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Research Report

Production of Corn Stover Feedstocks Using Rotary Shear Mill and Screen System

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Key Words:

Corn stover, comminution, specific energy, particle size, bulk density, preprocessing

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Abstract

Baled corn stover at 10% +/- moisture (wet-basis) was comminuted and sorted to obtain a particle size with a geometric mean diameter (Xgm) of 1.34 mm and particle size distribution to match the Idaho National Laboratory (INL) feedstock used to produce densified corn stover pellets for this project. Comminution (milling) was performed using four Forest Concepts Crumbler® rotary-shear comminution devices arranged in series with a Forest Concepts 2-deck orbital screen to remove fines and redirect oversize particles back through the system.

A total of 49 supersacks of final product were generated with an average weight of 479 dry-lbs (217 kg) per supersack. The final product had loose and tapped bulk densities of 7.61 and 9.86 and dry lb/cu.ft. respectively. The material losses in the system totaled approximately 9% of the total starting corn stover mass. Losses included dust, fines and soil from screening, and floor sweepings.

Neglecting energy consumption for sorting, total comminution system design energy was measured at 97.9 kWh/US Dry Tons. The total specific energy for comminution was measured at 73.5 kWh/US Dry Tons.

Introduction and Overview

The objective of this task was to convert baled corn stover from Iowa that had been procured by Idaho National Laboratory (INL) into rotary-shear-milled feedstocks for use throughout the project. INL arranged delivery of fourteen (14) bales of stover to Forest Concepts in late November 2017. The material arrived with moisture content below 15% (wb) so further processing and drying was not urgent. Shortly after receipt, two of the bales were processed through a 6.4mm Crumbler® P24M-150e rotary shear milling system and stored in supersacks until the final particle size was established for the entire production lot.

The original Purdue project proposal called for a comparison of the flowability, handling, and conversion performance of pelleted (densified) corn stover versus bulk material produced by Forest Concepts' rotary shear system. Conventionally milled corn stover using a debaler/shredder followed by hammer-milling results in shardy and fibrous feedstocks with very low bulk density and poor flowability. Densification into pellets improves both particle and bulk density as well has high flowability during storage and handling. In contrast, the Forest Concepts material was expected to be highly flowable in a bulk format with modest bulk density due to the lower aspect ratio particle shape that results from milling with a rotary shear instead of a hammermill.

The original Purdue proposal called for Forest Concepts to produce a nominal 4mm feedstock size which was similar to feedstock specifications used by commercial biorefineries. The Forest Concepts standard 4mm nominal size is produced by final screening with a 9.5mm (3/8-inch) round-hole top screen and a

2.4mm (3/32-inch) wire mesh bottom screen using the company's Model 2448 orbital screen system. However, preliminary results from Purdue during preparation of the proposal suggested that the Forest Concepts 4mm material reacted much slower during pretreatment and had lower chemical yield than pelleted material from INL. The performance difference could be explained by the order-of-magnitude difference in particle size (and subsequent surface area-to-volume ratio) independent of pelletization effects. In order to eliminate confounding effects of particle size, the standard Forest Concepts 2mm nominal size specification was modified so the final feedstocks would more closely match the particle size used by INL in their pelleting system.

Setting the Screen Decks for INL-Specified Particle Size Distribution (PSD)

An objective for the "DOE 8256 Purdue Flowability Project" was to compare the performance of densified corn stover pellets produced at Idaho National Laboratory to equivalent particle size rotary sheared feedstocks produced by Forest Concepts. The INL pellets were made using conventional two-stage grinding and hammer-milling. Raw hammermilled corn stover is known to have poor flowability and very low bulk density. Pelletizing increases the bulk density and flowability. The INL pellets were expected to cost more to produce but have a lower transportation and storage cost than the low-density bulk feedstock from Forest Concepts. The hypothesis was that the two materials would perform similarly during feeding and conversion. If so, then the choice of preprocessing method for a biorefinery or depot-biorefinery set would be one of transportation distance and storage systems.

Idaho National Lab processed their portion of the Iowa corn stover bales into pellets during December of 2017. They provided Forest Concepts with a particle size distribution curve for the material after milling and before pelletizing. Forest Concepts then conducted a set of small skirmish processing tests to define the cutter sets and screen decks needed to reproduce similar particle size distribution for the Forest Concepts rotary sheared and screened bulk feedstocks. Thus, feedstock particle size differences would be eliminated as a confounding factor in experiments.

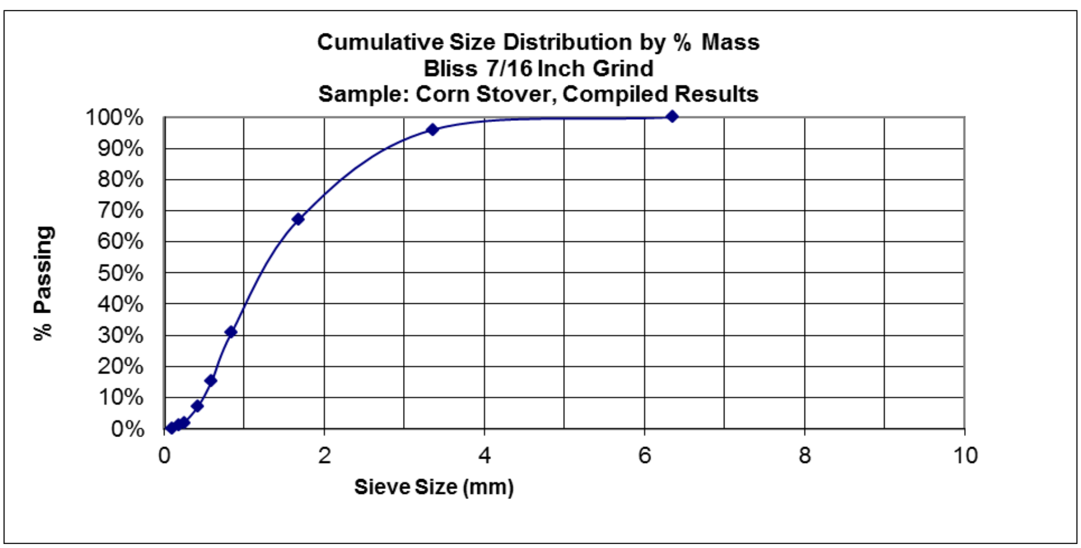

Figure 1. Particle size distribution from INL for feedstock used to make pellets.

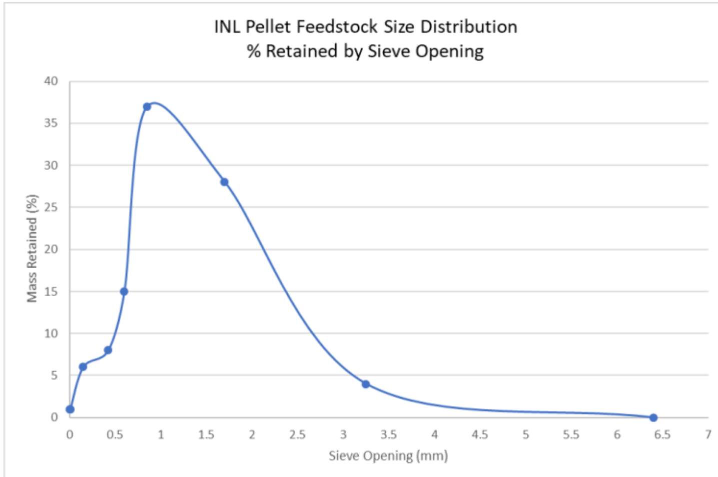

Figure 2. Particle size distribution expressed as a histogram (from INL for feedstock used to make pellets).

A round of experiments with alternative rotary-shear cutter sets and screens led to processing-equipment settings for the production run. The processing system was set to these parameters:

- Rotary-shear cutter thickness: 1.6mm (1/16 inch)
- Screen top deck: 3.2mm (1/8-inch round hole punched plate)
- Screen lower deck: 0.43mm (No. 40 wire mesh)

Production Process and Energy Results

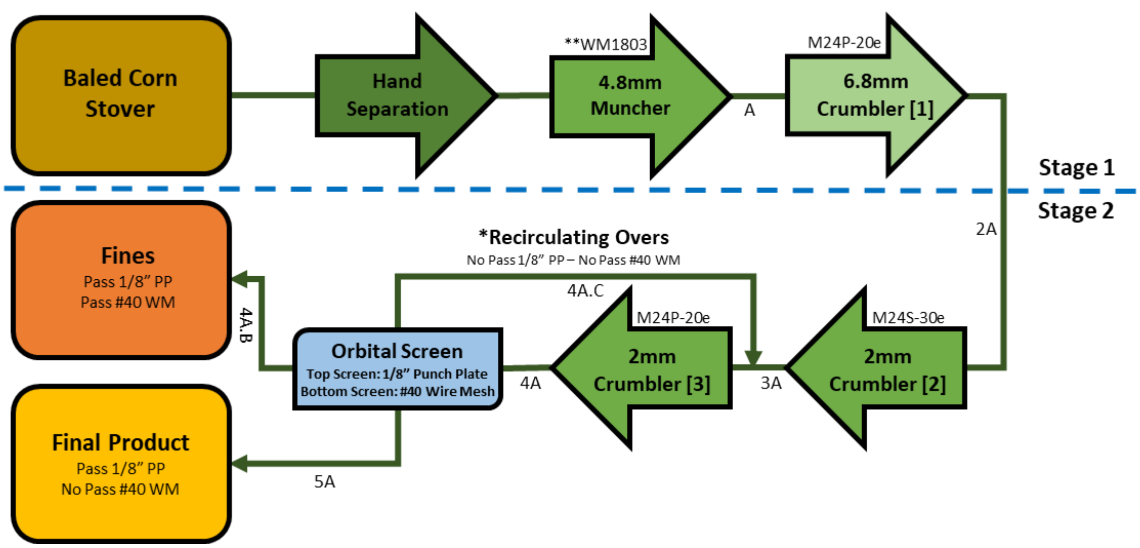

Figure 3: Corn stover comminution process. Thin dark green lines represent material conveyance between comminution or screening equipment and have ID labels (A, 2A, 3A, …, etc.) to indicate where samples for size and moisture content analysis were collected. For example: The material with sample ID 2018.05.30.001.A was collected between the 4.8mm Muncher and 6.4mm Crumbler but is only associated with the 4.8mm Muncher. *Recirculating Overs was performed during processing only. **WM1803 (Muncher) has been modified to shear material at shorter lengths by removing the anvil array.

Comminution and screening were accomplished using the Forest Concepts pilot-scale Crumbler® M24 series rotary sheer mills and a Forest Concepts 2448 orbital screen. The original intent was to use the company's commercial-scale system and mechanical debaler, but due to delay of funding the project by DOE, that system became unavailable as it was committed to another project and relocated to Tennessee. Thus, this processing was done with smaller equipment and the corn stover was debaled by hand.

As shown in Figure 3 above, first-stage comminution included hand separation and feeding onto the infeed conveyor of the 4.8mm rotary-shear Forest Concepts model WM1803 (Muncher) rotary shear, then conveyed into the 6.8mm rotary-shear M24P-20e (Crumbler [1]). The output from the first-stage system was fed into supersacks for interim storage and handling.

In Stage 2, the coarsely-milled corn stover collected from Stage 1 was fed into a series of two 2mm rotary-shear mills (models M24S-30e (Crumbler[2]) and M24P-20e (Crumbler [3] respectively. The milled corn stover was conveyed directly onto an orbital screen (Forest Concepts 2448 orbital screen) to be separated into the following three group: *Overs* (4A.C), *Fines* (4A.B), and *Final Product* (5A). During production, the *Overs* were conveyed back to the infeed of Crumbler 3 for recutting.

Baled Corn Stover

The baled corn stover was provided to Forest Concepts by INL from the same Iowa-sourced material as used by INL to produce pellet stover for the DOE Purdue project. The bale source information is included in Appendix 1. Post-harvest corn stalks were apparently chopped into sections (≤2ft in length) and baled. A total of 13 bales at 128 cu. ft each were received by Forest Concepts for comminution and screening. Upon arrival, the center of each bale was found to be discolored and likely moisture and heat affected. This phenomenon could be observed by removing the first few flakes from either side. Each bale varied in decomposition level, volume of affected region, and farm soil content. Moisture content varied from flake-to-flake with dryer material in the degraded center flakes and somewhat higher moisture at the ends of the bales (but not wet).

Hand Separation

To process the corn stover using Forest Concepts rotary-shear technology, the bales needed to be separated into small clumps with compressed thickness less than three inches. The separation was performed by two workers who allocated all their time to hand separation. Ideal separation involved rolling up each flake until fracture occurred. Once a chunk was removed from the flake, the process would repeat until clump size was suitable for feeding into the first coarse-milling rotary shear.

Figure 4: Hand separation of baled corn stover.

Comminution Energy Results

Comminution energy was measured with an automated data collection system attached to each of the comminution machines. The methods used for energy analysis are detailed in Appendix 2. Three-phase voltage and motor current were captured in real time by a LabView®-based data acquisition system. Analysis programs include automated power factor correction. As shown in the process flow diagram, the raw hand-debaled corn stover passed through a total of three (3) Crumbler® rotary-shear machines from bale to final product. The results below represent the average of three data collection runs for each machine. The energy consumption for each machine was measured in sequence with run-times ranging from 65 to 180 seconds per observation. The oven dry mass processed in each run was measured so that energy consumed per unit mass processed could be calculated. Biomass moisture content was measured to be 13% (wb) across the experiment.

Comminution energy is reported on an *oven dry infeed mass basis* into the machine(s). When used for facility planning, technoeconomic analysis, or Life Cycle Inventory, the comminution energy may need to be converted to an *outfeed mass basis* of final product passed on to the next unit operation.

4.8mm Muncher – 1st Cut

First-stage comminution was performed using a rotary-shear Forest Concepts Wood Muncher (WM1803) with 4.8mm cutters. Energy consumption was measured over 4.55 minutes of processing 52.3 odkg (115.3 dry lb) of hand separated corn stover. The design energy was found to be 36.9 MJ/odMg (9.3 kWh/US Dry Ton) with a specific energy of 21.0 MJ/odMg (5.3 kWh/US Dry Ton).

6.4mm Crumbler [1] – 2nd Cut

A second cut at large size was used to improve the flowability of the debaled stover by reducing particle length without affecting particle cross-section. The second cutting step was performed using a rotary-shear Crumbler (M24P-20e) with 6.4mm cutters. Energy consumption was measured over 4.26 minutes of processing 38.6 odkg (85.1 dry lbs) of hand separated corn stover. The design energy was found to be 20.5 MJ/odMg (5.16 kWh/US Dry Ton) with a specific energy of 6.0 MJ/odMg (1.5 kWh/US Dry Ton). Since the particle size was not materially reduced, the second cutting consumed relatively little energy.

2mm Crumbler [2] – 3rd Cut

After first-stage coarse processing, the cutter heads in the Crumbler® rotary-shear machines were replaced with heads having thinner 2mm cutter width. To be consistent with nomenclature used by INL, we call this processing "second stage." The first step in second-stage comminution was performed using a rotary-shear Crumbler (M24S-30e) with 2mm cutters. Energy consumption was measured over 8.1 minutes of processing 74.8 odkg (164.9 dry lbs) of corn stover. The design energy was found to be 96.1 MJ/odMg (24.2 kWh/US Dry Ton) with a specific energy of 82.8 MJ/odMg (20.9 kWh/US Dry Ton).

2mm Crumbler [3] – 4th Cut with Recirculation

The final step of comminution was performed using a second rotary-shear Crumbler (M24P-20e), also with 2mm cutters. The energy required from the 2mm Crumbler [3] included the additional processing energy of comminuting particles that were unable to pass through a 1/8" punch-plate orbital screen after all four comminution processes had occurred. This method is described as *recirculation* and is shown in Figure 3. Recirculation was performed during steady-state processing only and not during energy measurement experiments. The additional energy required for recutting the overs was determined using orbital screening fractions, measured comminution energy, and total mass in the system. The simulated recirculation energy is included in the results below.

Energy consumption was measured over 8.1 minutes of processing 74.8 odkg (164.9 dry lbs) of corn stover. The design energy was found to be 235.3 MJ/odMg (59.3 kWh/US Dry Ton) with a specific energy of 181.8 MJ/odMg (45.8 kWh/US Dry Ton).

Combined Comminution Energy Results

Table 1: Comminution Energy Results

Machine	Specific Energy (kWh/US Dry Tons)	Total Design Energy (kWh/US Dry Tons)
4.8mm Muncher	5.3	9.3
6.4mm Crumbler [1]	1.5	5.2
2mm Crumbler [2]	20.9	24.2
2mm Crumbler [3] with Recirculating Overs	45.8	59.3
Total:	**73.5**	97.9

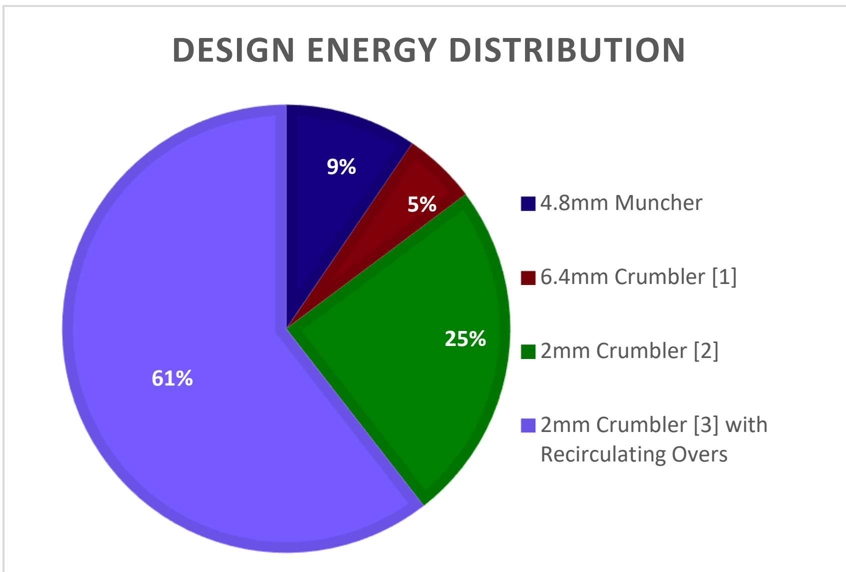

Figure 5: Distribution of comminution energy across the four rotary shear machines.

Neglecting energy consumption for conveyors and screens, total comminution system design energy was measured at 97.9 kWh/US Dry Tons. The total specific energy for comminution was measured at 73.5 kWh/US Dry Tons.

Separation of Fines, Final Product, and Overs

A two-deck orbital screen was used to separate particles into three size groups: Fines, Final Product, and Overs. Particles unable to pass through a 1/8" punch-plate deck (Overs) would be conveyed back through Crumbler [3] for reprocessing. This method is described as *recirculation* shown in Figure 3. Recirculation was performed during steady state processing and was not performed during energy measurement experiments.

Physical Properties and Yield Results

A key attribute and benefit of the Forest Concepts Crumbler® rotary-shear preprocessing system is its ability to produce uniform feedstocks having a narrow size distribution and controlled low aspect ratio. Plant-based biomass such as wood chips, switchgrass, and corn stover have strong fibers and fiber bundles that are oriented parallel to the stem or stalk length. While wood chips have a fiber bundle length of 2-10mm, corn stover has a fiber bundle length that extends 50-150mm from node to node in the stalk. In the Forest Concepts rotary shear equipment, particles or stem pieces that pass through the cutter head perpendicular to grain have their fibers sheared to the cutter width (2mm in this case). Particles and pieces that happen to pass through the cutter head parallel to grain are simply slit into long shards equal to the length of the piece and the fibers are not cut. Random orientation is more likely in a mass flow which results in a wide range of particle lengths along the grain.

Single-pass comminution with the Forest Concepts rotary shear equipment ensures that one dimension of each resulting particle is at or near the cutter width. While that control is important for subsequent heat transfer, diffusion, etc. during conversion, it does not improve material handling and flowability. Thus, the standard protocol at Forest Concepts is to "cascade" biomass through a sequence of rotary shear units to ensure that all particles are eventually cross-cut to a length that provides high flowability as well as optimal reactivity.

To minimize the number of rotary shear machines in a system, a carefully selected punched plate screen deck is installed in the orbital screen to remove over-length particles for recirculation back upstream of the mills. Thus, although random probability may result in any particular particle passing through the cutters many times essentially parallel to grain, eventually it will be crosscut such that it will pass through the screen deck into the *Final Product* stream. As noted earlier the final stage of processing included these settings:

- Rotary-shear cutter thickness: 1.6mm (1/16 inch)
- Screen top deck: 3.2mm (1/8-inch round hole punched plate)
- Screen lower deck: 0.43mm (No. 40 wire mesh)

Material retained on the top deck was recirculated; material passing the lower deck was discarded as fines; and material retained above the lower deck was conveyed to supersacks as final product accepts.

Mass Yield Results Within the Processing System and Overall Mass Yield

During the energy data collection process, timed samples were collected from the screen outfeed chutes. That material was weighed and averaged across all observations to produce the pie chart blow. At any time in the processing operation, approximately 46% of the mass is leaves the screening system as accepts in the Final Product classification.

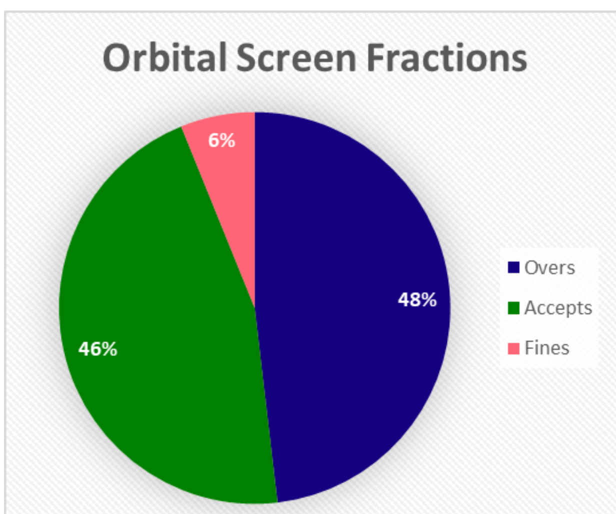

Figure 6: Mass allocations during processing based on screen output fractions. Overs are recirculated.

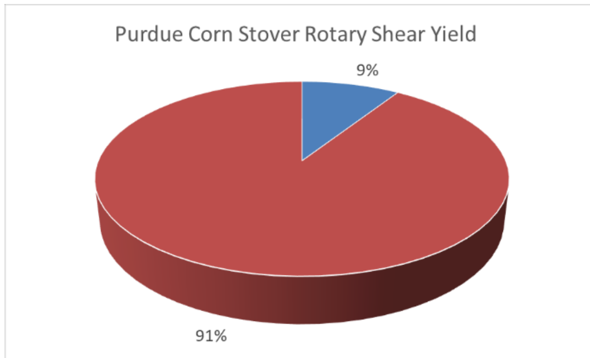

Figure 7: Total processing run yield of accepts final product and fines.

All the supersacks produced were weighed and all fines from screening, floor sweepings, and dust from dust collectors were weighed to estimate the final mass yield from milling. Additional minor losses from fugitive dust and uncollected sweepings are not accounted for. It is important to note that the fines fraction includes both soil and fine organic particles. We did not measure ash content in any fraction as that was to be part of the characterization work by others.

Final Product Particle Size Distribution, Moisture Content, and Bulk Density

The standard practice at Forest Concepts is to collect a "quality assurance" sample of approximately 2kg from the midpoint of each supersack of product produced. That sample is evaluated for moisture content, particle size distribution, and bulk density.

- Moisture content was measured with an Arizona Instruments Computrac Max4000XL rapid moisture analyzer.
- Particle size distribution was measured with a 300mm diameter sieve stack on a Gilson tapping sieve unit.
- Bulk density (loose and tapped) was measured using ISO standard containers with approximately 1-liter capacity.

Particle Size Distribution Results

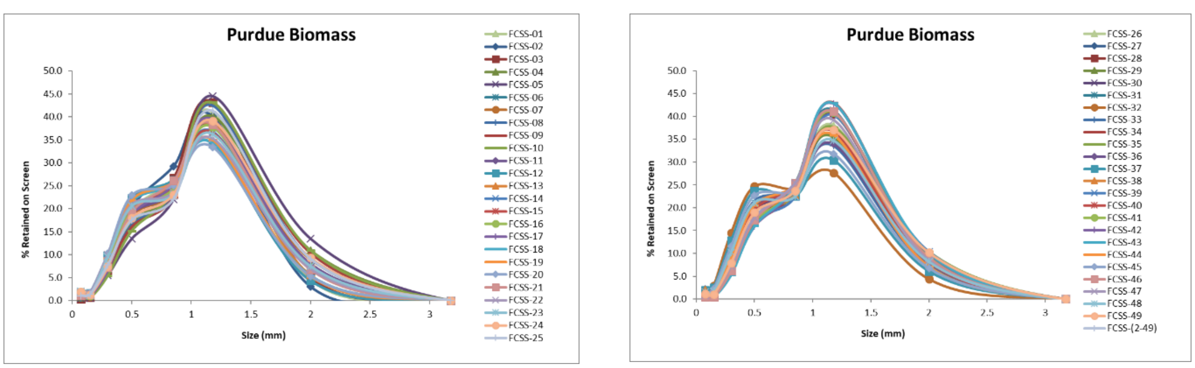

Figure 8: Particle size distribution curves for supersacks 1-25 (left) and 26-49 (right). Note the apparent plateau in the curves is an artifact of the opening sizes of sequential screens in the sieve stack.

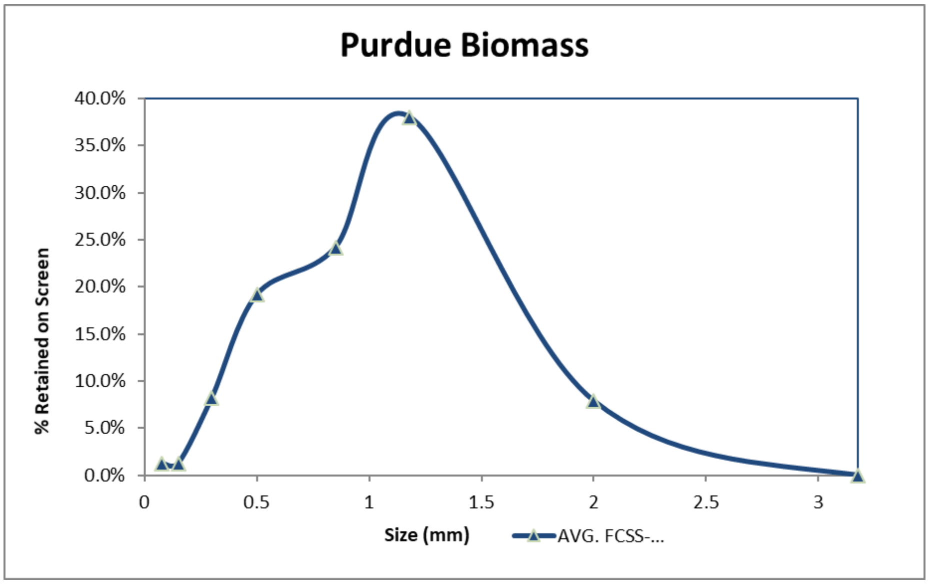

Figure 9: Average particle size values across all supersacks.

Table 2. Summary of particle size data. (Note the term FCSS relates to the labeling of each supersack.)

Purdue Biomass				
Sieve Size	Sieve Size (mm)	FCSS-(1-25)	FCSS-(26-49)	**AVG. FCSS-(1-49)**
3/8 inch	9.53	0.0%	0.0%	**0.0%**
No. 4	4.75	0.0%	0.0%	**0.0%**
1/8 inch	3.175	0.0%	0.0%	**0.0%**
No.10	2	7.4%	8.4%	**7.9%**
No.16	1.18	38.8%	37.3%	**38.0%**
No 20	0.85	24.5%	23.9%	**24.2%**
No 35	0.5	19.0%	19.3%	**19.2%**
No 50	0.3	7.9%	8.5%	**8.2%**
No 100	0.15	1.1%	1.3%	**1.2%**
Pan	0.075	1.2%	1.3%	**1.3%**

Table 3. Summary particle size metrics

Purdue Biomass	FCSS-(1-25)	FCSS-(26-49)	**AVG. FCSS-(1-49)**
Particle Size (Xgm, mm)	1.47	1.45	1.46
D(50)	1.84	1.82	1.83
Sgm	1.77	1.80	1.78
Span	1.25	1.29	1.27

Table 3 above summarizes the particles size in three common metrics. The geometric mean particle size (X_{gm}) and standard deviation of the geometric mean are calculated in accordance with ASABE Standard S424. Other engineering fields often use the D(50) value as the mean particle size and span to portray a sense of the breadth of the particle size distribution.

Bulk Density Results

Bulk density was measured using ISO standard containers and Forest Concepts' adaptation of the standard protocols. Loose and tapped bulk density were measured in duplicate and then the Hausner Index (an indicator of flowability) was calculated as the ratio of tapped density divided by loose density.

Table 4. Summary loose and tapped bulk density (kg/m^3) and Hausner Ratio.

Purdue Biomass		FCSS-(1-25)	FCSS-(26-49)	**AVG. FCSS-(1-49)**
Bulk Density at Tested MC (kg/m3)				
	Tapped	176	174	175
Bulk Density of Dry Matter (odkg/m3)				
	Loose	122	121	122
	Tapped	158	157	158
Hausner Ratio (Tapped/Loose)		1.3	1.3	1.3

Appendices:

Appendix 1:

Bale Source Data Sheet from Idaho National Laboratory

Feedstock:__Corn Stover Bales____

State:__Iowa____

County:__Poweshiek____

GPS Coordinates:__41.83 latitude/-92.59 longitude____

Field Size:__380 Ac____

Species:__Corn____

Cultivar / Variety:_ Pioneer P0157 AMX____

Date Harvested:__9/18/17____

Date Raked:__10/11/17____

Date Baled:__10/12/17____

Harvest Equipment: (Cut/Swathe/Bale/ect):_Hiniker shredder__, _Heston 2270XD baler__, _________

Cut Height:__4"____

Bale Size/Shape:_3ft x 4ft x 8ft____

%Moisture at Harvest:__23%____

Biomass Yield:_2ton/Acre____

Storage Methods: field edge stacked -t he stacks are not tarped and the mega stacks are in a stairstep like pyramid & the smaller stacks are just in rectangular stacks._______________________________

Comments (e.g., slope, drainage, etc. from where the bale was harvested):___2% slope_________

Appendix 2:

Comminution Energy Test Methods

The amount of energy consumed during comminution of biomass is a significant contributor to the cost for reactor-ready feedstocks. Energy consumption is typically reported on an "energy per unit mass" basis. Unfortunately, it is often unclear whether the amount of reported energy is the specific energy used in comminution, total energy consumed by a research-scale device used in experiments, or the projected total connected design energy of commercially relevant comminution machines.

The mass side of energy reporting is also a source of uncertainty. Many researchers report energy consumption in terms of the measured output mass at the as-processed moisture content, which could be anywhere from 10% to 50% on a wet basis (wb). This can greatly misrepresent energy consumption per unit dry matter when mass is reported as wet compared to dry. The preferred method for reporting energy consumption is to normalize the data to the "oven dry mass" regardless of the as-processed moisture content during experiments. An example of a mass normalized energy unit is mega joules per oven dry mega-gram (MJ/odMg). Multiplying the energy by the mass-flow rate then gives the power consumption in units such as kilowatts or horsepower.

Mass Measurement and Normalization

Forest Concepts follows a practice of measuring the actual mass at the outfeed from comminution equipment during energy experiments and then determining the as-processed moisture content. A sample of the outfeed material is either oven-dried with 50-500 gram samples or tested in a rapid moisture analyzer (Arizona Instruments Computrac® Max 4000XL) with 5-10 gram samples following standard protocols to determine the oven dry mass of the material processed. The mass flow rate during processing is then stated in terms of oven dry mass such as oven dry mega-grams per unit time (e.g. odMg/hour).

Total Energy (Measured)

Total energy is a value defined as the measured connected electrical load energy input into an actual machine used to conduct an energy consumption experiment. Total energy is expressed in terms of the unit mass of material processed. Total energy is important because it is the most directly measurable energy value from which specific and total connected design energy are calculated.

While measuring the electrical feed to a processing device, it is important to be aware that total energy to get the mechanical power output must be adjusted for the power factor. When processing biomass at partial load, total energy will be overstated if the only measurements are voltage and amperage. Power measurement must include volts, amps, and phase angle when the machine is powered by an electric motor. An extensive discussion of power measurement and calculation is included in an ASABE paper published in 2011 (Lanning, Dooley et al. 2011).

Forest Concepts' normal method to obtain energy data is to use a LabView® data acquisition system with appropriate voltage and current sensors attached to all legs of the power source. A sampling frequency of 960 hertz (hz) enables determination of the phase angle in 60 hz AC systems and detect small variations and spikes in motor loading to enable automated power factor correction.

$$E_T = \frac{\sum\left[(Instantaneous\ power) \times \left(\frac{1}{Sampling\ frequency}\right)\right]}{Oven\ dry\ mass\ at\ outfeed}$$

Equation 1: Measured Total Energy (E_T)

A limitation of the total energy method is that the reported energy consumption includes both the specific energy used in actual processing and the drive train energy due to friction in the motor, gearboxes, belts, chains, and the like. While the actual processing energy is expected to directly relate to biomass feed rates, the drive train energy (also called no-load energy) tends to be constant and essentially independent of biomass loading rate. Total energy is thus dependent on machine feed rates and does not scale well from laboratory experiments to commercial-scale well-designed machine systems.

An example may help readers to understand the implications of total energy measured across a range of machine loading rates. There is a minimum amount of energy consumed in operating a particular machine for a set period of time, even if no material is processed. This is called the no-load power for the machine. Recall that energy per time or energy flow rate is the definition of power. Now imagine measuring the energy consumed to operate the machine at 30% throughput capacity for a period of time. During another experiment, the energy consumed to operate the machine at 80% throughput capacity is measured for the same period of time. Since total energy is reported on a per unit mass basis, and more material is processed at 80% capacity for the set time period, the no-load energy is divided over a larger quantity of material than when processing at 30% capacity and therefore, the 80% capacity experiment results indicate less total energy consumed per unit mass.

Specific Energy (Calculated)

Specific energy can be conceptualized as the amount of energy that is consumed per unit mass of the process beyond that which is required to operate the machine with no material. It is the energy that goes into the material. This includes all energy expended in reducing the size of the material, raising the temperature of the material, particle friction, or changing the material's moisture content but does not include drivetrain losses, bearing friction, or motor inefficiencies.

Specific energy is a critical design value as it is scalable. It can be used to determine the energy requirements for both large and small-scale operations. This value can also be compared to other processes regardless of machine type, quantity, or mass flow rate of material processed.

Specific energy can be measured by connecting a torque-meter and tachometer between the drive system and the actual comminution device (hammer mill rotor, rotary shear input shaft, knife mill input shaft, etc.). Methods for torque-based measurement are detailed in Lanning, Dooley, et. al. (2011).

Specific energy is often calculated from measurements of the connected electrical load energy prior to processing biomass (no-load energy) and during processing of the biomass (total measured energy, as described above). Subtraction of the no-load from the total during processing yields a reasonable estimate of the specific energy, provided changes in power factor and other drive efficiencies are accounted for.

$$E_S = \frac{\sum\left[(Instantaneous\ power - Avg.\ no\ load\ power) \times \left(\frac{1}{Sampling\ frequency}\right)\right]}{Ovendry\ mass\ at\ outfeed}$$

Equation 2: Specific Energy (E_S)

Total Connected Design Energy (Calculated)

The total connected power (total energy multiplied by mass flow rate), or the total power needed at a machine including inefficiencies, is a critical value for scaled plant design. Because total energy is highly dependent on material flow rate and machine optimization, the directly measured value from lab experiments is not particularly useful for the design of a processing facility, yet some metric of total energy is needed to determine the total power required.

As noted, specific energy is scalable. As such, Forest Concepts uses a specific-to-total energy or "S/T ratio" to estimate a well-designed plant's total connected design electrical energy load from experimentally derived specific energy according to Equation 3. The following equations add estimated drivetrain and motor inefficiencies to the specific energy in order to calculate a design value for commercial-scale processing facilities.

$$E_{TCD} = \frac{E_S}{S/T\,ratio}$$

Equation 3: Total Connected Design Energy (E_{TCD})

$$P_{TCD} = E_{TCD} * Mass\ Flow\ Rate$$

Equation 4: Total Connected Design Power (P_{TCD})

The value of the S/T ratio is determined based on experience and is specific to a machine configuration and power source (electric, hydraulic, direct-drive, geared, pneumatic, etc.). A specific hammermill may not have the same S/T ratio as a rotary shearing Crumbler machine or a screen. For reference, when fully and continuously loaded, the Crumbler M24 routinely demonstrates an S/T ratio of 70% to 85%. As such, a reasonable S/T ratio value for the Crumbler machine is 75% for an at-scale production facility with continuous operation. All total connected design energies and powers reported in this document assume an S/T ratio of 75%.