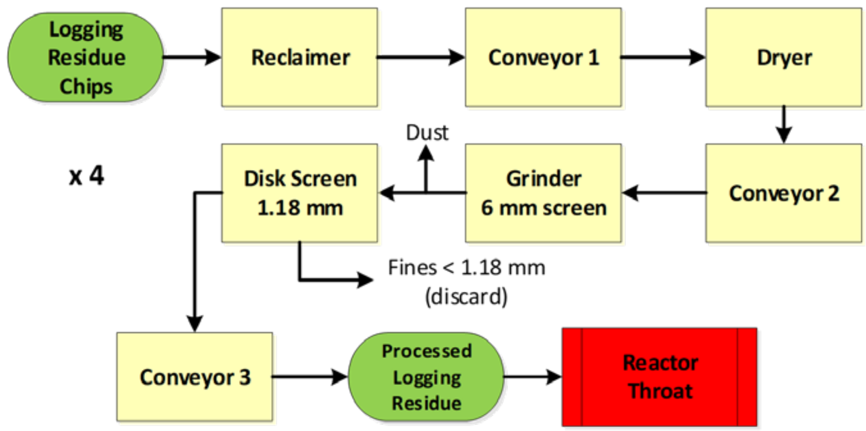


Figure 1. Flowsheet showing preprocessing operations for the Base Case

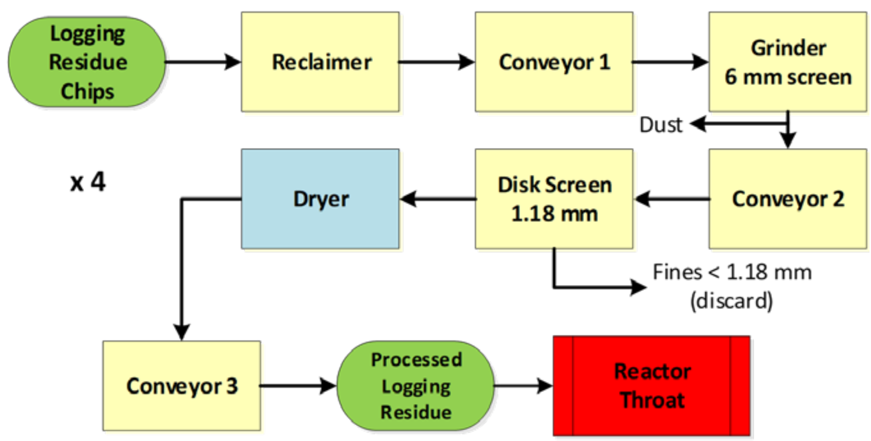


Figure 2. Flowsheet showing preprocessing operations for the Case Study

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, the rotary drum dryer is moved downstream of the disk screen in order to assess the cost impacts of reducing loss of fines (grinding drier material produces more fines) and more efficient drying (smaller particles dry more efficiently due to improved heat and mass transfer).

Laboratory data on the impacts of input particle size and moisture content on the exit particle size were received from FCIC Subtask 5.2: Preprocessing, High Temperature Conversion Preprocessing from their single particle impact population balance modeling study (Tiasha Bhattacharjee, INL). Additional throughput and energy consumption data were obtained from FCIC Subtask 5.2 (Jordan Klinger, INL) for the same grinder with a 6 mm screen in place. These data were utilized to develop the necessary response surface equations to perform throughput analysis using discrete event simulation. Because the particle size data that we received did not have associated ash contents and we did not have ash reduction data for a 1.18 mm disk screen, we chose to assume that the ash distributed proportionally with total mass into the unders and overs in the disk screen. While it is true that much of the soil ash would also leave with the fines resulting in improved quality of the delivered tons of material, to allow the delivered feedstock cost impacts of quality to be effectively assessed between the two cases, we chose the most conservative assumption for ash.

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 of grinder energy consumption between the cases (eliminates differences due to stochasticity of feedstock moisture content 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, Quality Performance Factor and Overall Operating Effectiveness 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 1,270 dry tons of material per day or 57.59% of the daily nameplate capacity (Throughput Factor of 0.5759). The Base Case daily production over the course of the year ranged from 259 dry tons/day (11.76% of the daily nameplate capacity) to 1,301 dry tons (59.01% of the daily nameplate capacity), with an overall standard deviation of 100 dry tons (4.53% of the daily nameplate capacity). For the Case Study, the daily mean production was approximately 1,585 dry tons of material per day or 71.89% of the daily nameplate capacity (Throughput Factor of 0.7189). The Case Study daily production over the course of the year ranged from 781 dry tons/day 35.40% of the daily nameplate capacity) to 1,620 dry tons (73.49% of the daily nameplate capacity), with an overall standard deviation of 115 dry tons (5.22% of the daily nameplate capacity).

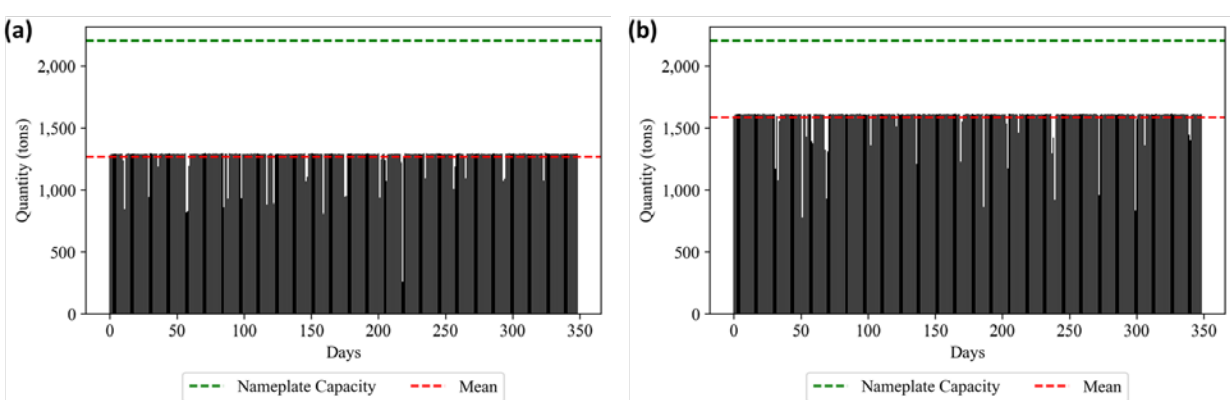


Figure 3. Daily output of the simulated preprocessing systems: (a) Base Case, and (b) Case Study; the green line indicates the daily nameplate capacity while the red line indicates the mean daily production rate for the year

The primary reason for the higher throughput achieved in the Case Study is the reduced loss of fines because grinding wetter material leads to generation of fewer fines (Figure 4); 444,379 dry tons were processed to the reactor throat in the Base Case (337,985 dry tons of fines discarded) while 554,731 dry tons were processed to the reactor throat in the Case Study (120,747 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

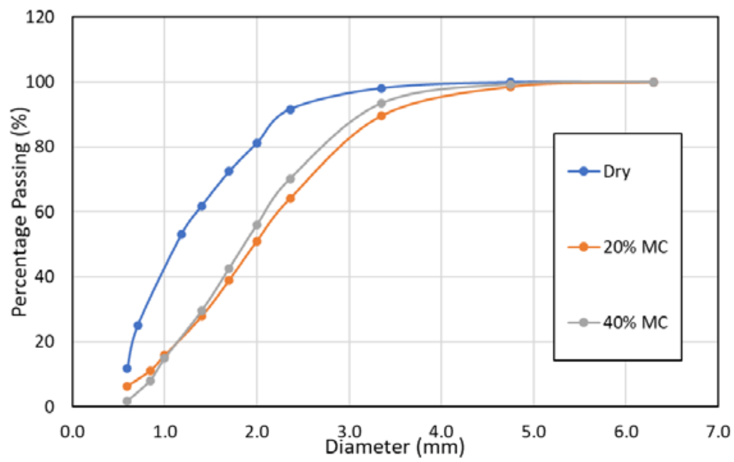


Figure 4. Cumulative %-passing for dry-ground logging residue and for residue ground at 20% and 40% moisture content

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

| | Base Case | Case Study |
|---|---|---|
| Production Cost ($/dry ton) | $78.54 | $61.44 |
| Cost with discarded fines ($/dry ton) | $137.46 | $72.04 |
| Added cost due to fines ($/dry ton) | $58.92 | $10.60 |

represents the cost to produce the material at the reactor throat without regard to compositional quality CQAs that define conversion yield. It is clear from Table 1 that the cost increase of a decrease in throughput from grinding wet material in the grinder is outstripped by the loss of considerably less material as fines, leading to the production of more feedstock meeting the particle size minimum. Even if the losses of material were the same between the two cases, the Base Case production cost would still have been higher than the Case Study production cost because the material is dried in that case prior to the grinder (it already has the cost of drying included). Additionally, there were significant benefits seen for the grinder-dryer pair (Figure 5). While the grinder energy consumption did increase from 26.2 kWh/dry ton for grinding dry material to 59.9 kWh/dry ton for grinding wet material, the drying energy requirement (which is the energy cost driver for the preprocessing system) was substantially reduced from 2,328 kWh/dry ton for drying wet chips to 1,238 kWh/dry ton for drying hammer milled residue, a

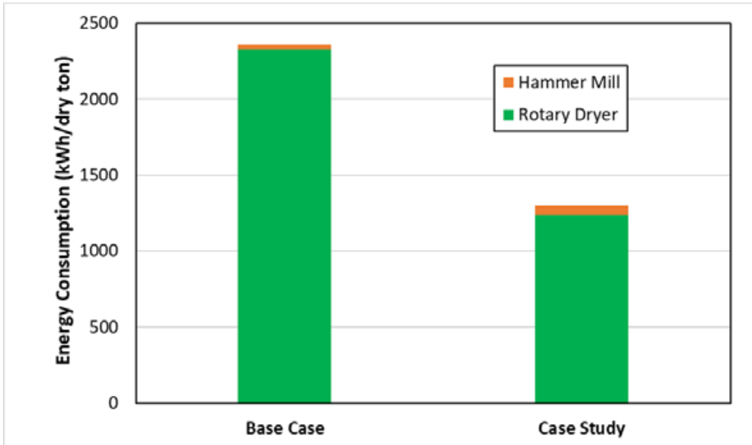


Figure 5. Energy consumption for the grinder-dryer pair in the two cases

nearly 47% reduction. Given that there are losses of moisture during wet milling due to frictional heating, the moisture content is also lower entering the dryer as well, further reducing the energy usage.

Modeled total energy consumption for preprocessing was 1,955,345 MWh for the Base Case and 741,478 MWh for the Case Study, which equate to 2,377 kWh/dry ton and 1,320 kWh/dry ton, respectively. Hence, in the Base Case the hammer mill accounted for 1.05% of total energy consumption while the rotary dryer accounted for 98.06% of total energy consumption. For the Case Study, the hammer mill represented 5.46% of total energy consumption with the rotary dryer amounting to 92.62% of total energy consumption.

Down events and downtime statistics for the two cases are shown in Table 2. Results were similar for the two cases, with ash failures being a larger contributor to downtime for the Case Study because more material went through the system than for the Base Case. Modeled time on-stream for the 350-day operating period was about 98%; taking into account the 15-day planned shutdown for annual maintenance, it decreased to about 94% for the year.

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

| | Base Case | Case Study |
|---|---|---|
| **Total Failures** | 23 | 20 |
| Moisture Failures (% of Total) | 0.0% | 0.0% |
| Ash (Wear) Failures (% of Total) | 47.8% | 50.0% |
| Regular Failures (% of Total) | 52.2% | 50.0% |
| **Total Operating Time (350 days) (min)** | 504,000 | 504,000 |
| **Total Downtime (min)** | 9,445 | 8,713 |
| Moisture Downtime (% of Total) | 0.0% | 0.0% |
| Ash (Wear) Downtime (% of Total) | 43.9% | 43.9% |
| Regular Downtime (% of Total) | 56.4% | 56.1% |
| **Actual time on-stream (350 days) (%)** | 98.1% | 98.3% |
| **Actual time on-stream (365 days) (%)** | 94.1% | 94.2% |

## 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 6. 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 0.8868 and it was 0.8879 for the Case Study.

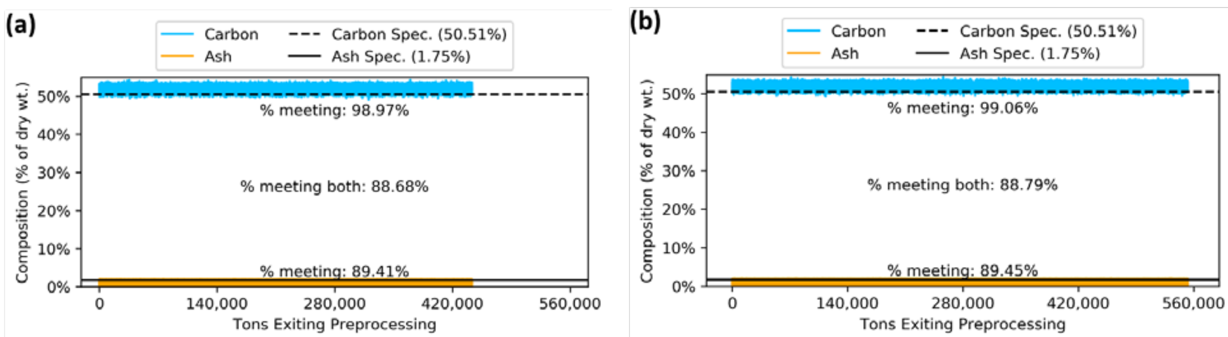


**Figure 6. Tons of preprocessed residue meeting the carbon specification, the ash specification and both specifications: (a) Base Case, and (b) Case Study**

For the Base Case, 50,307 dry tons of preprocessed material did not meet both specifications and would need to be discarded or repurposed to another use. For the Case Study, this amounted to 62,163 dry tons of preprocessed material. Hence, for the Base Case there were 394,071 dry tons fed to conversion and for the Case study 492,567 dry tons. The mean total carbon content delivered for the Base Case was 51.84%, with a standard deviation of 0.54% and a range of 50.51% to 54.30%, while for the Case Study it was 51.84%, with a standard deviation of 0.54% and a range of 50.51% to 54.42%. The mean total ash content delivered for the Base Case was 1.19%, with a standard deviation of 0.37% and a range of 0.30% to 1.75%, while for the Case Study it was 1.19%, with a standard deviation of 0.37% and a range of 0.30% to 1.75%.

The delivered cost distributions of processed material for the two cases are shown in Figure 7. For the Base Case, the mean delivered feedstock cost was $154.56/dry ton, with a standard deviation of $3.20/dry ton, a median of $154.31/dry ton and a range of $152.48-$569.67/dry ton. This gives a quality cost of discarded units not meeting specifications of $17.10/dry ton. For the Case Study, the mean delivered feedstock cost was $81.13/dry ton, with a standard deviation of $5.06/dry ton, a median of $81.12/dry ton and a range of $78.54-$746.65/dry ton, giving a quality cost of discarded units not meeting specifications of $9.09/dry ton.

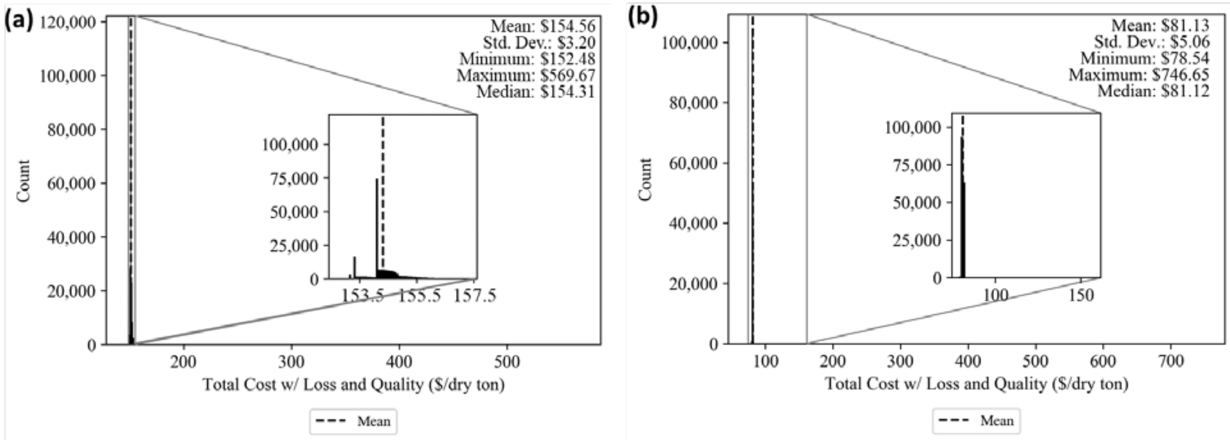


Figure 7. Delivered feedstock cost distributions of processed material for the two cases. (a) Base Case; and (b) Case Study

## 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 preprocessing systems. *OOE* is defined as the product of the Throughput Factor and the Quality Performance Factor, where the Throughput Factor ($F_f$) is the fraction of nameplate capacity achieved and the Quality Performance Factor ($F_B$) is the fraction of production delivered to the reactor throat meeting all quality specifications (CQAs). For the Base Case this is

$$OOE_{P,Base\ Case} = F_{f,P} \times F_{B,P} \times 100 = 0.5759 \times 0.8868 \times 100 = 51.07\%$$

while for the Case Study it is

$$OOE_{P,Case\ Study} = F_{f,P} \times F_{B,P} \times 100 = 0.7189 \times 0.8879 \times 100 = 63.83\%$$

The primary impacts of the Case Study in comparison to the Base Case are to delivered cost due to increased throughput, lower loss of fines and to significantly reduced energy usage for drying, with an additional 12.76 percentage point increase in *OOE* (25.0% improvement of *OOE*).

## 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 content of the units fed for the Base Case ranged from 50.51% to 54.30% while for the Case Study it ranged from 50.51% to 54.42%, which provides additional potential for lowering the MFSP due to increased bio-oil yields in both cases. The results for the units of feedstock fed to conversion are shown for the Base Case and Case Study in Figure 8. For the Base Case, the mean MFSP was \$4.75/gge, while for the Case Study, the mean MFSP was \$3.51/gge. There was thus a \$1.24/gge drop in the mean MFSP going from the Base Case to the Case Study, a decrease of 26%. This is a significant drop in MFSP, and if the added yield from the units fed that were higher than the minimum carbon specification was included, the decrease would be even larger.

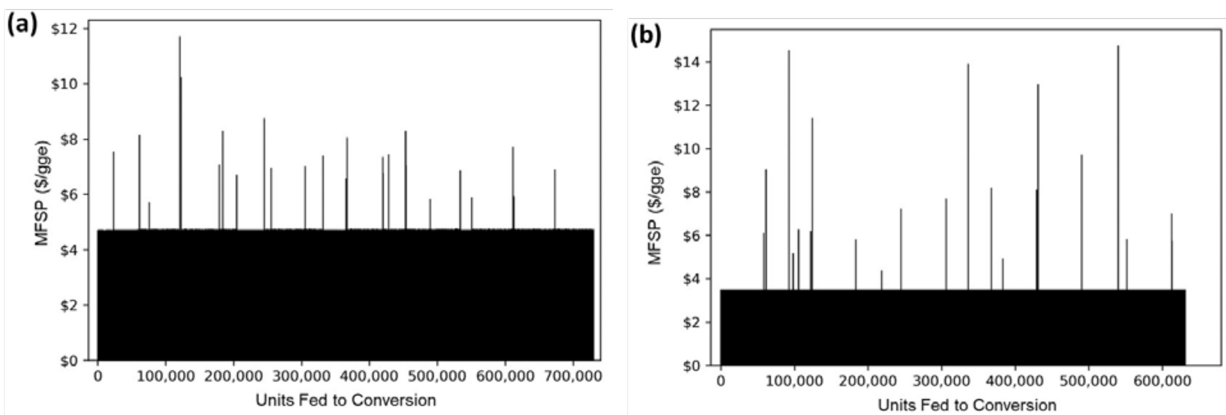


Figure 8. Estimated MFSP for the simulated feedstock units delivered to conversion: (a) Base Case, and (b) Case Study

## Conclusion and Next Steps

The goal of this Case Study was to quantify the impacts of variable moisture and ash on hammer mill throughput and energy consumption and on generation of fines that are not able to be fed to conversion, as compared to a status quo Base Case system. Key takeaways from this Case Study are that it is significantly more cost effective to hammer mill the residue prior to drying, even though the grinder throughput is lower and energy consumption is higher versus drying first before grinding. An effect of dry grinding versus high moisture grinding is the production of higher amounts of fines during dry grinding, leading to significantly more of the ground feedstock being rejected by conversion for being below a minimum particle size. With wet grinding the system is still able to produce more preprocessed feedstock meeting the minimum particle size specification even though the instantaneous throughput is lower than for the case of grinding dry feedstock. Additionally, even without the higher fines production from dry grinding, the status quo would still be more costly than wet grinding because the material is rejected after the drying energy has already been input for the dry grinding case. Finally, significant reductions in drying energy are obtained by drying after grinding, and those reductions are of far greater magnitude than the grinding energy increase.

### 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. 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.

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