

## Woody biomass size reduction with selective material orientation

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**Background:** Roundwood logs from forests and energy plantations must be chipped, ground, or otherwise comminuted into small particles prior to conversion to solid or liquid biofuels. **Results & discussion:** Rotary veneer followed by cross-grain shearing is demonstrated to be a novel and low energy consuming method for primary breakdown of logs into a raw material having high transport and storage density. Processing of high-moisture raw logs into 2.5–4.2-mm particles prior to drying or conversion consumes less than 20% of the energy required for achieving similar particle size with hammer mills, while producing a more uniform particle shape and size. **Conclusion:** Energy savings from the proposed method may reduce the comminution cost of woody feedstocks by more than half.

Size reduction, or **comminution**, is a fundamental processing step for lignocellulosic biomass feedstocks used as a raw material for production of liquid transportation fuels (ethanol, butanol, biodiesel, biocrude and so on), solid biofuels and biobased products. The predominant methods for comminution include rotary hammer mills, chippers and grinders of various designs. The attraction of such mass-flow comminution equipment is that they have high throughput and accommodate a wide range of feedstock forms. Major limitations for all these methods include high production of dust, excess production of overly fine materials, high power consumption and broad random distribution of particle sizes. A less-recognized limitation is that resulting particles tend to have a high length-to-width:thickness ratio that negatively affects conversion efficiency and makes handling difficult. For many uses, the resulting material must be further processed by additional comminution equipment for second-stage grinding to a more optimal particle size.

The engineering team involved in this project took a ‘clean sheet’ approach to the problem of comminution using the appreciative design process [1,2]. The design process began with a solution-neutral characterization of both the raw log materials and user-specified feedstock

physical properties. Fundamentals of structural biology and wood failure mechanics were modeled to establish a theoretical minimum comminution energy target. Functional elements of supply chain and material handling systems established additional functional requirements and constraints. Ideation and constraints were applied to seek processing solutions that maximized the utility and minimized invested energy. Potential design solutions were tested using models or logic processes to determine how close they could come to maximum utility and theoretical minimum energy consumption. The novel veneer and rotary shear technology presented in this paper is a product of this design process employed at Forest Concepts, LLC (WA, USA).

There are several biological and structural properties of cellulosic biomass that affect the amount of energy required for comminution. It is axiomatic that lower energy comminution processes can be developed by working with these properties rather than in opposition to them. Important wood properties affecting comminution energy include:

- Wood and other lignocellulosic plant materials have orthotropic mechanical properties that vary greatly

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## Key terms

**Comminution:** Breaking, chopping, grinding or other milling of larger objects into smaller particles.

**Grain:** Predominant direction in which wood fibers are aligned in a log or resulting particle. In conifers, the grain direction is parallel with the stem of the tree.

**Specific energy:** Actual work energy that goes into an activity net of mechanical drive inefficiencies, electrical power factor losses and friction. For the purposes of this article, specific energy is expressed as megajoules per oven dry megagram.

**Industrial-grade veneer:** Classification of wood veneer allowing for higher surface roughness, less appearance grading and higher volumetric yields than structural grades to produce raw materials for nonpanel products such as biofuel feedstocks, erosion control materials, composite beams and others.

**Rotary veneer:** Veneer peeled from a round log by turning the log about its axis against a knife to produce a continuous sheet of wood of a uniform thickness.

**Solid volume ratio:** Ratio of the volume of a material to the volume that a bulk quantity of the same material would occupy including void space between particles, pieces and the like.

depending on particle orientation with respect to its **grain** direction [3];

- Cellulosic feedstocks, including wood, stalks of corn or switchgrass, and similar materials are composed of fibers that align with the stem of the plant. Cutting fibers across grain consumes much more energy than slicing or cutting parallel to the grain;

- Fibers have finite length that is a function of the genetics of particular plant types, species and cultivars. Grinding with the grain, wet milling or crushing with a differential velocity device will tend to separate fibers without cutting cross-grain, again reducing the energy;

- In most chemical processes, including acid hydrolysis, enzymatic pretreatment, steam explosion and chemical digestion, the rate of reaction is a function of the diffusion distance from surface of a particle to the center and the pathway length along an intact vascular structure to cleanly cut ends of a particle. Thus, expending high amounts of energy to grind feedstocks to a fine powder

may not be necessary, provided that the material is reduced to an appropriate thickness and has a sheared or broken particle length that opens the end grain;

- In thermochemical conversion the prevailing wisdom is that heat transfer to the center of a particle is predominantly from the side faces into the center, while the gas escape is through the ends of the particle [4]. The heat transfer rate from the sides of a particle is substantially less than the gas flow rate out the ends of a particle. Thus, higher length to thickness particles may be more optimal for thermochemical conversion than for biochemical conversion;
- Moisture content (MC) is inversely related to cutting energy when shearing [5]. Drier materials take more energy to shear than moist materials. Thus, milling at higher moisture before drying, if needed, will consume less energy. Note that hammer mills take advantage of shattering that occurs at very low MC. Therefore, hammer-milling energy consumption tends to be more directly related to MC.

Woody biomass is expected to provide a significant amount of cellulosic biomass to second-generation

biorefineries [6]. Wood is typically transported from forests and plantations in either roundwood logs or in chip form. Transport in log form consumes only the fossil fuel used in transport, while in-woods chipping requires an additional 30–50 megajoules per oven dry megagram (MJ/Mg) for converting raw logs into chips [7,8]. Both logs and chips are transported in specialized trucks or trailers, which are unsuitable as back-haul carriers, making long-haul transport increasingly expensive.

Wood must be mechanically processed into particle sizes and shapes that meet the feedstock specifications of each conversion process. When raw logs are delivered to a biorefinery or preprocessing center, they are typically chipped, dried and then ground to particle sizes appropriate for the intended end-use process. In the case of raw logs, chipping in the field typically uses fossil fuel-powered mobile equipment, while fixed location industrial chipping at a power plant or biorefinery typically uses electrically powered equipment. The subsequent milling of chips into feedstocks is identical for each pathway. Miao and colleagues at the University of Illinois (IL, USA) measured the **specific energy** for comminution of several biomass materials including willow wood into a range of particle sizes [9]. The willow was processed by a Vermeer chipper to create raw material and then milled by knife or hammer mill to final screen size. Energy requirement to regrind willow chips to 1-mm size consumed more than 2100 kJ/kg (2100 MJ/Mg) and to regrind to 6-mm size consumed somewhat more than 200 MJ/Mg.

The object of this paper is to introduce and explore the concept of **industrial-grade veneer** as the first breakdown product from raw logs. Veneer making is a centuries-old process that is most often associated with the manufacture of toothpicks, match sticks and plywood [10]. The advantages of veneer as the primary breakdown product from small logs rather than chips include:

- Veneer has a high transport density on trucks or rail. This enables cost-effective delivery to more distant users;
- Shipping on common flatbed trailers or rail cars rather than specialized chip haulers is practical with veneer;
- Veneer controls one dimension (thickness) of secondary products, thus reducing the complexity of further processing the material into precision feedstocks or value-added products;
- Veneer sheets from **rotary veneer** lathes maintain the fiber orientation of a log with the grain direction across the sheet [11];

- Palletizing or unitizing veneer sheets for handling, storage and feeding into subsequent processes is relatively easy;
- Veneer manufacturing is a very low-energy process for primary breakdown of roundwood.

Unlike logs or chips, veneer can be transported on conventional flatbed trucks, trailers and railcars. Log trucks typically have a **solid volume ratio** of approximately 0.7, which suggests a maximum volumetric payload of approximately 350 kg/m<sup>3</sup> on a dry weight basis. In contrast, green veneer has a solid volume ratio of 1.0 (no void space), resulting in a transport and storage bulk density greater than 500 kg/m<sup>3</sup>, which maximizes the payload on all commercial forms of transport. The use of conventional modes of transport (flatbed truck/trailer, rail, barge and so on) significantly increases the economical transport distance between a veneer producer and a woody feedstock end user. Banded stacks (also known as units) of veneer are readily handled by forklifts further reducing the cost of storage and handling.

The conversion of log into continuous bands of rotary veneer consumes little energy since the veneer knife slices the log parallel-to-grain in a motion much like peeling an apple [12]. In a production facility, continuous bands of veneer from a log are clipped parallel-to-grain into individual sheets for stacking and banding into handling units. Again, the clipping action is low energy since it cuts predominantly parallel-to-grain.

A major innovation that was developed as part of the project being summarized here is a method to process sheets of veneer cross-grain through a large paper shredder-like rotary shearing machine developed by Forest Concepts. The rotary shear machine consists of a pair of driven shafts upon which can be stacked intermeshed sets of cutter wheels. The width of each cutter wheel determines the length along the grain of particles sheared from sheets of veneer. A biomass feedstocks producer would have sets of cutters for each particle length desired by end users. Typical cutter widths range from 1.5 to 10 mm to produce a full range of particle sizes desired for biochemical, thermochemical and densified solid biofuel products. In many cases the thickness of veneer produced from a lathe is specified to correspond with a rotary shear cutter set to produce essentially cubic wood particles.

Our theories about how wood structural properties and natural modes of failure relate to shearing forces and energy were described by Lanning *et al.* [13]. An object of the project discussed in this paper was to further refine our mathematical models to include experimentally derived data from a purpose-built laboratory-scale instrumented rotary bypass shear (also known as a Crumbler™ machine). We conducted more than 30 experiments with veneer cut parallel-to-grain and

cross-grain to develop shear force and energy relationships. The experiments reported in this paper relate comminution energy to grain orientation and nominal particle size.

### Experimental

We built a laboratory rotary bypass shear based on the engineering used for our WoodStraw® production machinery [14]. Our laboratory Crumbler device was designed to accept samples up to 16-mm thick, 130-mm wide and 1-m long. The cutting head was mounted on a pivot that was aligned with the drive mechanism so that we could directly measure torque going to the head itself. Direct torque measurements enabled us to quantify specific energy for comminution and measure forces acting on the samples being processed. The cutters were approximately 100-mm diameter and either 2-, 3- or 4.8-mm thickness. Cutters could be stacked to cut other particle lengths up to 16 mm. The experimental apparatus is shown in Figure 1.

The laboratory Crumbler processing head and infeed chute were mounted to the drive frame on a gimbaled support that is coaxial with the cutting head to enable direct measurement of torque driving the head. Driving torque was measured with a linear force transducer and the data was collected and analyzed using LabView™ data acquisition software, as detailed in a previous manuscript [15]. The time to process each test strip was combined with mean torque to calculate specific cutting



**Figure 1. Forest Concepts laboratory Crumbler™ showing the infeed chute and feedstock particles in collection tray.** Reproduced with permission from Forest Concepts © Forest Concepts, LLC.

energy for each sample and run. Energy data was analyzed using a proprietary Microsoft Excel® workbook that enabled calculation of the no-load energy, loaded energy and then application of those values to both the green and oven dry mass of a sample to compute the specific energy consumption in MJ/Mg.

The rotary veneer used in these experiments was commercially procured from CIPA Lumber Co Ltd (Delta, USA) and is designated as 'paralam' grade 1/10 and 1/6, representing the nominal veneer thickness in inches (nominally 2.5 and 4.2 mm).

The typical cross-grain comminution experimental process was to select reasonably clear sheets of veneer having a desired thickness, cut the veneer into strips approximately 130 mm along the grain to fit into our laboratory Crumbler rotary shear machine, and then feed the strips into the rotary shear. For experiments to determine the energy parallel-to-grain, the raw veneer sheets were cut parallel-to-grain into 130-mm wide strips and then cross-cut to 1-m lengths.

Prior to feeding each strip into the rotary shear, the thickness, length and width of the strip were measured at multiple locations, and the mass was measured. A subsample of strips was dried to determine MC for a production set. MC of veneer and comminuted particles was determined using a laboratory oven set at 105°C following the American Society of Agricultural Biological Engineers standard protocol [16]. All MCs are reported on a wet-weight basis (wb).

A replicated experiment (two-to-six runs per test) was conducted with fresh green Douglas fir (*Pseudotsuga menziesii*) wood that included two material thicknesses and two MCs. The comminution was performed with 4.8-mm width cutters (cutter width creates finished particle length) using the Forest Concepts laboratory Crumbler rotary shear machine. The 4.8-mm long wood particles are shown in Figure 2. The resulting large dataset was analyzed to determine cutting forces and specific energy consumption as a function of mass processed, shear area of the cutting zone, material thickness and particle size. The emphasis of this report is on specific energy per unit mass processed for each of two particle sizes since that data is most relevant to practitioners attending the US Department of Energy (DOE) Biomass Workshop where this information was reported and to those designing biomass processing facilities.

## Results & discussion

Comminution energy measurements are important for the design of mechanical processing equipment and for sustainability/life cycle assessments in the biofuels industry. These results can also be used in developing mathematical models to estimate the comminution energy for particles of various target dimensions with respect to grain orientation. For example, since the mean distance from particle surfaces to the center is controlling for the rate of heat transfer in pyrolysis reactors, the length of a particle appears to be less important than the cross-section dimensions [17]. The length-to-thickness ratio, also called aspect ratio, remains important for design of bulk handling systems, since it is a major factor in particle flowability [18].

A primary objective of the experiments was to determine the relative energy consumption to shear wood veneer parallel-to-grain versus cross-grain. If there is no difference in energy consumption with respect to grain orientation, then energy-minimal particles could be made cubic or other such simple shapes. However, if the difference between cutting parallel-to-grain and cross-grain is large, then more rectangular shapes would be less energy-intensive to manufacture. Thus, the first analysis of the results compared the comminution energy for comminution parallel-to-grain versus cross-grain for the 2.5- and 4.2-mm thick raw veneer.

The results depicted in Figure 3 are the data from each run of replicated experiments. The two graphs are from experiments with two different thicknesses of veneer (2.5 mm and 4.2 mm, respectively) at MC higher than fiber saturation of 30% MC (wb). The difference in specific energy (MJ/Mg) for cross-grain shearing versus shearing parallel-to-grain is statistically significant ( $p = 0.013$ ). The average specific energy for shearing high moisture 2.5-mm thickness Douglas fir veneer parallel-to-grain



**Figure 2. Wood feedstock particles 4.8-mm long made from 4.2-mm fir veneer using a prototype Crumbler™ machine.**

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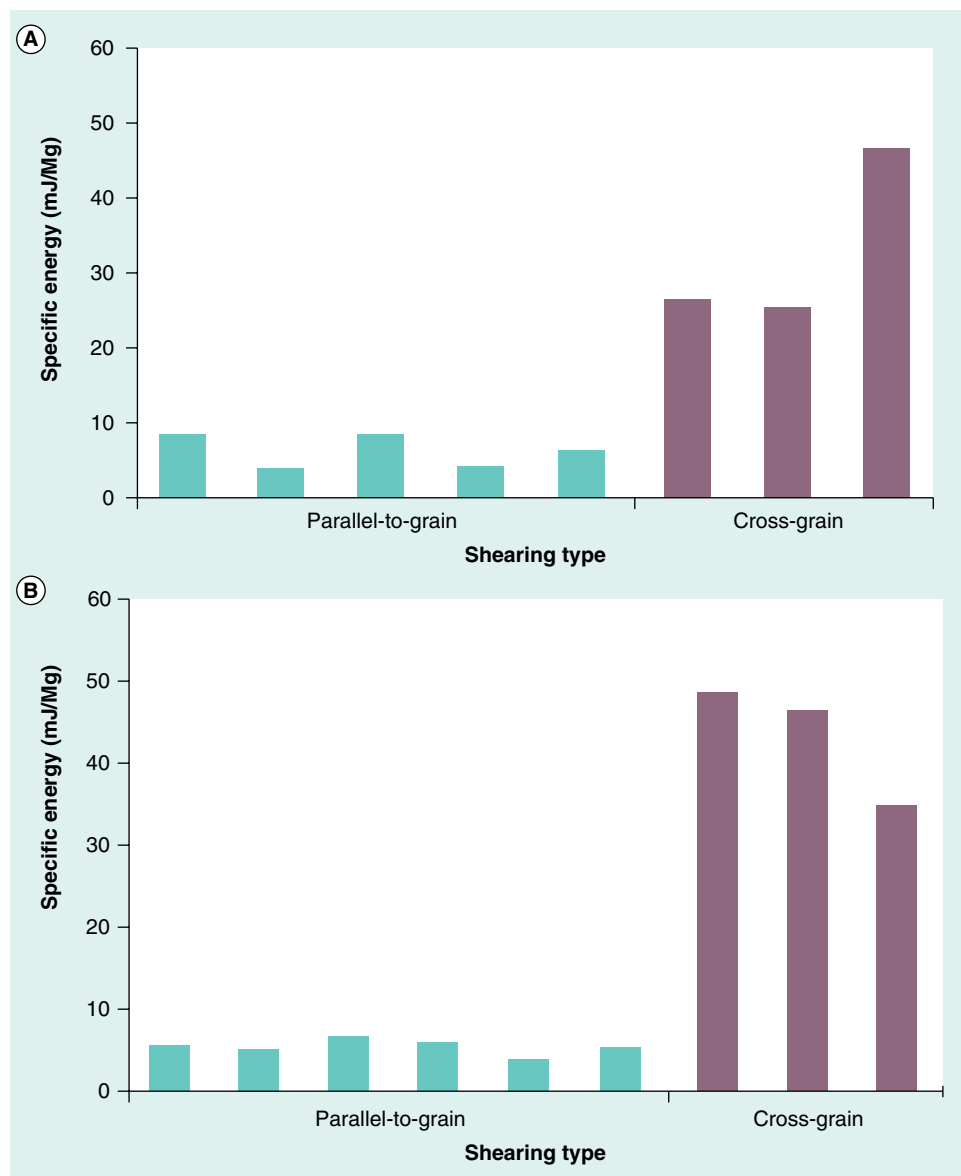
was 6.2 MJ/Mg (standard deviation [SD] = 2.2) versus a specific shearing energy of 33 MJ/Mg (SD = 7.6) for the cross-grain case. The average specific energy for shearing high moisture 4.2-mm thickness Douglas fir veneer parallel-to-grain was 5.4 MJ/Mg (SD = 0.9) versus a specific shearing energy of 43 MJ/Mg (SD = 7.5) for the cross-grain case. Differences between thicknesses in each case are not significant ( $p = 0.28\text{--}0.47$ ). We are not surprised that the effect of thickness is not significant when the energy consumption is expressed on the basis of mass processed. Doubling the material thickness would result in twice the volume produced for any particular particle length. Thus, if the cutting force was doubled, the resulting energy per unit mass would still be the same. As noted earlier, the energy consumption per unit mass produced is of most relevance to the audience for our studies.

The differences between specific energy for cutting parallel-to-grain versus cross-grain are as would be expected by anyone who has cut firewood – it is much easier to split a log than to chop a log with an axe. We were also interested to learn the difference between specific energy consumption for shearing veneer that was high moisture defined as higher than 30% MC (wb) as compared with drier veneer defined as less than 30% MC (wb). The cutoff was established to be generally coincident with the fiber saturation point for conifers, which represents a phase transition point between brittle failure and plastic failure in bending and shear [3].

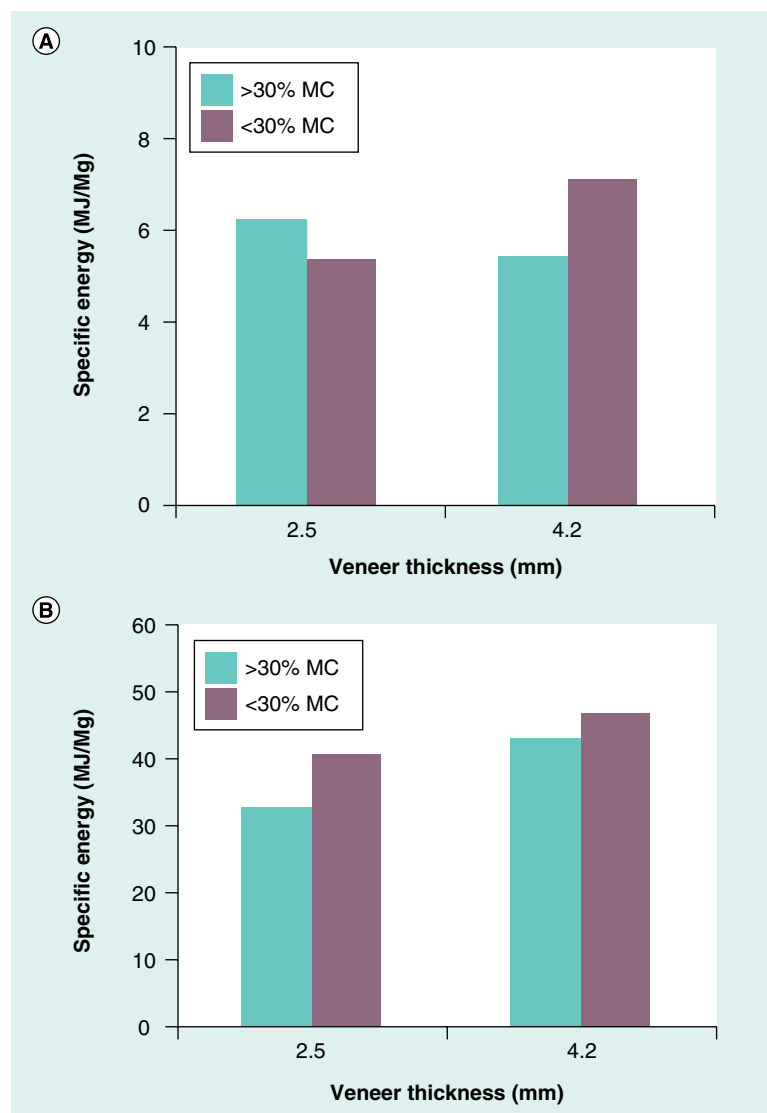
The amount of energy per unit mass to shear parallel-to-grain at high and low MC is shown in Figure 4A. In spite of five replicates in each experiment, the differences between MCs and between thicknesses were not found to be significant ( $p = 0.05\text{--}0.46$ ). The range of energy values across experimental treatments and runs ranged from 4 to 8 MJ/Mg, and differences between means are likely to be masked by variance due to fiber grain structure and other anatomical differences across samples. Figure 4B shows the cross-grain results for moisture and thickness. Here we found that the moisture effect was not significant for

either material thickness ( $p = 0.36\text{--}0.53$ ). This result was somewhat counterintuitive, since when fibrous materials such as wood are sheared across the grain, higher moisture softens the fibers and cellulosic material making it more plastic and easily cut.

As also expected, there is no real difference in shear energy per unit mass (MJ/Mg) as a function of veneer thickness. That is not to say that the amount of driving torque or force is unrelated to material thickness. To our point, if the shear energy is essentially a linear relationship with shear area then, as measured, the



**Figure 3. Summary results for parallel-to-grain rotary shearing compared with cross-grain shearing of high moisture (>30% moisture content wet-weight basis) Douglas fir wood veneer at two thicknesses. (A) 2.5-mm veneer x 4.8-mm cutter and (B) 4.2-mm veneer x 4.8-mm cutter. Bars of same shade show measured results from each replicate experimental run. Data taken from [FOREST CONCEPTS, UNPUBLISHED DATA].**



**Figure 4. Summary results for average specific comminution energy (MJ/Mg). (A) Of parallel-to-grain shearing and (B) of cross-grain rotary shearing of Douglas fir wood veneer at two thicknesses and two MCs. Note differences in vertical axis scale.**

MC: Moisture content.

Data taken from [FOREST CONCEPTS, UNPUBLISHED DATA].

energy per unit mass will be constant as raw material thickness increases. The implication for machine design is that, at a constant cutting speed, the power to drive a machine will increase in direct proportion to raw material thickness.

Uniformity of particle-size distribution for comminuted materials is also a factor that affects conversion efficiency. More uniform particles enable better process design. Particle-size distribution of the 2-mm veneer particles after comminution is shown below in [Figure 5A](#) and can be compared with the size distribution for shredded similar veneer in [Figure 5B](#).

The materials shown in [Figure 5](#) had a geometric mean particle size of 2.3 mm for the sheared particles from the Crumbler machine and 1.8 mm for the hammer milled wood chips, respectively. The similarity of the nominal size is visually indicated by the centering of both distributions on the no. 16 sieve. Nominal sieve size as expressed by sieve analysis is common in the biomass and biofuels industry; however, other dimensional information that is more difficult to determine with automated equipment would be useful for facility designers and operators. Additional data on the dimensional properties of these two samples, including particle length, width, thickness and shape, were collected by hand measurement of several hundred particles from each processing method. Analysis and reporting of that data and management implications are the subject of future work.

The key finding from this series of experiments is the fivefold difference in specific energy between cutting parallel-to-grain versus cutting cross-grain, which should guide feedstock material designers to favor more rectangular particles with the long axis along the grain when possible. These results are consistent with our earlier models reported by Lanning *et al.* [13]. The implication of the results is that selective orientation of woody biomass raw materials as they are subjected to comminution can result in lower energy consumption per unit mass, particularly when the length-to-thickness ratio of desired particles is greater than 1.

### Operational & management discussion

In our preferred solution to manufacturing precision wood particles, we envision that roundwood will be converted to veneer using a parallel-to-grain slicer or rotary lathe. The rotary lathe operation would be coupled to a Crumbler cross-grain shear containing a specific set of cutters that would cut veneer strips from the lathe into precision fiber-length particles.

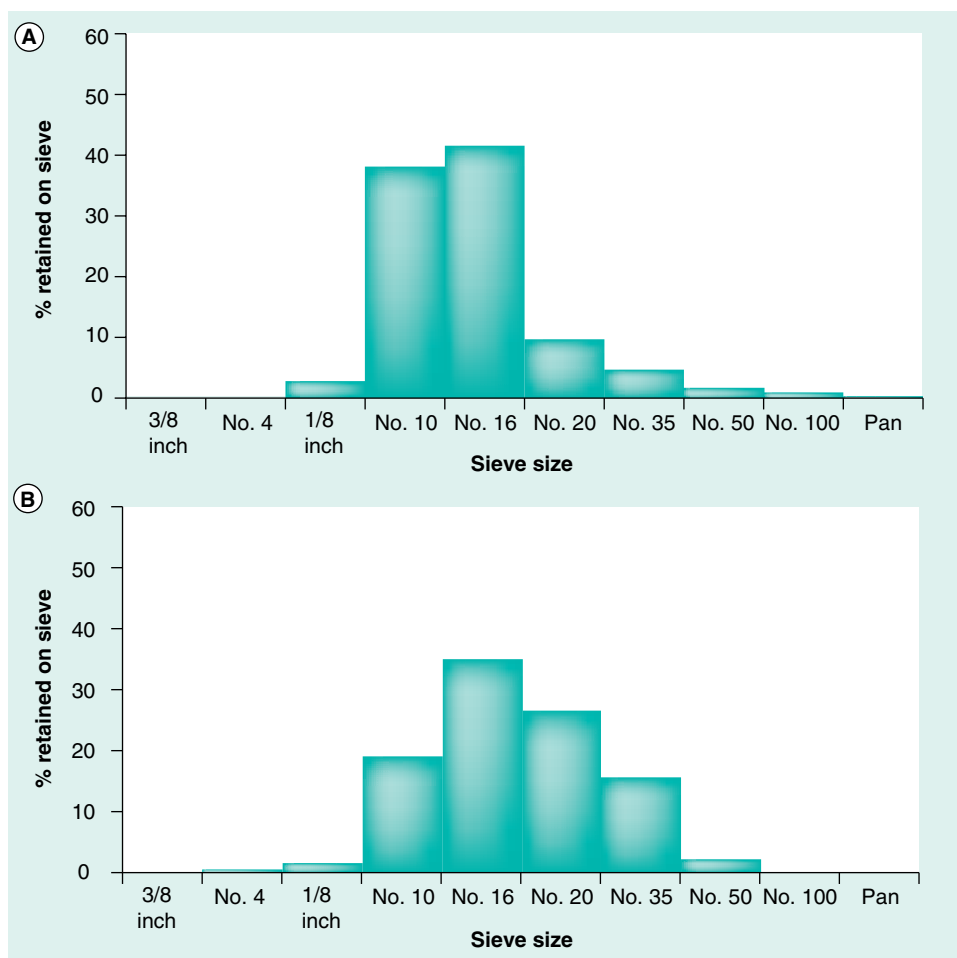
If we combine the results of this study with other evaluations of the specific energy for rotary veneer making, we can suggest that the combination of rotary veneer and cross-grain rotary shearing can produce 2-mm precision conifer wood particles using less than 60 MJ/Mg and 4.8-mm particles for approximately 50 MJ/Mg [19,20]. In both cases, the comminution energy is a small fraction of what would be consumed to make similar size particles by first drying and then using a chipper and hammer mill to comminute dried wood chips [21].

These results are consistent with another recent study of processing fresh-cut hybrid poplar logs into 2-mm thickness industrial-grade veneer and then into 1.6-mm feedstock particles using the Forest Concepts rotary shearing equipment [20]. In that study, veneer making consumed approximately 11 MJ/Mg based on measured

veneer produced, which is to be expected since veneer peeling primarily consists of shearing parallel-to-grain. Cross-grain shearing into 1.6-mm long particles consumed an additional 130 MJ/Mg, for a total energy from log to 1.6-mm particle size of approximately 141 MJ/Mg. This is less than 30% of the energy expected for hammer milling of similar wood, and did not require additional energy investment for pre-drying to 15% moisture, as would be required prior to hammer milling to small particle sizes [22].

We conducted a full capital and operating cost analysis for a stand-alone woody feedstock production facility that purchased raw logs and shipped 4-mm high-moisture feedstocks in bulk. The economic analysis was created as an expansion and scaling of equipment and processes developed and validated during the DOE-funded Small Business Innovation Research project (DE-SC0002291) at Forest Concepts. Thus, the economics represent a 'first-of-kind' pioneer facility. For this stand-alone case, the raw log specification would be for pulp-grade poplar logs that are 125–300 mm (5–12 inches) top diameter and multiples of 1.2-m (4-ft) lengths. Raw poplar logs were estimated to have a delivered price of approximately 28.80 US\$/Mg per the billion-ton study by DOE [6]. All other capital and operating cost information was estimated by the experienced engineers at Forest Concepts with guidance from an industry consultant. Detailed costs and energy balance data is held proprietary under the terms of DOE contract DE-SC0002291.

A 400 Mg/day production facility to produce 4-mm nominal size high-moisture feedstocks from purchased poplar logs would have a total capital cost of approximately US\$14.7 million to construct. The minimum economic selling price including all sales, general and administrative costs plus a reasonable profit would be in the range of \$100/Mg for this first-of-a-kind facility, and approximately \$65/Mg for the nth facility. Total energy consumption for the facility is expected to be approximately 220 MJ/Mg of product produced. Approximately half of the energy is for comminution and the balance is for conveyors, feeders and so on.



**Figure 5. Particle sieve size distribution. (A)** For 2-mm veneer processed cross-grain through 2-mm cutters using the Forest Concepts laboratory Crumbler™ machine, sample number 2012.04.24.001 and **(B)** for wood chips processed through hammer mill with screen to produce 2-mm nominal particle size, sample number 2012.04.10.001.

Data taken from [FOREST CONCEPTS, UNPUBLISHED DATA].

A similar cost and capital plan was developed to produce 2-mm nominal size dry (10% MC) poplar feedstocks for thermochemical conversion users. In this case, the feedstocks are still processed at field moisture through the veneer making and comminution operations, and are dried after milling. The addition of drying and additional materials handling equipment, as well as equipment specific to the smaller particle size, raises the capital cost to approximately \$28 million. Increased energy consumption and lower throughput raise the minimum economic selling price to \$136/Mg and the energy consumption to 6200 MJ/Mg. It is obvious that drying dramatically increases energy consumption compared with the high-moisture product case. These cost and capital are for a first-of-a-kind facility, with modest reductions anticipated for the nth facility.

## Conclusion

A novel pathway to convert roundwood logs into small precision particles appropriate for conversion into liquid or solid biofuels was demonstrated to consume an order of magnitude less specific comminution energy than conventional chipping followed by grinding. The low-energy comminution was achieved by careful understanding of the natural modes of failure within wood materials, minimizing energy-intensive cross-grain shearing, processing at high MC and only manipulating each face of the particles once.

Commercial implementation of the engineering knowledge developed in this study will necessarily involve the design of new types of veneer lathe equipment and an entirely new class of rotary shear comminution machinery. It is expected that others will apply the principles of biomass failure mechanics and modes of failure to improve the energy efficiency of existing hammer mills, grinders and other comminution machinery.

## Future perspective

Woody biomass is expected to play a major role in meeting global demands for solid and liquid biofuels. Historic methods for comminution of woody feedstocks are energy inefficient and result in significant challenges for designers of feedstock materials handling equipment and conversion processes. The net result is that feedstock costs for woody biomass are often cited as a major deterrent to its use.

In addition to high raw material costs, the amount of energy consumed to convert tree-size logs into millimeter-sized particles suitable for conversion is excessive. Sustainability and life cycle assessments often identify feedstock preprocessing energy as the highest or among the highest energy costs through the supply chain and conversion operations.

Parallel to the novel engineering and rotary shear technology reported in this paper, the opportunities to achieve similar advancements in low-energy, high-precision processing of herbaceous energy crops and other feedstocks are high. While existing manufacturers of preprocessing equipment must continue to develop incremental improvements in performance or energy consumption, it is likely that well-funded clean sheet explorations that identify theoretical minimum costs and energy for delivery of herbaceous feedstocks will lead to novel and game-changing process technologies. As new energy crops are created through breeding and molecular biology, careful attention to the engineering implications of fiber grain orientation and processing properties will be increasingly important as both a challenge and as an opportunity.

## Financial & competing interests disclosure

*The authors are employees of Forest Concepts, LLC, which is developing commercial applications of the technologies discussed in this paper. Precision wood particles that are the subject of this paper are covered by three US Patents – US 8158256, US 8039106 and US 8034449 – and other US and international patent applications are pending. Wood products manufactured by the process described in this paper are marketed under the Crumbles® trade name. Crumbles, Precision Feedstocks®, WoodStraw® and Crumbler™ are trademarks of Forest Concepts. This material is based upon research and development that was supported in-part by the US Department of Energy Office of Biomass Programs Small Business Innovation Research Program Contract No. DE-SC0002291. This manuscript is based on a public workshop presented by the lead author as part of the Idaho National Laboratory August 2011 Biomass event. The authors have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed. No writing assistance was utilized in the production of this manuscript.*

## Executive summary

### Background

- Industrial-grade veneer provides a high-density form for transport, storage and handling of woody biomass from forests and plantations.
- Comminution energy to convert roundwood into small precision particles can be minimized through careful appreciation of modes of failure.

### Experimental

- Commercial Douglas fir veneer was processed using a 4.8-mm width cutter set on a 130-mm wide rotary shear by feeding parallel-to-grain and cross-grain while measuring the specific comminution energy.

### Results

- Shearing 2.5 and 4.2-mm thickness high-moisture fir veneer parallel-to-grain consumed less than 5–7 MJ/Mg while cross-shearing the same material with a 4.8-mm cutter set consumed 30–40 MJ/Mg.

### Discussion

- Comminution to desired small particle size at field moisture before drying can increase dryer throughput and improve energy efficiency.
- Production of industrial-grade veneer as the primary breakdown of raw logs establishes uniform particle thickness and preserves fiber grain orientation for subsequent processing unit operations.
- Rotary shearing of veneer raw material precisely controls particle length along the fiber grain, an important factor for feedstock flowability and conversion efficiency.



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