Techno-Economic Analysis of Forest Concepts, LLC Crumbler® Operated at Proton Power to Process Crumbles from Hardwood Chips

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February, 2019

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1. Introduction

Developing cost-effective methods for processing biomass into an economic biofuel product is critical to the success for the bioenergy industry in the United States. Size reduction and drying of the material, where used, are two of the most costly and energy-intensive operations that are undertaken during preprocessing. Reducing the energy required during these two phases will lower the cost of processing and ultimately reduce the overall cost to the final user. In an effort to lower the cost for size reduction, Forest Concepts, LLC has developed a rotary shear for the comminution of biomass feedstocks. Forest Concepts has called this rotary shear the Crumbler®, which uses intermeshed rotating disks that shear the material rather than using impact to reduce the particle size of the materials. Forest Concepts, LLC has teamed with Proton Power, Inc., located in Lenoir City, Tennessee, to set up a pilot plant that uses the Crumbler® to produce roughly ¼-inch crumbles that ultimately feed a renewable diesel plant in Rockwood, Tennessee. INL was contracted to test Crumbler® performance and provide a techno-economic analysis of the process.

This demonstration used chipped (roughly 2-inch) hardwood trees, harvested locally near the Rockwood facility. Following the chipping process, a two-stage Crumbler® process was used to size-reduce chips to approximately ¼-inch particles. The material produced from the Crumbler® ("crumbles") is normally dried prior to feeding a bank of "CHyP" engines operated at Proton Power to make renewable diesel. Some of the processed crumbles were shipped to INL to be dried using the Biomass Feedstock National User Facility (BFNUF) process demonstration unit (PDU) rotary drier to measure the energy required to dry the crumbles to less than 10% moisture content. Additionally, raw chips were shipped to INL and dried prior to hammer milling to compare the two methods and provide data for the techno-economic analysis.

2. Test Methods -- Crumbler® Demonstration

The test facility was set up to process 2-inch raw hardwood chips (Figure 1), which were chipped on site. The raw chips were fed into a feed hopper and conveyed into the Crumbler®.

Figure 1. Raw 2-inch chipped hardwood on conveyor.

The Crumbler® is composed to two sets of rotary shears (orange in Figure 2). Each set of rotary shears is powered by two 75-HP electric motors (located on each side of the Crumbler® - Figure 2). The two sets of rotary shear heads (Module 1 and Module 2) are positioned one over the top of the other allowing gravity to be used to feed material from the conveyors through each of the modules. The discharge from Module 2 is conveyed to a screen that separates the material into "Unders", which pass through a 20-mesh, or 0.841 mm, woven wire; "Overs", which pass over a ½-inch, or 12.7mm, round hole screen); and "Accepts," which do not pass through the 20-mesh woven wire screen but pass through the ½-inch round hole. The Unders are removed from the process. The Overs are recycled and sent back through the Crumbler® modules a second time. The Accepts (on-spec material) are loaded into super sacks and stored to be used in the process downstream as needed.

Figure 2. Two Crumbler® modules in a tower arrangement.

For this test, approximately 16.5 tons of processed crumbles were collected and stored in super sacks. Samples of raw hardwood chips were collected prior to milling or crumbling to determine moisture content and particle size. Samples were also collected after the Module 1 Crumbler®, the Module 2 Crumbler®, and from each of the streams leaving the screener (Unders, Overs, and Accepts). Again these samples were analyzed for moisture content and particle size. Flow measurements were made at the outlet for the processed material (Accepts) by weighing all of the product produced over the run time of the test. Fines (Unders) were also collected, weighed, and time stamped based on the run time of the test. The flow rate for the Overs was measured at the point of the discharge from the screen by capturing the amount of material that would flow through the process in a 1-minute interval and measuring its mass. Data loggers were used to measure the current, voltage, and power factor to calculate energy used for each mill.

For the purpose of comparing the drying costs prior to hammer milling vs the drying costs after the Crumbler®, four super sacks of crumbles and four super sacks of raw hardwood chips were shipped back to INL to dry and collect the associated energy consumption for comparison. The four super sacks of raw chips were dried in the INL rotary drier followed by hammer milling with a ½-inch screen to achieve a similar particle size. The four super sacks of crumbles were also dried and the energy data for drying was used in the techno-economic analysis. For the hammer mill test, raw chips (four super sacks) were weighed, dried, weighed again, hammer milled (time and mass were measured during milling), and sampled to measure moisture content and particle size. To calculate the energy consumed on a dry-ton basis, the current (amps), voltage, and power factor were measured. This energy analysis included the energy consumption of the air handling system, which was needed to efficiently move material through the hammer mill. The cost of air handling was also included in the analysis for the Crumbler®, but it is reported as a separate line item. Air handling for dust control or conveyance was not needed at the Proton Power facility, but in some cases, where dust suppression is needed, air handling may be required. To address situations where dust suppression is needed, the energy requirements for air handling are provided in both processes as a separate line item.

3. Techno-Economic Analysis Methods

The Biomass Logistics Model (BLM) was used to perform the techno-economic analysis for this project. The BLM incorporates information from a collection of databases that provide (1) engineering performance data for hundreds of equipment systems, (2) spatially explicit labor cost datasets, and (3) local tax and regulation data. The BLM's analytic engine is built in the systems dynamics software package Powersim™. The BLM is designed to (1) work with both thermochemical- and biochemical-based biofuel conversion platforms and (2) accommodate a range of lignocellulosic biomass types (e.g., agriculture residues, short-rotation woody and herbaceous energy crops, woody residues, and algae). BLM simulates the flow of biomass through the entire supply chain while tracking changes in feedstock characteristics (i.e., moisture content, dry matter, ash content, and dry bulk density) that result from interactions along the supply chain (Cafferty et al. 2013). The model accounts for all of the equipment that comes into contact with the feedstock from the time that it is harvested to the point where the material enters the conversion reactor. Tracking the machine interactions along with the associated property changes allows for highly detailed economic cost and energy consumption analyses. The results from the BLM can be used as inputs to additional models that provide indications of sustainability or material quality. For this analysis, the process information for the Crumbler® equipment was collected from the Proton Power pilot plant. The drying data and the hammer milling data were collected using the BFNUF PDU located at Idaho National Laboratory.

3.1. Modeling Scenarios

This techno-economic analysis is limited to the secondary size-reduction operations that occur when feeding wood chips into a biochemical or thermochemical conversion process. The economic calculations cover the operations of these processes only and do not consider differences that may arise in the supply chain beyond the secondary size-reduction operation. It is assumed that each scenario is processing enough material to produce 800,000 dry short tons per year, or 95 dry short tons per hour. The individual equipment in the model has operating capacities less than 95 dry short tons per hour, which requires that multiples of each equipment type is used in the model to reach the required capacity. The basis for comparison between the operational scenarios is total cost in dollars per dry U.S. short ton. Each scenario begins with the same feedstock material (pulp-quality hardwood chips were used). Moisture content and particle size were measured and are provided later in this report. The chips are conveyed to the secondary size reduction processes from a storage pile. After conveyance, each scenario differs in the order of the processing operations and the equipment used. Some of the assumptions used in the techno-economic analysis are provided in Table 1.

Table 1. Techno-Economic Analysis Assumptions.

Parameter	Cost
Wood Chip Cost	$37.00/dry ton
Electricity Cost	$0.071/kWh
Natural Gas	$5.39/MMBtu
Off-Road Diesel Cost	$3.29/gal
Interest Rate	8%

3.1.1. Hammer Mill, Dry Material

The Hammer Mill, Dry Material scenario represents the most common method of secondary size reduction of hardwood chips (Figure 3). In this scenario, the chipped hardwood material is conveyed to a rotary dryer and dried to less than 10% moisture content wet basis. The dried material is conveyed to a hammer mill with a ½-inch opening grate, where it is ground. The material that leaves the grinder is screened. Unders are rejected by passing through a 20-mesh, or 0.841-mm, woven wire screen and are disposed. Overs pass over a ½-inch, or 12.7mm, round hole and are recirculated back to the hammer mill. Accepts (material meeting the size specification) continues through the screening process and are placed in covered storage to await feeding to the conversion reactor. Table 2 provides the parameters used for each piece of equipment and measured performance values. Table 2 also shows the screening performance.

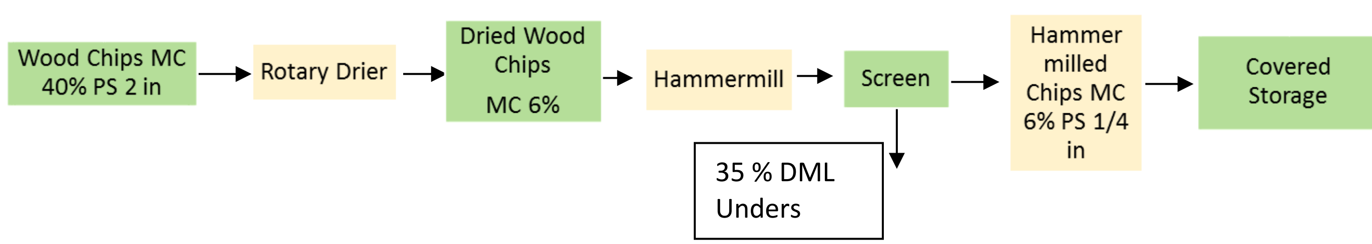

Figure 3. Diagram of the Hammer Mill, Dry Material scenario.

Table 2. Hammer Mill, Dry Material equipment parameters.

	Rotary Dryer	Hammer Mill	Orbital Screen	Blower
Purchase Price (2014 USD)	$351,000	$113,000	$75,000	$352,000
Energy (kWh/dry ton)	2328	11.2	1.39	2.0
Capacity (dry ton/hour)	2.4	3.9	5.0	
% Overs			0%	
% Unders			35%	

*No orbital screening actually took place. Values for orbital screen numbers were estimated from the particle-size distribution measured following the hammer mill.

3.1.2. Rotary Shear with Drying

The process that is assumed for secondary size reduction using the rotary shear is presented in Figure 4. The parameters used are reported in Table 3. The Rotary Shear with Drying scenario is different from the previous scenario in that the wood chips are crumbled prior to drying. This creates a cost advantage for the Crumbler® because smaller particles are fed to the drying process, which results in a significant reduction in drying costs. (The energy required to dry smaller particles decreases as a result of the high surface area/volume ratio.) The chips are conveyed to the rotary shear, where they are size-reduced with ¼-inch (6.4mm) cutters. The outfeed of the rotary shear conveys the processed material to the screen, where Accepts continues on to a rotary drier and is dried to less than 10% moisture content wet basis. The screened Unders pass through a 20-mesh woven wire, or 0.841 mm, screen and are discarded. The Overs (passing over a 1/2 inch, or 12.7mm, round hole) are recirculated back to the rotary shear.

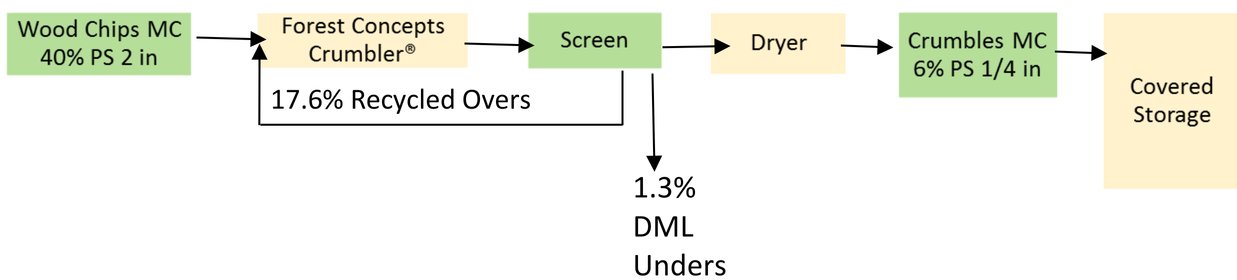

Figure 4. Diagram of the Crumbler® with Drying scenario.

*Note 1.3% dry matter loss is calculated based on total amount of fines produced/total material processed.

Table 3. Crumbler® equipment parameters.

	Crumbler®	Rotary Dryer	Orbital Screen
Purchase Price (2014 USD)	$750,000	$351,000	$65,000
Energy (kWh/dry ton)	18.4	1238	0.80
Capacity (dry ton/hour)	5.68	4.8	10
% Accepts			81.3%
% Overs			17.6%
% Unders			1.1%

*Note 1.1% Unders are calculated based on percent of undersized material present directly following the milling process, which includes recycled Overs.

4. Results

During testing at the Proton Power pilot plant, 16.5 tons of wood chips were converted to crumbles. A loader was used to load chipped hardwood into a hopper that fed the Crumbler®. Energy data and physical samples were collected and analyzed. Samples were collected from the chipped hardwood following the Module 1 Crumbler® deck, following the Module 2 Crumbler® deck, from the discharge of Unders from the screen, from the discharge of Overs from the screen, and from the Accepts. The samples were analyzed for moisture content and particle size. Table 4 provides the results from the samples that were collected. Samples were analyzed in triplicate for each data point provided in the table.

Table 4. Sample data from the Proton Power Crumbler® test.

Material Sampled	Raw Chips	After Module 1	After Module 2	Unders	Overs	Accepts	Crumbles After Drier
Moisture content (wet wt%) average (St dev)	39.2% (3.0%)	36.7% (3.5%)	39.9% (3.6%)	48.3% (5.4%)	37.7% (3.1%)	38.5% (1.98%)	4.67% (0.81%)
Mean particle size (mm) average (St dev)	20.26 mm (0.924)	6.50 mm (0.043)	5.44 mm (0.148)	0.65 mm (0.043)	7.91 mm (0.278)	5.19 mm (0.14)	
Aspect ratio (length/width)						5.0	

*Particle size is expressed as the geometric mean size per ASABE Standard 424

Material was also sent to the INL to process through a hammer mill for comparison. Approximately 1.5 tons of wood chips were dried and hammer milled at INL. The chips at INL were hammer milled using a 1/2 inch opening grate in an attempt to achieve a similar particle size. Samples from this run at the INL were also analyzed for moisture and particle size and distribution. Table 5 lists the results for the samples run on the hammer mill. Table 5 summarized the data generated during the hammer milling tests at the INL. Although we did not utilize a screen to separate out the Overs and Unders, we used the particle-size distribution data to determine the theoretical amounts that would fall into each grate-size selection. With this screen-size selection, the resulting material did not have any Overs. The mean particle size for the fines was 0.62mm, which made up 35% of the total mass. The remainder was Accepts, which was 65% of the total mass.

Table 5. Sample data from the INL Hammer Mill test.

Material Sampled	Raw Chips	Dried Chips	Unders	Overs	Accepts
Moisture content (wet wt%) average (st dev)	51.3% (2.45%)	4.88% (0.92%)	4.68% (0.37%)	na	4.68% (0.37%)
Mean particle aize (mm) average (st dev)	20.4 mm (1.18)	17.1 mm (1.02)	0.62 mm (0.026)	na	2.78 mm (0.007)
Aspect ratio (length/width)					9.1

In comparing the materials generated by the hammer mill with those generated by the Crumbler®, the geometric mean particle size for the hammer mill chips was much lower at 2.78 mm compared to the samples from the Crumbler®, which were 5.19 mm. In addition, the Crumbler® is able to generate a more uniform particle size when comparing the length and width of the particles. Samples were analyzed using a two-dimensional particle scanner, a Clemex Analyzer. This method provides a measure of the aspect ratio, which is the measure of the length divided by the width of the particles analyzed. For the crumbled chips, the aspect ratio was 5.0, meaning the particles on average were about five times as long as they were wide. This was compared to the hammer milled samples, where the aspect ratio was 9.1, indicating that the particle lengths were about 9 times longer than they are wide, on average.

Figures 5 through 10 show the particle-size distribution, cumulative particle-size distribution, and aspect ratio for the hammer milled and crumbled particles. The hammer milled samples were more heavily weighted to the smaller size with a long tail tapering off with larger sieve size, dropping off completely after 6.25 mm. The particle-size distribution for the Crumbler® samples was much more uniformly distributed and possessed a more bell shaped curve. Figures 9 and 10 compare the aspect ratios for the Crumbler® and the hammer mill samples. The hammermill typically generates particles that are longer and thinner compared to the particles generated by the Crumbler®. The result is a more flowable product coming from the Crumbler®, potentially resulting in less down time associated with conveyance issues and a more uniform conversion rate.

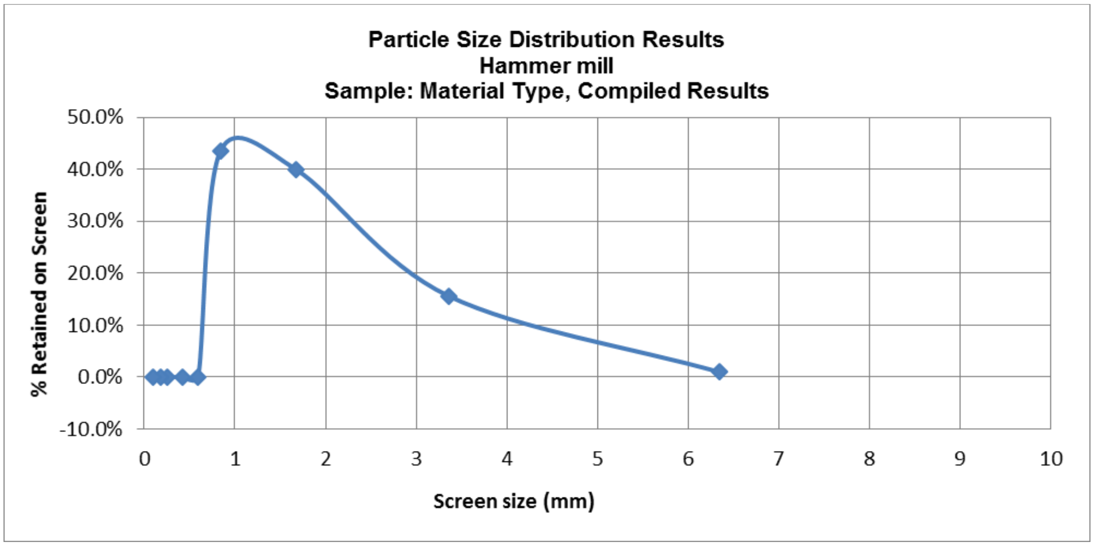

Figure 5. Particle-size distribution for hammer milled wood chips.

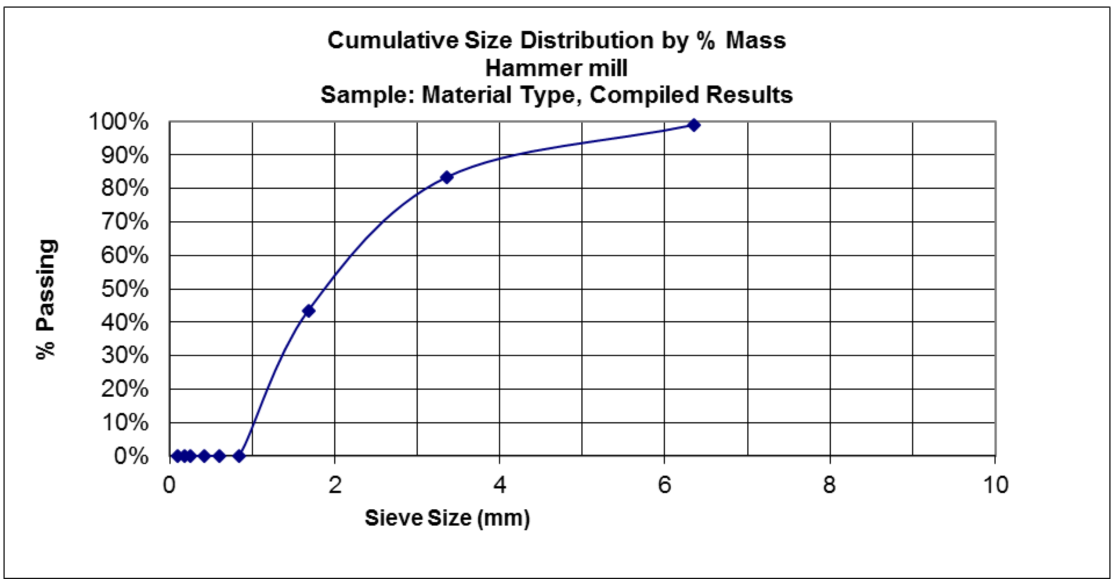

Figure 6. Cumulative particle-size distribution for hammer milled wood chips.

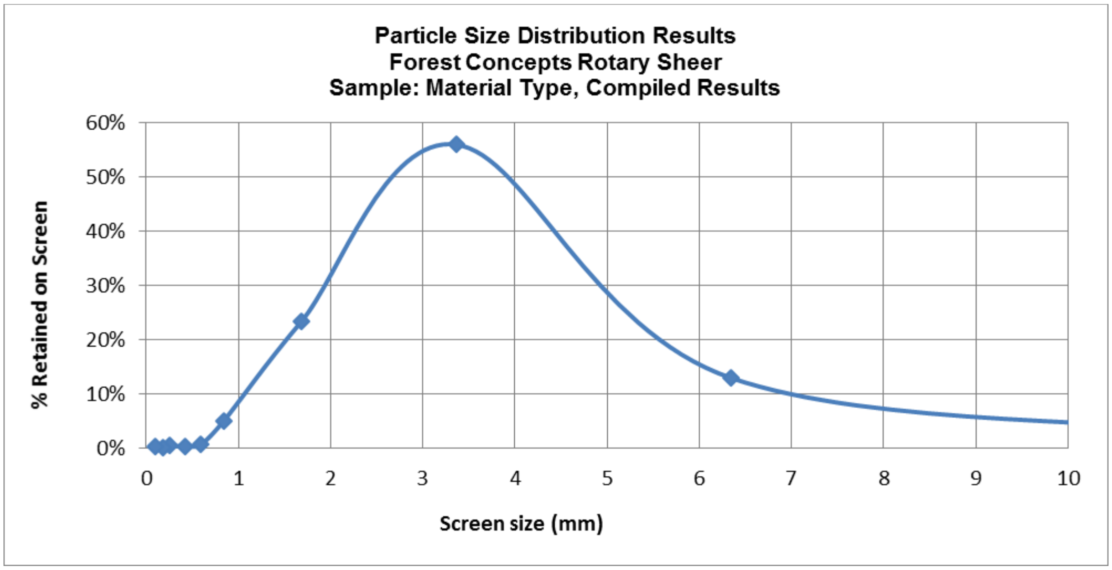

Figure 7. Particle-size distribution for Crumbles® from hardwood chips.

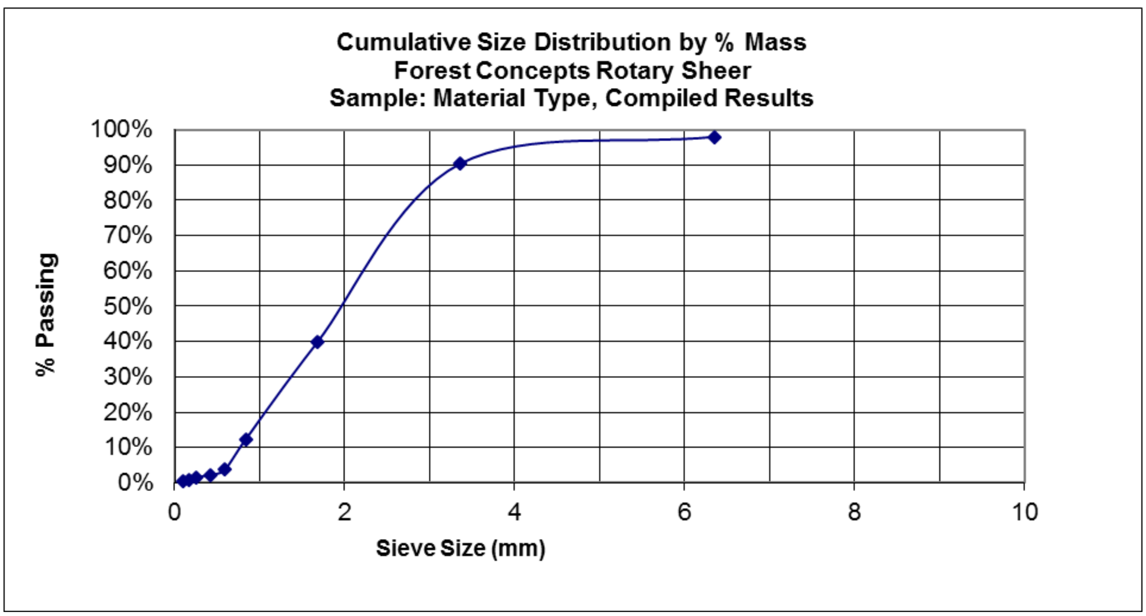

Figure 8. Cumulative particle-size distribution for Crumbles® from hardwood chips.

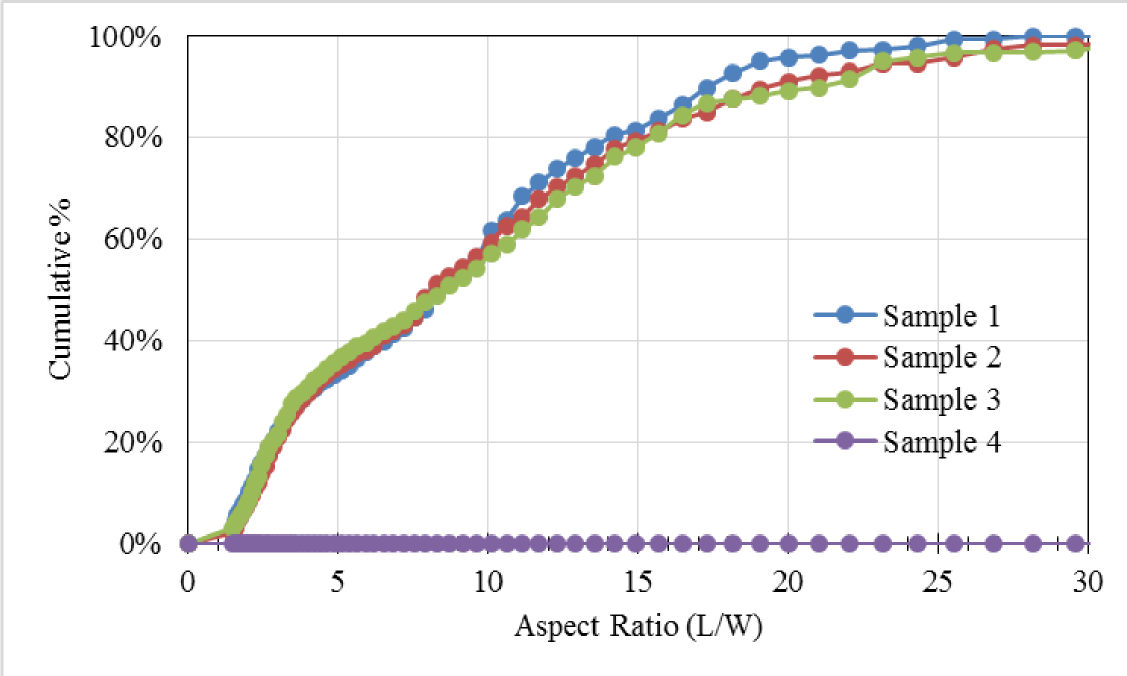

Figure 9. Aspect ratio (particle length/particle width) of hammer milled hardwood chips.

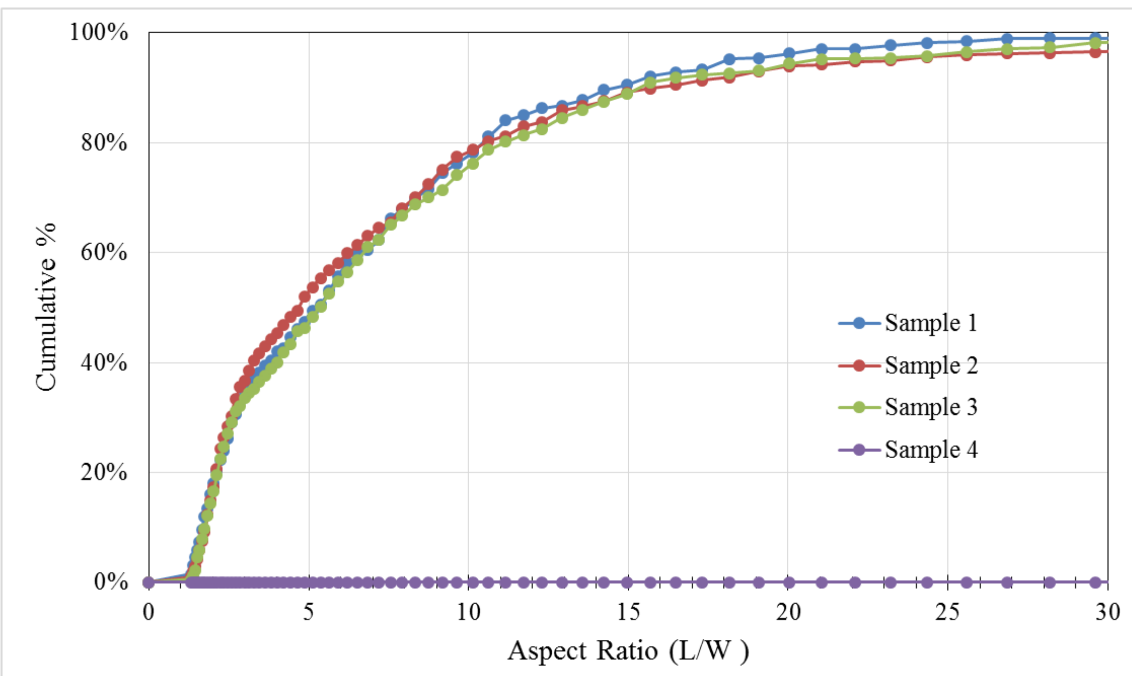

Figure 10. Aspect ratio (particle length/particle width) - Crumbles® from hardwood chips.

During the testing completed at the Proton Power pilot plant, 16.5 wet tons (9.9 dry tons) of wood chips were processed. Energy data was collected during the test and is reported in Table 6. While the energy to hammer mill dry chips (11.2 kWhr/dry ton) is less than the energy to create crumbles from wet chips (18.4 kWhr/dry ton), there is a tremendous difference between drying wet chips (2314 kWhr/dry ton) and drying wet crumbles (1220 kWhr/dry ton). The throughput through the dryer is also significantly higher for the crumbles compared to the wet chips.

Table 6. Processing data from Proton Power.

	Overall Processing Rate	Milling Energy	Drying EnergyNG/dry ton	Air handlers/Blowers (kWhr/dry ton)	Total Energy Consumed (kWhr/dryton)
Forest Concepts Crumbler®	5.51 dry ton/hour	18.4 kWhr/ dry ton	4164 SCF/dry ton (1220 kWhr/dry ton)	2.0 kWhr/ dry ton	1238 kWhr/dry ton
INL Bliss Hammer Mill	3.95 dry ton/hour	11.2 kWhr/ dry ton	7898 SCF/dry ton (2314 kWhr/dry ton)	2.0 kWhr/ dry ton	2330 kWhr/dry ton

Tables 7 and 8 provide the results from the techno-economic analysis. Because the drying cost prior to hammer milling are so much higher than the drying costs after the Crumbler®, there is significant cost savings by drying after the Crumbler® when the chip size is much lower.

Table 7. Cost summary for hammer milled hardwood chips.

Equipment	Ownership Cost ($/dry ton)	Operating Cost ($/dry ton)	Lost Material Cost ($/dry ton)	Total Cost ($/dry ton)
Dryer	$1.31	$45.39	$0.00	$46.70
Hammer mill	$0.89	$3.71	$46.17	$50.77
Conveyors	$0.05	$0.04	$0.00	$0.09
Dust Collection	$0.18	$0.66	$0.00	$0.84
Total	**$2.64**	**$49.80**	**$46.17**	**$98.40**

Table 8. Cost summary for Crumbles® from hardwood chips.

Equipment	Ownership Cost ($/dry ton)	Operating Cost ($/dry ton)	Lost Material Cost ($/dry ton)	Total Cost ($/dry ton)
Rotary Shear	$2.50	$3.32	$0.67	$6.49
Dryer	$1.31	$24.40	$0.00	$25.71
Conveyors	$0.05	$0.04	$0.00	$0.09
Dust Collection	$0.16	$0.65	$0.00	$0.81
Total	**$4.02**	**$28.41**	**$0.67**	**$33.10**

May or may not need the dust collection here.

Scaling to Reference Biorefinery

If the performance of the hammer mill comminution pathway and the rotary shear pathway is scaled to the reference biorefinery, which has a capacity of 95 dry short tons per hour (800,000 dry tons per year), the economic value of the rotary shear pathway can be further appreciated. The economic benefit of $65.30 ($98.40–33.10) per dry short ton may be as high as $52.24 million per year.

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Energy Efficiency & Renewable Energy, and Bioenergy Technologies Office Small Business Innovation Research Program under Award Number DE-SC-0010122.

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