U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

# FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

## Impact of Anatomical Fractionation of Corn Stover on Hammer Mill Throughput and Energy Consumption

DOE/EE-2736 • July 2023

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# 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 |
| 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 loss of very wet stover that causes failures in the first stage grinder and that are not able to be fed to conversion, as compared to a status quo Base Case system. Also considered was convertible carbohydrate content (minimum total carbohydrate specification), maximum ash content and the delivered feedstock cost impacts of not being able to feed stover that did not meet the total carbohydrate specification to the conversion reactor. Laboratory data on the impacts of moisture content and tissue fraction on throughput and energy consumption in a stage 2 hammer mill were received from FCIC Subtask 5.1: Preprocessing, Corn Stover Preprocessing (Neal Yancey and Sergio Hernandez, INL). Additional air classifier throughput, energy consumption and separation efficiency data were obtained from FCIC Subtask 5.1 (Neal Yancey, INL) for the new air classifier, which has three exit streams (lights, middle and heavies). These data were utilized to develop the necessary

response surface equations to perform throughput analysis using discrete event simulation. Because the ash contents and particle sizes had not been analyzed in the laboratory at the time of the model runs, we assumed that the ash distributed proportionally with total mass into the lights and heavies in an air classifier having two exit streams (lights and heavies) and that the lights fraction from the air classifier was not removed.

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 Low-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 a total carbohydrate content ≥ 59 wt% and an ash content ≤ 4.93 wt%, both on a dry basis. Additional Preprocessing CQAs include a moisture specification of 20 wt% on a wet basis and particle size of ¼-in. minus. In both cases, only the carbohydrate content was tracked as a CQA for the quality cost analysis because of the missing ash and particle size data at the time of modeling. Supply Logistics were assumed to be identical to the three-pass corn stover supply system design presented in the Low-Temperature Conversion Feedstock 2020 OOE SOT. In the Case Study presented here, an air classifier is inserted following the first stage hammer mill to produce two streams having significantly different physical and structural characteristics. The two streams are milled separately in parallel second stage hammer mills and then recombined in order to assess the cost impacts of potential improvements in grinding energy and throughput in the parallel second stage grinders versus the single second stage grinder Base Case.

The two cases achieved similar throughput capacities primarily because moisture failures in the first stage grinder dominated the downtime. The production costs (includes grower payment, harvest and collection, storage, transportation and preprocessing) adjusted for discarded wet material that clogged the first stage grinder were $98.19 and $98.35/dry ton preprocessed for the Base Case and Case Study, respectively (all costs are reported in 2016$). For the Base Case the second stage grinder consumed 26.31 kWh/dry ton as compared to the weighted combined energy consumption of 12.86 kWh/dry ton for the two parallel second stage grinders in the Case Study, a more than 51% reduction. While the reason for the lowered grinding energy of the separated fractions is not completely clear at this point, it is possible that particle-particle interactions among the different tissues of whole corn stover may impact the ability to pass material quickly through the screen following comminution. This may help to explain the preponderance of fines due to longer than necessary residence time in the grinder. When the carbohydrate CQA was considered (feeding to the reactor throat only preprocessed tons meeting the compositional CQA), the final delivered feedstock costs for the Base Case and Case Study rose to $178.28 and $178.60/dry ton, respectively. FCIC Subtask 8.4: Crosscutting Analysis, Low Temperature Conversion TEA (Ryan Davis, NREL) provided us a multiple regression model of MFSP ($/gge) as a function of feedstock cost and carbohydrate content assuming constant conversion yields, which was based on the 2019 SOT for the acids pathway reflective of burning the lignin. The Base Case mean MFSP estimate was $10.48/gge, while the estimate for the Case Study was $10.49/gge. While this is a small decrease, it is worth noting that it does not include the impact of ash removal during air classification in the quality cost.

Key takeaways from this Case Study are that due to lower energy consumption, it is more cost effective to hammer mill fractionated corn stover tissues than whole stover. Reduction of grinding energy was significant and may possibly be connected to particle-particle interactions in the grinder that lead to increased residence time of leaves and husks, resulting in decreased throughput and higher generation of fines when milling whole stover. While we did not see significant impacts to throughput, this was due to moisture failures of the first stage grinder in each system dominating failures and downtime. The operating cost savings of reduced grinding energy in the second stage hammer mills alone was high enough to offset the added capital cost of the air classifier and an extra grinding line. It is notable that the tons fed to conversion met or exceeded the total carbohydrate CQA, which indicated 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 energy and production cost impacts of variable moisture and ash of physically and structurally different corn stover tissue fractions on hammer mill throughput and energy consumption and on the need to dispose of very wet stover causing stage one hammer mill failures. Also considered was convertible carbohydrate content (minimum total carbohydrate specification) and maximum ash content and the delivered feedstock cost impacts of not being able to feed stover that does not meet the total carbohydrate specification to the conversion reactor. In this Case Study Brief, 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 Low-Temperature Conversion Feedstock 2020 Overall Operating Effectiveness (OOE) State of Technology (SOT) report (Hartley, Thompson and Griffel 2020). Preprocessing Critical Quality Attributes (CQAs), which are equivalent to the Conversion CMAs set by the biorefinery, include a total carbohydrate content ≥ 59 wt% and an ash content ≤ 4.93 wt%, both on a dry basis. Additional Preprocessing CQAs include a moisture specification of 20 wt% on a wet basis and particle size of ¼-in. minus. In both cases, only the carbohydrate content was tracked as a CQA for the quality cost analysis because of the missing ash and particle size data at the time of modeling. Flowsheets for the Base Case and Case Study are shown in Figures 1 and 2.

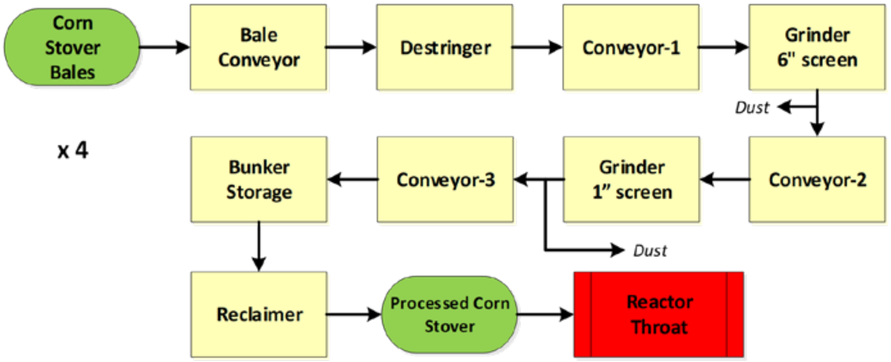

Figure 1. Flowsheet showing preprocessing operations for the Base Case

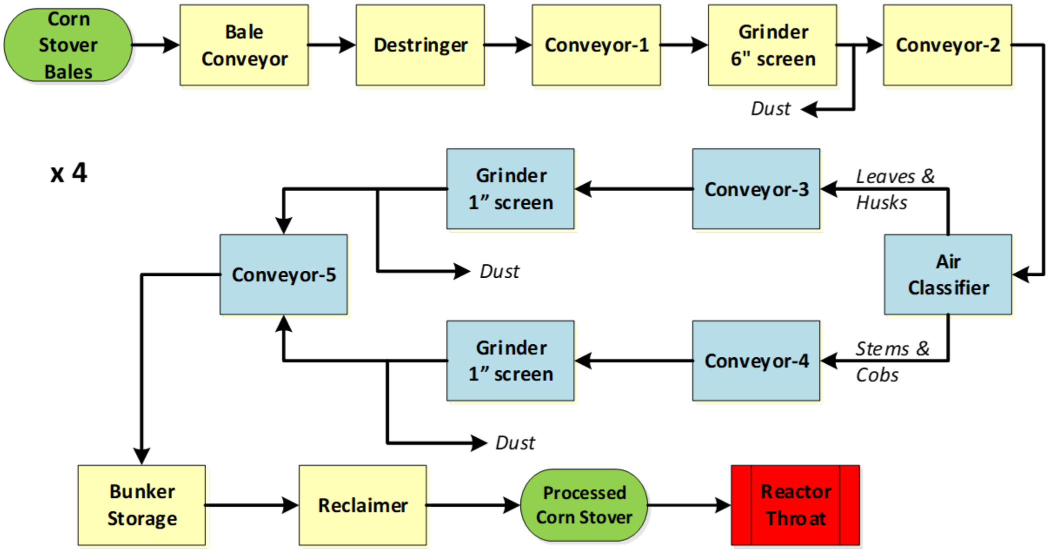

Figure 2. Flowsheet showing preprocessing operations for the Case Study

Supply Logistics were assumed to be identical to the three-pass corn stover supply system design presented in the Low-Temperature Conversion Feedstock 2020 OOE SOT (Hartley, Thompson and Griffel 2020). In the Case Study, an air classifier is inserted following the first stage hammer mill to produce two streams having significantly different physical and structural characteristics. The two streams are milled separately in parallel second stage hammer mills that are sized to the expected mass fractions of the two streams relative to the whole material, and operated at conditions determined experimentally to be more suitable for the different materials. After grinding, the two streams are recombined to assess the cost impacts of potential improvements in grinding energy and throughput in the parallel second stage grinders versus the single second stage grinder Base Case.

Laboratory data on the impacts of moisture content and tissue fraction on throughput and energy consumption in a stage 2 hammer mill were received from FCIC Subtask 5.1: Preprocessing, Corn Stover Preprocessing (Neal Yancey and Sergio Hernandez, INL). Additional air classifier throughput, energy consumption and separation efficiency data were obtained from FCIC

Subtask 5.1 (Neal Yancey, INL) for the new air classifier, which has three exit streams (lights, middle and heavies). These data were utilized to develop the necessary response surface equations to perform throughput analysis using discrete event simulation. Because the ash contents and particle sizes had not been analyzed in the laboratory at the time of the model runs, we assumed that the ash distributed proportionally with total mass into the lights and heavies in an air classifier having two exit streams (lights and heavies) and that the lights fraction from the air classifier was not removed. While it is true that removal of the soil ash would result 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 Low-Temperature Conversion Feedstock 2020 OOE SOT (Hartley et al. 2020a). Additionally, the same stochastic composition and moisture generators as used in the Low-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 Low-Temperature Conversion Feedstock 2020 OOE SOT document (Hartley, Thompson and Griffel 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 756 dry tons of material per day or 34.3% of the daily nameplate capacity (Throughput Factor of 0.3430). The Base Case daily production over the course of the year ranged from 360 dry tons/day (16.3% of the daily nameplate capacity) to 1,041 dry tons (47.2% of the daily nameplate capacity), with an overall standard deviation of 116 dry tons (5.27% of the daily nameplate capacity). For the Case Study, the daily mean production was approximately 747 dry tons of material per day or 33.9% of the daily nameplate capacity (Throughput Factor of 0.3386). The Case Study daily production over the course of the year ranged from 363 dry tons/day (16.5% of the daily nameplate capacity) to 1,006 dry tons (45.6% of the daily nameplate capacity), with an overall standard deviation of 113 dry tons (5.12% of the daily nameplate capacity).

While fractionating the stover prior to grinding allowed higher throughputs through the two second stage grinders as borne out in the data from FCIC Subtask 5.1, it can be seen that this had little effect on the overall system throughput. The similar results between the two cases are a result of moisture failures in the first stage grinder being the dominant impact on downtime for the system. Additionally, fixing the stochastic unit moisture draw order between the two cases contributed. A total of 264,619 dry tons were processed to the reactor throat in the Base Case (34,384 dry tons of very wet stover discarded) while 261,320 dry tons were processed to the reactor throat in the Case Study (33,923 dry tons of very wet stover discarded).

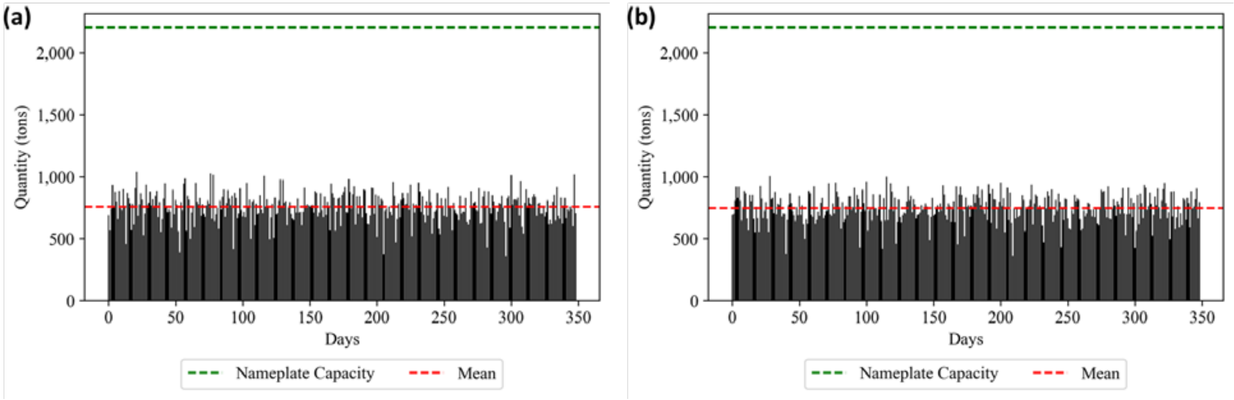

Figure 3. Daily output of the simulated preprocessing systems: (a) Base Case, and (b) Case Study; the green line indicates the daily nameplate capacity while the red line indicates the mean daily production rate for the year

The base production costs (2016$) for the preprocessed tons 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.

Table 1. Average base production costs and added costs due to discarding the wet stover that caused the first stage hammer mill to fail; the added cost does not include disposal costs or tipping fees for landfilling

| | Base Case | Case Study |
|---|---|---|
| Production Cost ($/dry ton) | $88.82 | $88.98 |
| Cost with discarded wet stover ($/dry ton) | $98.19 | $98.35 |
| Added cost due to discarded wet stover ($/dry ton) | $9.37 | $9.37 |

The production cost in the Case Study did not change significantly from the Base Case because the reduced grinding energy in the parallel second stage grinders (Figure 4) seen in the fraction grinding data from FCIC Subtask 5.1, was effectively offset by the added capital expenditures for the air classifier and additional grinder. For the Base Case the second stage grinder consumed 26.31 kWh/dry ton as compared to the weighted energy consumption of 12.86 kWh/dry ton for the two second stage grinders in the Case Study, a more than 51% reduction. While the reason for the lowered grinding energy of the separated fractions is not completely clear at this point, it is possible that particle-particle interactions among the different tissues of whole corn stover may impact the ability to pass material quickly through the screen following comminution. This may help to explain the preponderance of fines arising from leaves due to longer than necessary residence time in the grinder. Total modeled energy consumption for preprocessing was 29,366 MWh for the Base Case and 22,881 MWh for the Case Study, which equate to 91.088 kWh/dry ton and 85.620 kWh/dry ton, respectively. Hence, in the Base Case the second stage hammer mill accounted for 28.8% of specific energy consumption while for the Case Study the second stage

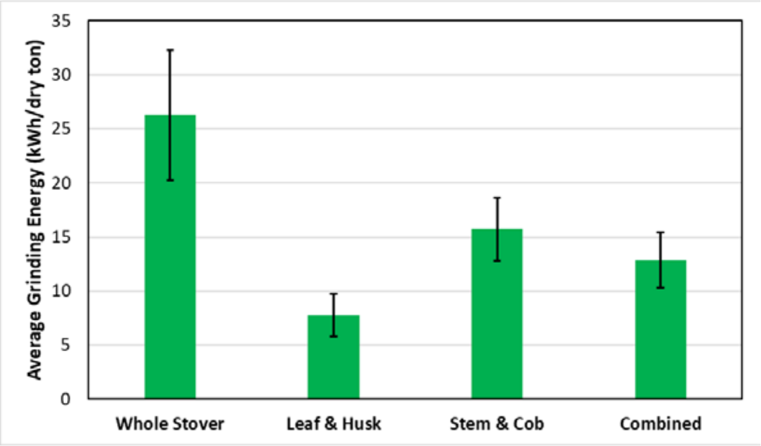

Figure 4. Specific energy consumption the second stage grinders for the Base Case (Whole Stover) and Case Study (Leaf & Husk and Stem & Cob; the "Combined" bar is the specific energy consumption for the parallel second stage grinders in the Case Study, weighted for the relative proportions of material passing through each grinder

Leaf & Husk and Stem & Cob hammer mills together accounted for 15.1% of specific energy consumption, a decrease of nearly 46% versus the Base Case. The air classifier accounted for only 0.74% of the specific energy consumption.

Down events and downtime statistics for the two cases are shown in Table 2. Results were very similar for the two cases because all moisture failures occur in the first stage grinder, while ash (wear) failures occur in both the first and second stage grinders. The relative impact of ash (wear) failures increased in the Case Study as compared to the Base Case because the ash was assumed to remain in the air classified fractions. For the Base Case the modeled time on-stream for the 350-day operating period was about 40%; taking into account the 15-day planned shutdown for maintenance, it decreased to about 38% for the year. For the Case Study the modeled times on-stream were about 38% and 36%, respectively.

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

| | Base Case | Case Study |
|---|---|---|
| Total Failures | 11,007 | 10,856 |
| Moisture Failures (% of Total) | 86.8% | 86.8% |
| Ash (Wear) Failures (% of Total) | 0.38% | 0.61% |
| Regular Failures (% of Total) | 12.9% | 12.6% |
| Total Operating Time (350 days) (min) | 504,000 | 504,000 |
| Total Downtime (min) | 304,077 | 314,320 |
| Moisture Downtime (% of Total) | 94.4% | 91.1% |
| Ash (Wear) Downtime (% of Total) | 4.82% | 7.66% |
| Regular Downtime (% of Total) | 0.76% | 1.22% |
| Actual time on-stream (350 days) (%) | 39.7% | 37.6% |
| Actual time on-stream (365 days) (%) | 38.0% | 36.1% |

## 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 total carbohydrate and ash content CQAs

(≥ 59% and ≤ 4.93%, respectively). Any units processed must also meet those CQAs to be fed to the reactor throat of conversion; because this case study was focused toward energy savings and throughput improvements and because the ash content data were not available for the air classified streams, we considered only the total carbohydrate CQA for this analysis. Hence, we applied this specification to the produced units of preprocessed material to determine the actual tons meeting all specifications and distributed the cost of the produced tons not meeting the specifications over the tons that did meet or exceed the specification. Tons of preprocessed stover meeting the total carbohydrate specification are shown in Figure 5. The percentage meeting the total carbohydrate specification is equivalent to the Quality Performance Factor used to calculate the Overall Operating Effectiveness; for the Base Case it was 0.5508 and it was 0.5507 for the Case Study.

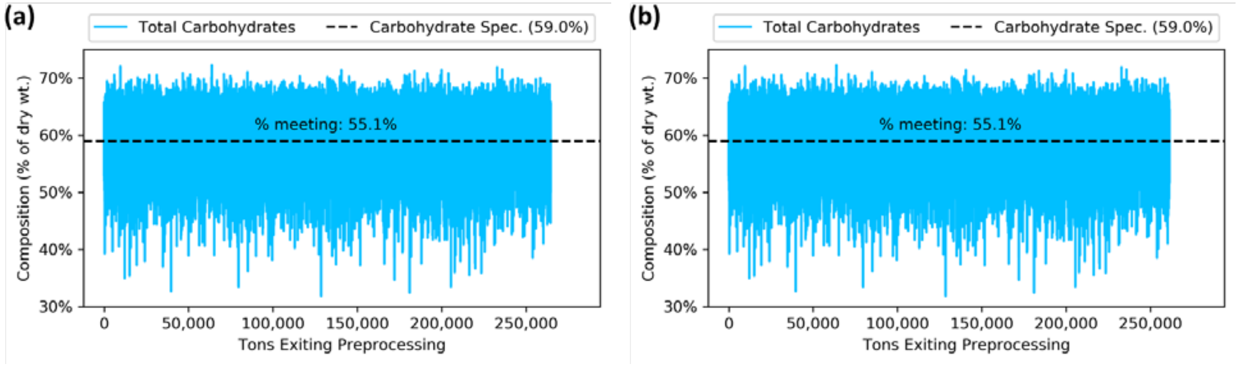

Figure 5. Tons of preprocessed stover meeting the total carbohydrate specification: (a) Base Case, and (b) Case Study

For the Base Case, 118,870 dry tons of preprocessed material did not meet the total carbohydrate specification and would need to be discarded or repurposed to another use. For the Case Study, this amounted to 117,418 dry tons of preprocessed material. Hence, for the Base Case there were 145,748 dry tons fed to conversion and for the Case study 143,902 dry tons. The mean total carbohydrates delivered for the Base Case was 61.9%, with a standard deviation of 2.04%, a median of 61.5% and a range of 59.0% to 72.3%, while for the Case Study it was 61.9%, with a standard deviation of 2.04%, a median of 61.9% and a range of 59.0% to 72.3%. While not utilized as a CQA in this analysis due to lack of data availability at the time of the analysis, the average total ash delivered for the Base Case was 5.56%, with a standard deviation of 1.82%, a median of 4.64% and a range of 4.30% to 19.3%, while for the Case Study it was 5.56%, with a standard deviation of 1.82%, a median of 4.64% and a range of 4.30% to 19.3%.

The delivered cost distributions of processed material for the two cases are shown in Figure 6. For the Base Case, the mean delivered feedstock cost was $178.28/dry ton, with a standard deviation of $17.17/dry ton, a median of $172.82/dry ton and a range of $167.98-$759.30/dry ton. This gives a quality cost of discarded units not meeting specifications of $80.09/dry ton. For the Case Study, the mean delivered feedstock cost was $178.60/dry ton, with a standard deviation of $14.51/dry ton, a median of $174.81/dry ton and a range of $171.79-$874.59/dry ton, giving a quality cost of discarded units not meeting specifications of $80.25/dry ton.

## Overall Operating Effectiveness of the Preprocessing Systems

To maintain comparability of these analyses to the Low-Temperature Conversion Feedstock 2020 OOE SOT, we also calculated the Overall Operating Effectiveness for the two 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 Performance Factor ($F_B$) is the fraction of production delivered meeting all quality specifications (CQAs). For the Base Case this is

$$OOE_{P,Base\ Case} = F_{f,P} \times F_{B,P} \times 100 = 0.3430 \ \times 0.5508 \times 100 = 18.89\%$$

while for the Case Study it is

$$OOE_{P,Case\ Study} = F_{f,P} \times F_{B,P} \times 100 = 0.3386 \ \times 0.5507 \times 100 = 18.65\%$$

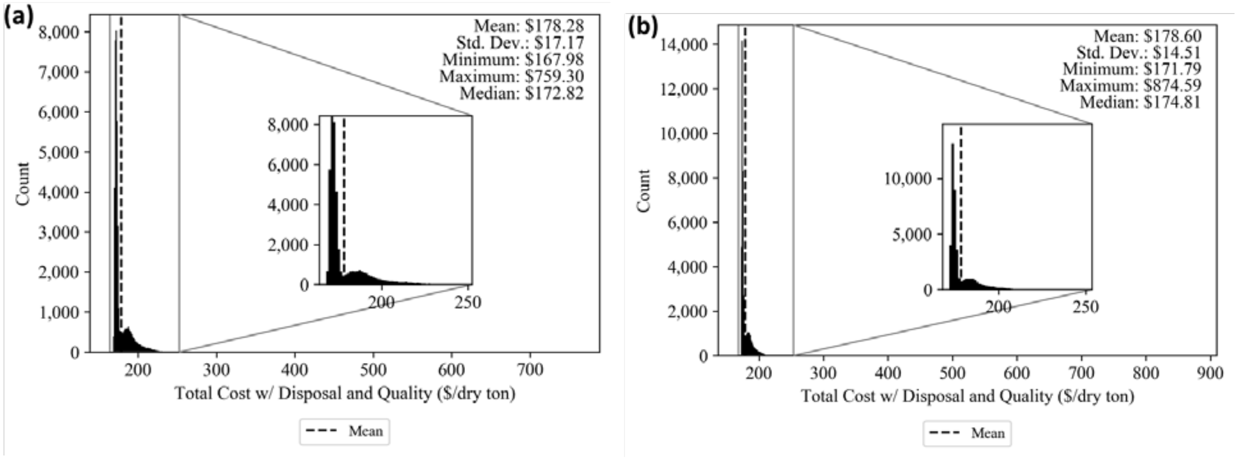

Figure 6. Delivered feedstock cost distributions of processed material for the two cases: (a) Base Case, and (b) Case Study

The primary impacts of the Case Study in comparison to the Base Case are to significantly reduced energy usage for the second stage grinding which offsets the cost of the added equipment, with little differences seen among either throughput, production cost or compositional quality.

## 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 carbohydrate contents fed to conversion (the tons fed to conversion met or exceeded the total carbohydrate CQA of 59%) contributed to the Minimum Fuel Selling Price (MFSP). FCIC Subtask 8.4: Crosscutting Analysis, Low Temperature Conversion TEA (Ryan Davis, NREL) provided us with a multiple regression spreadsheet model based on the 2019 SOT for the acids pathway, reflective of burning the lignin (Davis, Bartling and Tao 2020). The spreadsheet model estimates MFSP ($/gge) from feedstock cost and carbohydrate content assuming constant conversion yields. It was developed such that the feedstock cost and carbohydrate content ranges could be varied to cover different ranges. The equation developed for our carbohydrate content range of 59.0-72.3% and a feedstock cost range of \$150-\$200/dry ton was

$$MFSP = -15.0 * (Carbohydrates) + 0.0263 * (Feedstock\ Cost) + 15.1$$

where Carbohydrates are expressed in % of dry weight and Feedstock Cost is in \$/dry ton. The results for the units fed to conversion are shown for the Base Case and Case Study in Figure 7. For the Base Case, the mean MFSP was \$10.48/gge, with a standard deviation of \$0.54/gge, a median of \$10.46/gge and a range of \$8.81-\$25.94/gge. For the Case Study, the mean MFSP was \$10.49/gge, with a standard deviation of \$0.48/gge, a median of \$10.50/gge and a range of \$8.86-\$28.77/gge. There was an insignificant \$0.01/gge increase in MFSP going from the Base Case to the Case Study, an increase of only 0.095%.

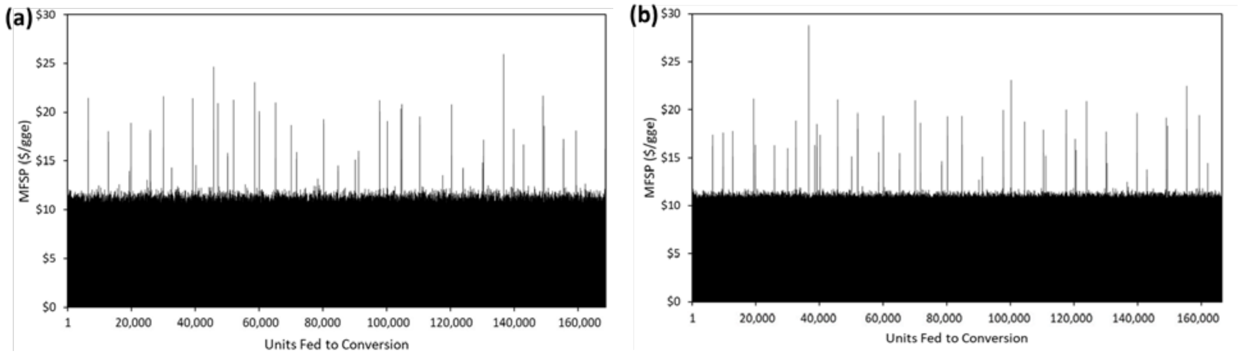

Figure 7. Estimated MFSP for the simulated feedstock units delivered to conversion: (a) Base Case, and (b) Case Study

## 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 loss of very wet stover that causes failures in the first stage grinder and 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 from an energy consumption perspective, it is more cost effective to hammer mill fractionated corn stover tissues than whole stover. Reduction of grinding energy was significant and may possibly be connected to particle-particle interactions in the grinder that lead to increased residence time of leaves and husks, resulting in decreased throughput and higher generation of fines when milling whole stover. While we did not see significant impacts to throughput, this was due to moisture failures of the first stage grinder in each system dominating failures and downtime. The operating cost savings of reduced grinding energy savings in the second stage hammer mills alone was high enough to offset the added capital cost of the air classifier and extra grinding line.

### Next Steps

It is notable that the tons fed to conversion met or exceeded the total carbohydrate CQA, 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. Next steps include repeating this analysis for a second stage knife mill or rotary shear for comparison to the hammer mill results. Other potential next steps may include looking at a more moisture-tolerant stage one size reduction such as a knife mill or bale processor, the effect of aspect ratio on the efficiency of air classification, and benefits that extend beyond the boundaries of preprocessing, for example, tying this with the conversion study done under FCIC Subtask 8.4 to look at the overall value proposition across the supply chain for anatomical fractionation.

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## Acknowledgements

This work was performed as part of the Feedstock Conversion Interface Consortium (FCIC) with funding graciously provided by the U.S. Department of Energy Bioenergy Technologies Office. This article was authored by Idaho National Laboratory, operated by Battelle Energy Alliance, LLC, under U.S. Department of Energy Idaho Operations Office Contract No. DE-AC07-05ID14517. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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