

Task:	Subtask 8.2 – Preprocessing and Subtask 8.3 – High-Temperature Conversion
Title	Sensitivity analysis of air classification of forest residue for tissue and ash separation efficiency with regard to the air speed CPP, the particle size CQA floor and a fixed carbon CQA ceiling
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**Executive Summary:**

The goal of this cross-boundary Case Study was to expand the FY21 Q2 Preprocessing Case Study “Air classification of forest residue for tissue and ash separation efficiency (HT-P-11)” to evaluate the sensitivity of preprocessing and high-temperature conversion with regard to the air speed preprocessing CPP, the particle size conversion CMA floor and a fixed carbon conversion CMA ceiling, as compared to the 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 which would cause feeder failures are removed. Also considered were moisture and ash impacts on throughput and overall operating effectiveness (OOE), total feedstock production cost and delivered feedstock cost, and the estimated minimum fuel selling price (MFSP).

For the preprocessing portion of this cross-boundary Case Study, laboratory data on the impacts of fan speed and moisture content on the separation efficiency of soil ash, needles and bark from white wood received from Subtask 5.2 (Jordan Klinger and Tiasha Bhattacharjee) for the previous Case Study HT-P-11 were reused for this analysis. Average throughput and energy consumption data obtained from the Bioenergy Feedstock National User Facility (BFNUF) (Neal Yancey) for the same air classifier were also reused for this analysis. Additionally, information from the 13/23 Year-Old Tree high-temperature conversion Case Study were used together with literature to develop a distribution of fixed carbon for Loblolly pine logging residues to allow its used as a more predictive conversion CMA for bio-oil yield. The discrete event simulation model developed previously for HT-P-11 was utilized to generate results for three classifier air speed CPPs (0 Hz which was the no air classifier Base Case), 10 Hz and 28 Hz), three particle size CQAs ( $\geq 0.6\text{mm}$ ,  $\geq 0.7\text{ mm}$  and  $\geq 1.18\text{ mm}$ ) and two fixed carbon CQAs ( $\leq 18\%$  and  $\leq 21\%$ ). In addition to air speed, particle size floor and fixed carbon ceiling, feedstock CQAs for ash content ( $\leq 1.75\text{ wt\%, dry basis}$ ) and moisture content ( $\leq 10\text{ wt\%, wet basis}$ ) were used. Because the status quo Base Case 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.

For the high-temperature conversion portion of this cross-boundary Case Study, experimental fast pyrolysis conversion data from Task 6 were used together with the NREL Catalytic Fast Pyrolysis TEA model to develop a series of correlations for predicting MFSP as a function of ash content, fixed carbon content, feedstock cost, and feed scale. These correlations were integrated with the stochastic preprocessing model to enable the generation of an MFSP distribution for each case.

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 (725,000 dry tons/year). 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 the Base Case and Case Study runs, a



disk screen is inserted after the hammer mill to separate out fines. In the Case Study, an air classifier is inserted after the dryer to assess the quality and cost impacts of removing soil, needles and bark from the system.

Key takeaways from this Case Study are that in an operating biorefinery it will not be economic to dispose of large quantities of material once it has been preprocessed given the large range of delivered feedstock costs; either the material not meeting the ash and fixed carbon specifications must be converted to biofuel or it must be valorized in some other way (such as a value-added co-product or sold into another market). Recognizing this, we considered whether the tons not meeting all of the conversion quality specification would lead to acceptable Minimum Fuel Selling Price (MFSP) if the conversion process were robust enough to accept the ash and fixed carbon ranges exiting preprocessing without causing conversion process upsets.

Integrating the MFSP correlation into the preprocessing model provided valuable insight into the ultimate field-to-fuel economic of each scenario considered. Overall, it was demonstrated that inclusion of an air classifying step in the preprocessing of forestry residues could counteract the additional costs, matching economics compared to using unclassified residues. The higher quality air classified feedstocks demonstrated increased fuel yields, associated with an economic benefit approximately equal to the additional costs associated with air classification at lower fan speeds. Higher fan speeds were shown lead to even higher CFP yields, but also resulted in significant material loss during preprocessing, resulting in a net economic penalty. However, it is possible that an intermediate fan speed could demonstrate a more significant net benefit vs. unclassified residues if the tradeoff between higher CFP yields and material losses was optimized.

The importance of optimizing the minimum particle size fed to conversion was also demonstrated. It is understood that feeding particles on the order of 1 mm or less to conversion has the potential to create operability issues for the feeding system; however, the minimum particle size is also strongly tied to material losses in preprocessing that are difficult to overcome. This highlights the value in identifying a minimum particle size that can balance the competing effects of material losses and operability issues. Having quantified the economic material losses, the next step is to gain a better understanding of how particle size impacts the operability of the pyrolyzer, which to this point is mostly limited to informal communication with contacts in the industry.

<b>Material Attributes</b>	<b>Processing Attributes</b>	<b>Quality Attributes</b>
Moisture content & variability	Fan speed	Minimum particle size
Ash content & variability	Feed rate	Maximum fixed carbon content
Fixed carbon & variability	Screen size	Maximum ash content
		Maximum moisture content
		Achievable throughput

## **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 expand access to biomass resources. Through 2012, BETO-funded research on feedstock supply systems focused on improving conventional feedstock supply systems. Conventional feedstock supply system designs rely on existing technology and systems to supply feedstock to biorefineries. 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.

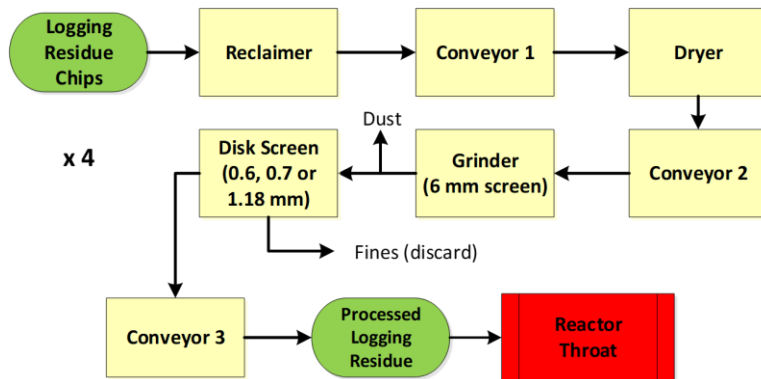
In this Case Study, we focused on evaluating the sensitivity of preprocessing and high-temperature conversion with regard to the air speed preprocessing CPP, the particle size conversion CMA floor and a fixed carbon conversion CMA ceiling. Also considered were moisture and ash impacts on throughput and overall operating effectiveness (OOE), total feedstock production cost and delivered feedstock cost, and the estimated minimum fuel selling price (MFSP). In this Case Study Brief, 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

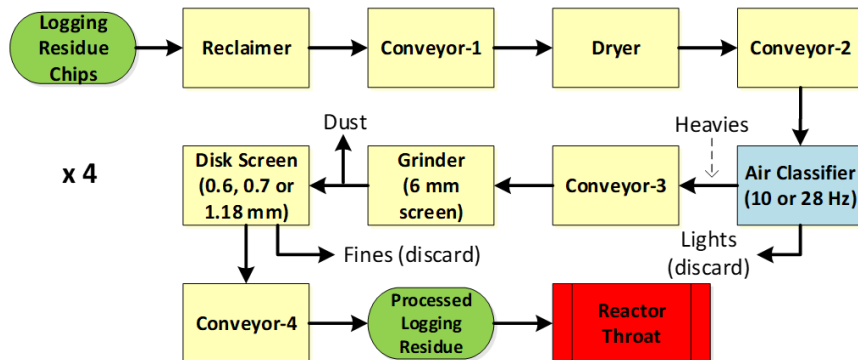
Both the Base Case and Case Study assume a nameplate biorefinery design capacity of 2,205 dry tons of feedstock per day, with 350 operating days/year assuming 90% time on-stream over the year (725,000 dry tons/year) which are the same as in the High-Temperature Conversion Feedstock 2020 Overall Operating Effectiveness (OOE) State of Technology (SOT) report<sup>1</sup>. The discrete event simulation model developed previously for HT-P-11 was utilized to generate results for three classifier air speed CPPs (0 Hz which was the no air classifier Base Case), 10 Hz and 28 Hz), three particle size CQAs ( $\geq 0.6\text{mm}$ ,  $\geq 0.7\text{ mm}$  and  $\geq 1.18\text{ mm}$ ) and two fixed carbon CQAs ( $\leq 18\%$  and  $\leq 21\%$ ). In addition to air speed, particle size floor and fixed carbon ceiling, feedstock CQAs for ash content ( $\leq 1.75\text{ wt\%}$ , dry basis) and moisture content ( $\leq 10\text{ wt\%}$ , wet basis) were used. Because the status quo Base Case 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. Flowsheets for the Base Case and Case Study are shown in Figures 1 and 2.

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<sup>1</sup> Hartley, D.S., Griffel, L.M., Thompson, D.N. (2020), High-Temperature Conversion Feedstock 2020 Overall Operating Effectiveness State of Technology. Milestone Completion Report, Idaho National Laboratory, Idaho Falls ID. INL/EXT-20-59981.



**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. In both cases presented here, a disk screen is inserted after the hammer mill to separate out fines. In the Case Study, an air classifier and an additional conveyor are inserted just upstream 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).

For the preprocessing portion of this cross-boundary Case Study, laboratory data on the impacts of fan speed and moisture content on the separation efficiency of soil ash, needles and bark from white wood received from Subtask 5.2 (Jordan Klinger and Tiasha Bhattacharjee) for the previous Case Study HT-P-11 were reused for this analysis. Average throughput and energy consumption data obtained from the Bioenergy Feedstock National User Facility (BFNUF) (Neal Yancey) for the same air classifier were also reused for this analysis. Additionally, information from the 13/23 Year-Old Tree high-temperature conversion Case Study were used together with literature to develop a distribution of fixed carbon for Loblolly pine logging residues to allow its used as a more predictive conversion CMA for bio-oil yield. The discrete event simulation model developed previously for HT-P-11 was utilized to generate results for three classifier air speed CPPs (0 Hz which was the no air classifier Base Case), 10 Hz and 28 Hz), three

particle size CQAs ( $\geq 0.6\text{mm}$ ,  $\geq 0.7\text{ mm}$  and  $\geq 1.18\text{ mm}$ ) and two fixed carbon CQAs ( $\leq 18\%$  and  $\leq 21\%$ ). In addition to air speed, particle size floor and fixed carbon ceiling, feedstock CQAs for ash content ( $\leq 1.75\text{ wt\%}$ , dry basis) and moisture content ( $\leq 10\text{ wt\%}$ , wet basis) were used. Because the status quo Base Case 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.

In the discrete event simulation of preprocessing, 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. Additionally, the same moisture and ash distributions and generators as used in the High-Temperature Conversion Feedstock 2020 OOE SOT were utilized here. The single change from the prior Case Study (HT-P-11) was a shift from a carbon content CQA floor to a fixed carbon CQA ceiling to better represent compositional impacts on bio-oil yield. Measured data on the average fixed carbon content of loblolly pine logging residues (19.57%) were received from the 13/23 Year-Old Tree high-temperature conversion Case Study, however, with only two measurements available there were not sufficient data to get a standard deviation to construct a distribution of fixed carbon. As a mitigation we used the standard deviation for fixed carbon in the crown of pulp-grade Loblolly pine trees (1.3) from a recent Master's thesis (Loxley<sup>2</sup>) to develop a distribution of fixed carbon for Loblolly pine logging residues around the average from the 13/23 Year-Old Tree high-temperature conversion Case Study. The distribution selected was a Gamma distribution with a shape parameter of 12, a scale parameter of 0.0045 and a location parameter of .141, which resulted in a mean of 19.5 and a standard deviation of 1.3. The fixed carbon values for each unit of residue fed to preprocessing were randomly selected from this distribution at biomass generation in the model.

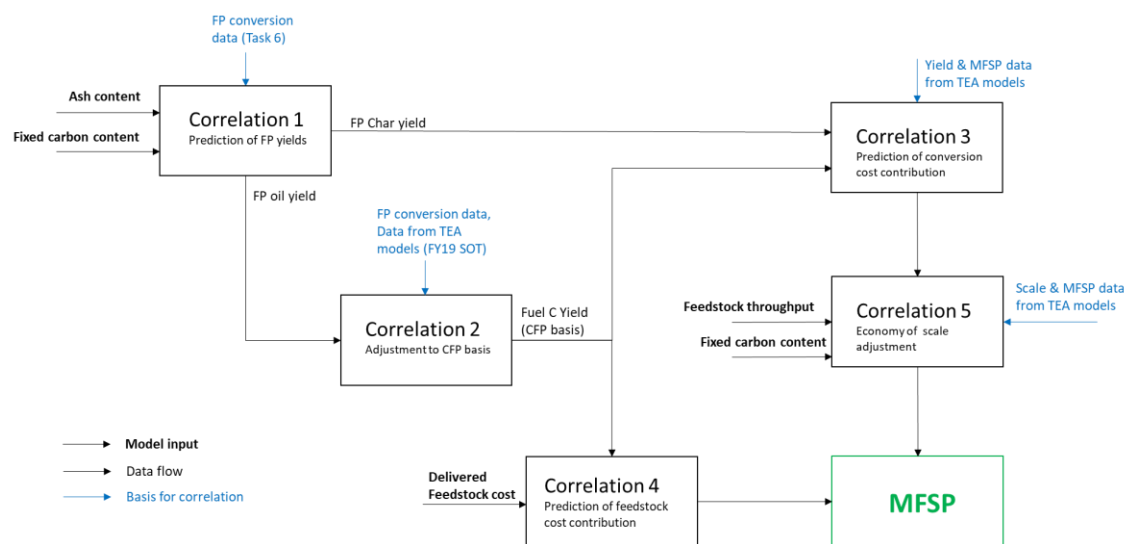
In both the Base Case and the Case Study, no data were available to predict changes to fixed carbon through losses in the grinder (as dust) or from the disk screen (as fines), hence, were assumed to be unmodified by these unit operations. For the air classifier in the Case Study, the distributions of fixed carbon in the heavy fraction exiting the air classifier were adjusted proportionally to experimental data for fixed carbon observed in the 13/23 Year-Old Tree high-temperature conversion Case Study for logging residue (19.64%), 10 Hz heavies (18.31% or -6.772% from residue) and 28 Hz heavies (17.15% or -12.68% from residue). For the 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 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<sup>3</sup>.

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<sup>2</sup> Loxley, T.A. (2018), Within-tree Fuel Quality of Loblolly Pine (*Pinus taeda*). Master's Thesis, Auburn University, Biosystems Engineering Department, Auburn, AL. May 5, 2018, 136 pp.

<sup>3</sup> Hartley, D.S., Thompson, D.N., Griffel, L.M. (2020), The effect of biomass properties and system configuration on the operating effectiveness of biomass to biofuel systems. *ACS Sustainable Chemistry & Engineering* 8, 7267-7277. DOI: 10.1021/acssuschemeng.9b06551.

For the high-temperature conversion portion of this cross-boundary Case Study, a series of correlations were developed from existing techno-economic models and fast pyrolysis (FP)/catalytic fast pyrolysis (CFP) data. These correlations are imperfect by nature but are useful for the high-throughput generation of an MFSP, given inputs of (1) ash content, (2) fixed carbon content, (3) feedstock cost, and (4) feed scale. A high-level flow chart of the MFSP generation tool is shown in Figure 3.

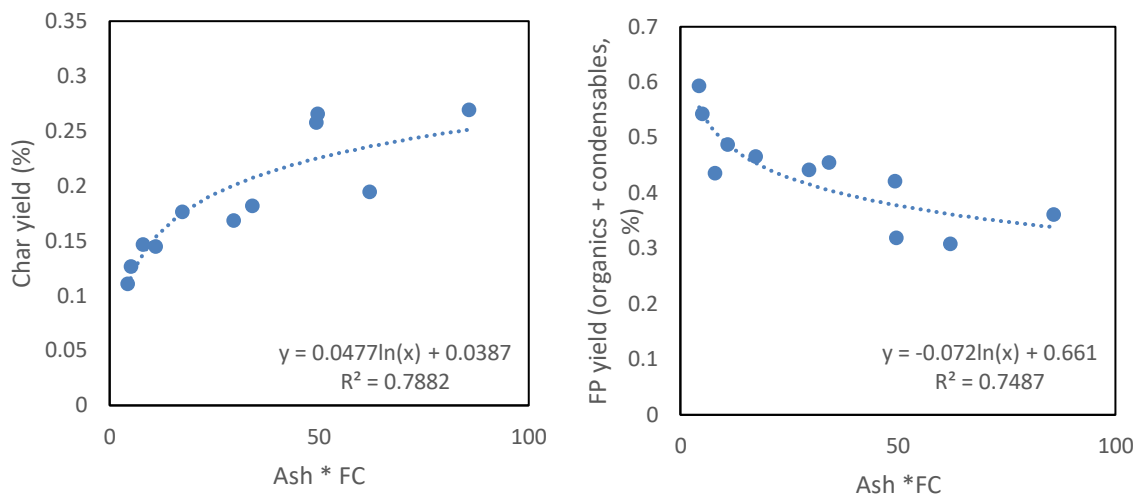


**Figure 3.** Flow chart depicting various correlations used in the MFSP generation tool.

### Correlation 1: Prediction of FP yields

Data for the fast pyrolysis (FP) of various feedstocks was obtained from Task 6<sup>4</sup> in order to correlate feedstock attributes to parameters more predictive of process economics. These data covered a variety of feedstocks, including those enriched in specific anatomical fractions (e.g., stem wood, bark, needles, tops and branches), those subjected to varying levels of air classification, and trees of varying ages. Ash and fixed carbon (FC) were chosen from the available data based on good correlation with char and FP oil yield. These correlations, shown in Figure 4, are inexact ( $R^2=0.7882$  and  $0.7487$  for char and oil yield respectively) but are useful for predicting approximate yields that can eventually be used to generate high-level MFSP estimates.

<sup>4</sup> Carpenter D, Parks J, Wiggins G, Webb E, Ciesielski PN, Pecha B, et al. FCIC Task 6 FY2021 Annual Milestone Report: Multi-Scale Validated Simulation Framework for Capturing the Effects of Variations in Biomass Feedstock on Pyrolysis Oil Quality. 2021.



**Figure 4.** Correlation of ash and fixed carbon correlated to char and FP oil yield. Data generated by Task 6 for various woody feedstocks<sup>4</sup>.

*Correlation 2: Adjustment to CFP basis*

The yields predicted by Correlation 1 are relevant for the production of non-catalytic FP oil only and therefore require an adjustment to predict the MFSP of a CFP-based biorefinery. FP yields were adjusted based on the ratio of the fuel carbon yield of the FY19 SOT report<sup>5</sup> vs. the FP yield measured by Task 6 for the conversion of a feedstock analogous to that used in the FY19 SOT (a mixture of 50% clean pine and 50% forestry residues).

*Correlation 3: Prediction of conversion cost contribution*

Fuel carbon yield and char yield were used as inputs into a piecewise linear correlation described in previous work<sup>6</sup>. This correlation yielded a predicted MFSP relevant for a feedstock cost of \$70.15/GGE and a facility throughput of 2000 dry tonnes/day. This intermediate MFSP can be reduced to a conversion cost contribution (adjusted by facility throughput via Correlation 5) before being combined with the adjusted feedstock contribution (Correlation 4).

*Correlation 4: Prediction of feedstock cost contribution*

The cost contribution of feedstock in a CFP biorefinery accounts for a significant portion of total operating costs and is independent from the facility scale. Feedstock contribution can be calculated by

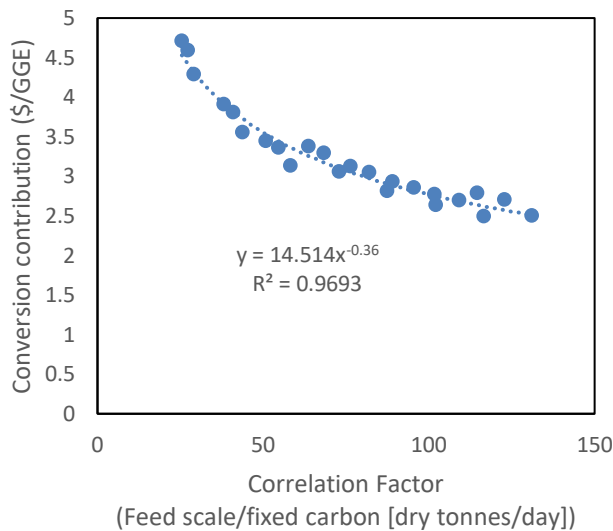
<sup>5</sup> Dutta A, Iisa MK, Talmadge M, Mukarakate C, Griffin MB, Tan EC, et al. Ex Situ Catalytic Fast Pyrolysis of Lignocellulosic Biomass to Hydrocarbon Fuels: 2019 State of Technology and Future Research. National Renewable Energy Lab. (NREL), Golden, CO (United States); 2020. <https://doi.org/10.2172/1605092>.

<sup>6</sup> Wiatrowski MR, Dutta A, Pecha MB, Crowley M, Ciesielski PN, Carpenter D. A simplified integrated framework for predicting the economic impacts of feedstock variations in a catalytic fast pyrolysis conversion process. *Biofuels, Bioproducts and Biorefining* n.d.;n/a. <https://doi.org/10.1002/bbb.2319>.

the feedstock cost (\$/ton) divided by the fuel yield (GGE/ton). Fuel yield was determined by correlation to fuel carbon yield ( $R^2=0.9999$ ) to yield an adjusted feedstock cost contribution

*Correlation 5: Economy of scale adjustment*

The conversion cost contribution calculated in correlation 3 is further adjusted to reflect impacts from the facility throughput. TEA models for each feedstock (unclassified residues and residues classified at 10 Hz and 28 Hz) were exercised at various feed scales to generate correlations of conversion contribution vs. feed scale. The economy of scale effect for each feedstock was found to be slightly different, likely due to differences in fuel/char yields impacting the relative costs for different unit operations. Accordingly, a correlation factor (feed throughput divided by fixed carbon) was developed to generate one curve that could apply to all feedstocks and enable a more streamlined MFSP prediction (Figure 5).



**Figure 5.** Correlation between correlation factor (defined as feed scale in dry tonnes/day divided by fixed carbon %) and conversion contribution.

**Results and Discussion**

Throughput Analysis

The Throughput Factors ( $F_{f,p}$ , achieved tons at the reactor throat divided by the Nameplate Design Capacity) for all cases are shown in Table 1, along with their Mean Production Costs and statistics. The Mean Production Cost is the cost to move the material through the system before taking into account the material losses, and is the correct value to compare to nth-plant designs which assume that all operational issues have been solved. Two of the three parameters that were varied impact the throughput in the systems, the air classifier fan speed (no air classifier in the Base Case) and the particle size floor. Ash content also impacts throughput by causing failures in the grinders, however, this impact would be constant for a given fan speed. The  $F_{f,p}$  in the Base Case increased from 0.5395 for a 1.18 mm

particle size floor to 0.8099 for a 0.6 mm particle size floor, due to less material being removed as fines. For the 10 Hz cases, this shifted the  $F_{f,p}$  range to 0.5210 at 1.18 mm to 0.7820 at 0.6 mm, with the decrease due to additional material removed in the air classifier lights. For the 28 Hz cases, the  $F_{f,p}$  range shifted further to 0.3117 at 1.18 mm to 0.4679 at 0.6 mm, with the decrease due to removal of significantly more material in the air classifier lights.

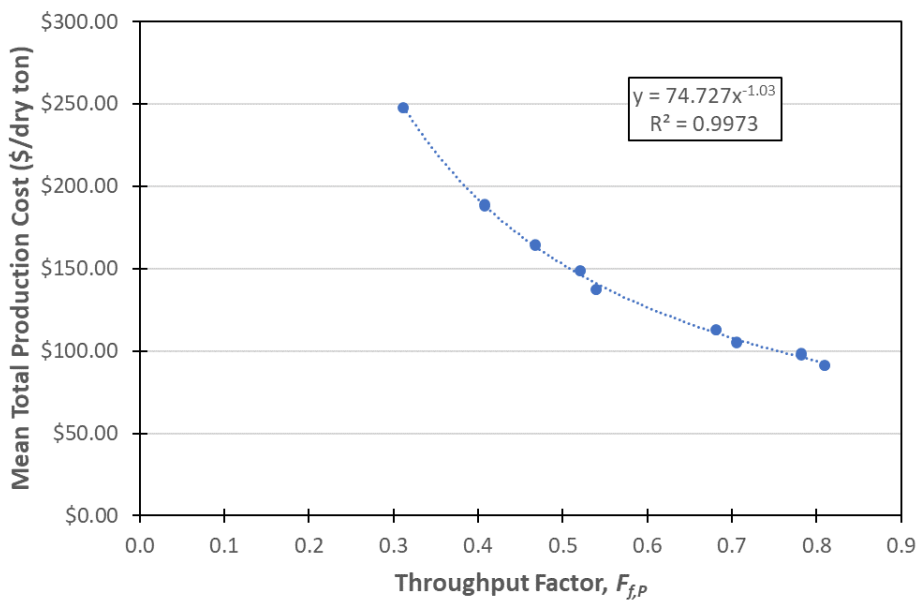
**Table 1.** Throughput Factors and Base Production Costs with statistics for the Base Case and Case Study analyses. A fan speed of 0 indicates the Base Case, which had no air classifier.

Fan Speed (Hz)	Particle Size Floor (mm)	Fixed Carbon Ceiling (%)	Throughput Factor $F_{f,p}$	Base Production Cost (\$/dry ton)				
				Mean	Median	Standard Deviation	Minimum	Maximum
0	0.6	18	0.8099	\$74.77	\$74.60	\$6.68	\$71.32	\$576.11
0	0.6	21	0.8099	\$74.76	\$74.60	\$5.12	\$71.32	\$551.57
0	0.7	18	0.7053	\$74.73	\$74.60	\$5.18	\$71.32	\$464.46
0	0.7	21	0.7053	\$74.91	\$74.60	\$5.06	\$71.32	\$506.93
0	1.18	18	0.5395	\$74.61	\$74.60	\$6.42	\$71.32	\$547.91
0	1.18	21	0.5395	\$74.89	\$74.60	\$6.40	\$71.32	\$523.20
10	0.6	18	0.7820	\$77.94	\$78.08	\$7.26	\$73.43	\$495.70
10	0.6	21	0.7820	\$77.18	\$78.08	\$5.91	\$73.43	\$461.04
10	0.7	18	0.6810	\$77.63	\$78.08	\$5.48	\$73.43	\$438.76
10	0.7	21	0.6810	\$77.59	\$78.08	\$5.64	\$73.43	\$511.11
10	1.18	18	0.5210	\$78.13	\$78.08	\$5.16	\$73.43	\$537.77
10	1.18	21	0.5210	\$78.16	\$78.08	\$5.21	\$73.43	\$432.86
28	0.6	18	0.4679	\$77.70	\$78.08	\$7.87	\$73.43	\$522.66
28	0.6	21	0.4679	\$77.50	\$78.08	\$6.73	\$73.43	\$623.13
28	0.7	18	0.4075	\$77.33	\$78.08	\$6.74	\$73.43	\$506.00
28	0.7	21	0.4075	\$77.77	\$78.08	\$6.00	\$73.43	\$557.30
28	1.18	18	0.3117	\$77.93	\$78.08	\$6.33	\$73.43	\$516.01
28	1.18	21	0.3117	\$77.80	\$78.08	\$5.55	\$73.43	\$428.01

The modeled Mean Production Costs do not include the added cost of lost material and so are relatively similar within a given system design, rather, they are more a function of CAPEX and thus won't vary much. For the Base Case (no air classification), Mean Production Costs ranged from \$74.61 to \$74.91/dry ton (2016\$). For the Case Study system, Mean Production Costs ranged from \$77.18 to \$78.16/dry ton. For all cases, the Mean Production Cost varied significantly from minimum to maximum modeled costs, which is reflective of the throughput impacts of variable biomass properties.

Moving beyond Mean Production Cost to include the cost of material losses from the system, the added cost of the lost material is calculated and added to the Mean Production Cost to give the Total Production Cost (Table 2). The higher the losses (from whatever source), the higher the added cost of

lost material. The Total Production Cost in the Base Case decreased from \$137.66/dry ton for a 1.18 mm particle size floor to \$91.45/dry ton for a 0.6 mm particle size floor, due to the removal of less material as fines. For the 10 Hz cases, this shifted the Total Production Cost range to \$148.86/dry ton at 1.18 mm to \$97.81/dry ton at 0.6 mm, with the increase due to additional material removed in the air classifier lights. For the 28 Hz cases, the Total Production Cost range shifted further to \$248.01/dry ton at 1.18 mm to \$164.13 at 0.6 mm, with the increase due to removal of significantly more material in the air classifier lights. FAs for the Mean Production Costs, the Total Production Cost varied significantly from minimum to maximum modeled costs. It is worth noting that the Mean Total Production Cost can be predicted by  $F_{f,p}$  using a power law function (Figure 6).



**Figure 6.** Mean Total Production Cost as a function of Throughput Factor.

**Table 2.** Added cost of lost material from all sources including air classifier, grinder and screen, and the resulting Total Production Costs for the Base Case and Case Study analyses. A fan speed of 0 indicates the Base Case, which had no air classifier.

Fan Speed (Hz)	Particle Size Floor (mm)	Fixed Carbon Ceiling (%)	Added Cost of Lost Material (\$/dry ton)	Total Production Cost (\$/dry ton)				
				Mean	Median	Standard Deviation	Minimum	Maximum
0	0.6	18	\$16.69	\$91.46	\$91.30	\$6.68	\$88.02	\$592.80
0	0.6	21	\$16.70	\$91.45	\$91.30	\$5.12	\$88.02	\$568.27
0	0.7	18	\$30.26	\$105.00	\$104.87	\$5.18	\$101.59	\$494.73
0	0.7	21	\$30.34	\$105.25	\$104.94	\$5.06	\$101.66	\$537.27
0	1.18	18	\$62.53	\$137.14	\$137.13	\$6.42	\$133.85	\$610.44
0	1.18	21	\$62.77	\$137.66	\$137.37	\$6.40	\$134.09	\$585.97
10	0.6	18	\$20.91	\$98.78	\$98.91	\$6.81	\$94.26	\$516.54
10	0.6	21	\$20.94	\$97.81	\$98.71	\$5.35	\$94.06	\$481.67
10	0.7	18	\$35.59	\$112.99	\$113.44	\$7.13	\$108.79	\$474.13
10	0.7	21	\$35.19	\$112.94	\$113.42	\$6.51	\$108.77	\$546.45
10	1.18	18	\$70.77	\$148.80	\$148.74	\$6.74	\$144.09	\$608.44
10	1.18	21	\$70.36	\$148.86	\$148.78	\$6.26	\$144.12	\$503.56
28	0.6	18	\$86.58	\$164.56	\$164.94	\$5.23	\$160.28	\$609.52
28	0.6	21	\$86.84	\$164.13	\$164.71	\$6.11	\$160.06	\$709.77
28	0.7	18	\$110.55	\$188.10	\$188.85	\$6.23	\$184.20	\$616.77
28	0.7	21	\$110.63	\$189.15	\$189.47	\$5.42	\$184.82	\$668.69
28	1.18	18	\$170.12	\$248.01	\$248.16	\$5.91	\$243.51	\$686.09
28	1.18	21	\$170.05	\$247.61	\$247.88	\$7.51	\$243.23	\$597.81

### Quality Analysis

The Quality Performance Factors ( $F_{B,P}$ , preprocessed tons at the reactor throat that meet all conversion CMAs divided by the total preprocessed tons) for all cases are shown in Table 3. Conversion CMAs impacting the quality assessment include ash content  $\leq 1.75$  wt% (dry basis) and the fixed carbon ceilings ( $\leq 18\%$ ,  $\leq 21\%$ ). For the 18% fixed carbon ceiling,  $F_{B,PS}$  of  $\sim 0.15$ ,  $\sim 0.49$  and  $\sim 0.78$  were modeled for particle size floors of 0.6 mm, 0.7 mm and 1.18 mm, respectively, while for the 21% fixed carbon ceiling these were  $\sim 0.75$ , 0.96 and 0.99, respectively. This shows that the higher the fixed carbon ceiling and higher the fan speed, the larger the fraction of preprocessed tons that meet all of the conversion CMAs, indicating that removal of the lights fraction from the nominal 2-in. residue chips by air classification prior to grinding has a large impact on meeting the quality specifications. Ash, bark and needles are removed in the lights fraction as well as small white wood particles, with larger amounts of white wood being removed in the lights as the fan speed is increased. Ash removal in the lights lowers

the ash content of the remaining heavies, and removal of bark and needles (which have higher fixed carbon) than the white wood lowers the fixed carbon in the remaining heavy fraction.

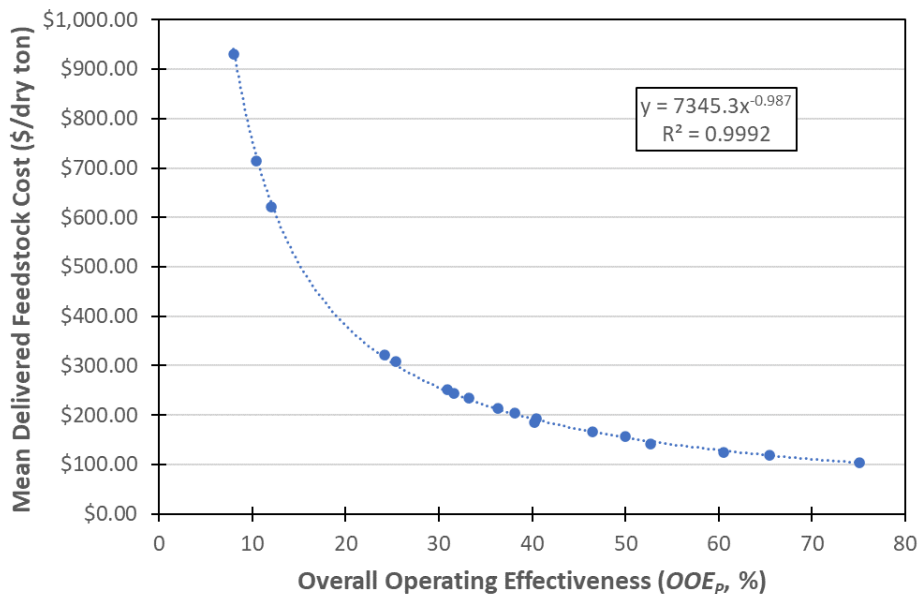
The Overall Operating Effectiveness ( $OOE_p$ ) of the preprocessing system is also shown in Table 3.  $OOE_p$  is a measure of the effectiveness of the system of meeting both operability targets (throughput) and quality targets (meets all CQA and is the product of  $F_{f,p}$  and  $F_{B,p}$  multiplied by 100 to give a percentage). For the Base Case,  $OOE_p$  ranged from 8.01% to 52.68%, while for the 10 Hz and 28 Hz fan speeds  $OOE_p$  ranged from 25.42% to 75.08% and 22.42% to 46.47%, respectively. In general, as the fan speed is

**Table 3.** Quality Performance Factor, Overall Operating Effectiveness, added cost of quality disposal if the tons not meeting quality are not fed to conversion, and the resulting delivered feedstock cost for the Base Case and Case Study analyses. A fan speed of 0 indicates the Base Case, which had no air classifier.

Fan Speed (Hz)	Particle Size Floor (mm)	Fixed Carbon Ceiling (%)	Quality Performance Factor $F_{B,p}$	Overall Operating Effectiveness $OOE_p$ (%)	Added Cost of Quality Disposal (\$/dry ton)	Mean Delivered Feedstock Cost (\$/dry ton)
0	0.6	18	0.1485	12.02	\$530.36	\$621.82
0	0.6	21	0.7470	60.49	\$32.13	\$123.58
0	0.7	18	0.1484	10.47	\$608.81	\$713.80
0	0.7	21	0.7470	52.68	\$36.96	\$142.20
0	1.18	18	0.1485	8.01	\$794.19	\$931.32
0	1.18	21	0.7468	40.29	\$48.36	\$186.02
10	0.6	18	0.4879	38.15	\$105.52	\$204.30
10	0.6	21	0.9601	75.08	\$4.98	\$102.79
10	0.7	18	0.4880	33.23	\$120.62	\$233.61
10	0.7	21	0.9601	65.39	\$5.76	\$118.69
10	1.18	18	0.4879	25.42	\$158.73	\$307.52
10	1.18	21	0.9601	50.02	\$7.57	\$156.42
28	0.6	18	0.7769	36.36	\$49.16	\$213.72
28	0.6	21	0.9931	46.47	\$2.65	\$166.78
28	0.7	18	0.7769	31.66	\$56.18	\$244.28
28	0.7	21	0.9930	40.47	\$3.05	\$192.20
28	1.18	18	0.7771	24.22	\$73.94	\$321.96
28	1.18	21	0.9930	30.96	\$3.99	\$251.60

increases and as the particle size floor increases,  $F_{f,p}$  decreases due to increasing material losses. As the fan speed increases  $F_{B,p}$  increases for each particle size floor. The best system from an  $OOE_p$  perspective was the 10 Hz, 0.6 mm floor, 21% fixed carbon ceiling case at 75.08%, while the worst was the no air classification, 1.18 mm floor, 18% fixed carbon ceiling case.

The added cost of quality due to not feeding the tons not meeting the conversion quality CMAs and the mean delivered feedstock cost at the reactor throat are shown in Table 3. For all fan speeds there was a significantly higher penalty at the 18% fixed carbon ceiling than at 21%, which is reflective of the significantly lower  $F_{B,p}$  values at the lower fixed carbon ceiling. This led to delivered feedstock costs ranging from \$123.58 to \$931.32/dry ton for the Base Case, \$102.79 to \$307.52 for the 10 Hz Case Study cases, and \$166 to \$321.96/dry ton for the 28 Hz Case Study cases. It is worth noting that the delivered feedstock cost following the quality assessment can be predicted by  $OOE_p$  using a power law function (Figure 7).



**Figure 7.** Mean delivered feedstock cost following the quality assessment as a function of Overall Operating Effectiveness.

In an operating biorefinery it will not be economic to dispose of this much material once it has been preprocessed given the large range of delivered feedstock costs; either the material not meeting the ash and fixed carbon specifications must be converted to biofuel or it must be valorized in some other way (such as a value-added co-product or sold into another market). Recognizing this, we considered whether the tons not meeting all of the conversion quality specification would lead to acceptable Minimum Fuel Selling Price (MFSP) if the conversion process were robust enough to accept the ash and fixed carbon ranges exiting preprocessing. In this case, the feedstock cost would be equivalent to the Total Production Cost, which captures the cost of lost material due to air classification, dust losses during grinding, and fines removed to avoid conversion reactor feeding failures.

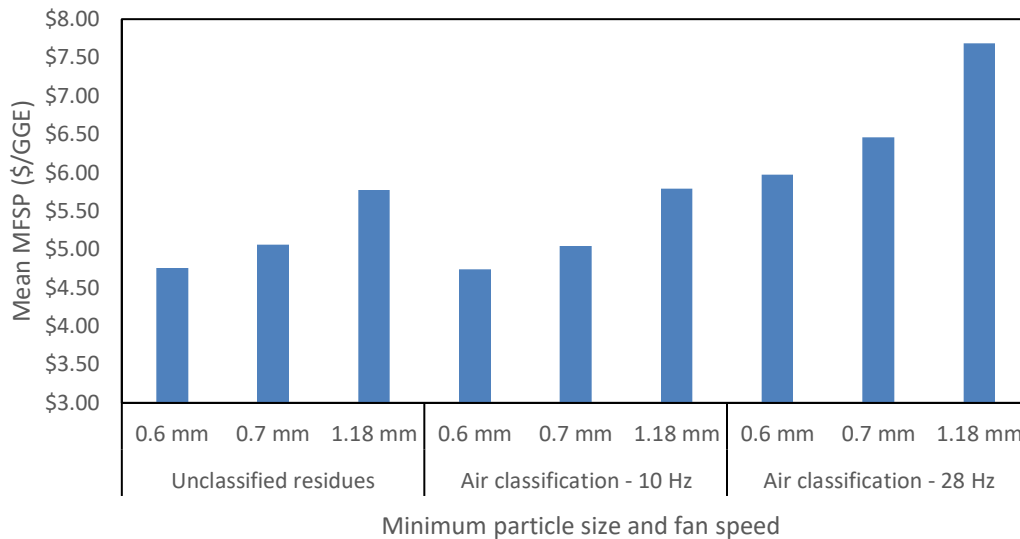
#### MFSP Analysis

To assess the ultimate economic impact of the various cases considered, an MFSP distribution was produced for each case using the series of correlations described previously. The MFSP calculation uses the total production cost of the feedstock, which includes the cost of lost material during normal

processing (i.e., in air classification, the hammer mill, and disk screen) but does not consider the disposal of any additional material to meet fixed carbon and/or ash specifications as described in the quality analysis. Statistics for the MFSP distributions of each case are shown in Table 4 and Figure 7. Feedstocks classified at a lower fan speed (10 Hz) demonstrated economics roughly equivalent to the unclassified residues despite higher feedstock costs and lower delivered throughputs. This was enabled by higher fuel yields and lower char yields for the air classified feedstocks. Residues classified at a higher speed (28 Hz) showed the potential for further improved CFP yields; however, higher feedstock costs, driven by significant material losses during preprocessing, resulted in a net increase in MFSP.

**Table 4.** MFSPs (with statistics) estimated using the feedstock Total Production Costs, fixed carbon and ash contents of individual units of material exiting preprocessing to the conversion reactor (feeding all units produced without a quality assessment) for the Base Case and Case Study analyses. A fan speed of 0 indicates the Base Case, which had no air classifier.

Fan Speed (Hz)	Particle Size Floor (mm)	Fixed Carbon Ceiling (%)	Estimated MFSP (\$/GGE)				
			Mean	Median	Standard Deviation	Minimum	Maximum
0	0.6	18	\$4.76	\$4.76	\$0.22	\$4.32	\$18.60
0	0.6	21	\$4.76	\$4.76	\$0.19	\$4.33	\$17.99
0	0.7	18	\$5.06	\$5.06	\$0.22	\$4.52	\$18.29
0	0.7	21	\$5.07	\$5.07	\$0.21	\$4.52	\$18.83
0	1.18	18	\$5.77	\$5.77	\$0.32	\$4.83	\$25.06
0	1.18	21	\$5.78	\$5.78	\$0.32	\$4.84	\$25.09
10	0.6	18	\$4.74	\$4.74	\$0.22	\$4.35	\$15.80
10	0.6	21	\$4.72	\$4.72	\$0.19	\$4.30	\$15.18
10	0.7	18	\$5.04	\$5.04	\$0.21	\$4.53	\$17.25
10	0.7	21	\$5.04	\$5.04	\$0.21	\$4.48	\$18.77
10	1.18	18	\$5.79	\$5.79	\$0.26	\$4.86	\$23.57
10	1.18	21	\$5.80	\$5.80	\$0.26	\$4.86	\$20.82
28	0.6	18	\$5.98	\$5.98	\$0.36	\$5.49	\$25.52
28	0.6	21	\$5.97	\$5.97	\$0.31	\$5.44	\$29.99
28	0.7	18	\$6.46	\$6.46	\$0.36	\$5.78	\$27.93
28	0.7	21	\$6.48	\$6.48	\$0.33	\$5.78	\$30.81
28	1.18	18	\$7.68	\$7.68	\$0.46	\$6.28	\$36.82
28	1.18	21	\$7.68	\$7.68	\$0.41	\$6.22	\$31.00



**Figure 7.** Mean MFSP over a range of minimum particle size and fan speed. Results shown for a FC ceiling of 18% only for simplicity.

The lowest MFSPs were observed for cases with the lowest minimum particle sizes, again driven by lower material losses during preprocessing. Residues classified at 10 Hz with a minimum particle size of 0.6 and FC ceiling of 18% demonstrated an MFSP of \$4.74/GGE, slightly lower than the MFSP of \$4.76/GGE observed for the unclassified residues at the same particle size and FC ceiling. MFSP increased for cases which considered higher minimum particle sizes due to a higher amount of material loss at the disk screen; moving from a 0.6 mm specification to 0.7 mm was associated with a \$0.3-0.5/GGE increase, while moving from 0.7 mm to 1.0 mm was associated with another increase of \$0.4-0.7/GGE. This highlights the importance of balancing material losses against feeding consistency issues that may arise at lower particle sizes. Feedback from industry has suggested that there may be operational issues observed when feeding particles <1mm into the pyrolysis reactor; however, this has not yet been confirmed experimentally. Further experiments on how particle size impacts pyrolyzer operability could provide valuable insight into what an appropriate minimum particle size would be for the pyrolysis reactor.

### Conclusions and Next Steps

The goal of this Case Study was to expand the FY21 Q2 Preprocessing Case Study “Air classification of forest residue for tissue and ash separation efficiency (HT-P-11)” to evaluate the sensitivity of preprocessing and high-temperature conversion with regard to the air speed preprocessing CPP, the particle size conversion CMA floor and a fixed carbon conversion CMA ceiling, as compared to the 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 which would cause feeder failures are removed. Also considered were moisture and ash impacts on throughput and overall operating effectiveness (OGE), total feedstock production cost and delivered feedstock cost, and the estimated minimum fuel selling price (MFSP).



Key takeaways from this Case Study are that in an operating biorefinery it will not be economic to dispose of large quantities of material once it has been preprocessed given the large range of delivered feedstock costs; either the material not meeting the ash and fixed carbon specifications must be converted to biofuel or it must be valorized in some other way (such as a value-added co-product or sold into another market). Recognizing this, we considered whether the tons not meeting all of the conversion quality specification would lead to acceptable Minimum Fuel Selling Price (MFSP) if the conversion process were robust enough to accept the ash and fixed carbon ranges exiting preprocessing without causing conversion process upsets.

Integrating the MFSP correlation into the preprocessing model provided valuable insight into the ultimate field-to-fuel economic of each scenario considered. Overall, it was demonstrated that inclusion of an air classifying step in the preprocessing of forestry residues could counteract the additional costs, matching economics compared to using unclassified residues. The higher quality air classified feedstocks demonstrated increased fuel yields, associated with an economic benefit approximately equal to the additional costs associated with air classification at lower fan speeds. Higher fan speeds were shown lead to even higher CFP yields, but also resulted in significant material loss during preprocessing, resulting in a net economic penalty. However, it is possible that an intermediate fan speed could demonstrate a more significant net benefit vs. unclassified residues if the tradeoff between higher CFP yields and material losses was optimized.

The importance of optimizing the minimum particle size fed to conversion was also demonstrated. It is understood that feeding particles on the order of 1 mm or less to conversion has the potential to create operability issues for the feeding system; however, the minimum particle size is also strongly tied to material losses in preprocessing that are difficult to overcome. This highlights the value in identifying a minimum particle size that can balance the competing effects of material losses and operability issues. Having quantified the economic material losses, the next step is to gain a better understanding of how particle size impacts the operability of the pyrolyzer, which to this point is mostly limited to informal communication with contacts in the industry.

Potential next steps include potential blending options should ash content be determined to cause significant process upsets in the conversion. Additionally, further experiments on intermediate fan speeds between 10 Hz and 28 Hz could identify an optimum air classification severity, potentially demonstrating additional cost reductions compared to unclassified residues. On the conversion side, future analyses should focus on refining and formally validating the MFSP correlations developed here, as well as expanding them for other applications. These correlations dramatically increase the personnel and computing time required to generate economic results. In this analysis, outputs of the correlations were limited to MFSP; however, future work may also generate other useful metrics such as fuel yield and capital/operating costs.