Demonstration of a Pilot-Scale Plant for Biomass Torrefaction and Briquetting

M. A. Severy, C. E. Chamberlin, A. J. Eggink, A. E. Jacobson

Abstract. *A semi-mobile torrefaction and densification pilot plant was constructed in order to determine ideal operating conditions and evaluate briquette quality and throughput rate using forest residuals as the input feedstock. Experiments were conducted at various conditions with feedstock moisture content ranging from 4% to 25% (wet basis), reactor residence times of 10 and 20 min, and final product temperatures between 214°C and 324°C. Optimal operating conditions, evaluated based on throughput rate, specific electricity demand, torrefied briquette grindability, briquette volumetric energy density, and briquette durability, were identified to occur with a short residence time (10 min), low feedstock moisture content (<11% wet basis), and high final product temperature between 267°C and 275°C. These conditions were able to process 510 to 680 kg h^{-1} (wet basis) feedstock with a dry mass yield of 79% to 84% to produce torrefied biomass with a higher heating value of 21.2 to 23.0 MJ kg^{-1} (dry basis) compared to 19.6 MJ kg^{-1} for the original biomass. Torrefied briquettes produced at these conditions had a neatly stacked packing density of 990 kg m^{-3} and a volumetric energy density of 21,800 MJ m^{-3}. Their specific grinding energy was an average 37% of the energy required to grind a raw biomass briquette. These torrefied briquettes were more durable (94% DU) than raw briquettes (85% DU) directly following production, but were less durable after undergoing temperature and humidity fluctuations associated with long distance transportation (74% DU for torrefied and 84% DU for raw biomass briquettes). Results from this pilot plant are promising for commercial scale production of high quality torrefied briquettes and should lead to additional research and development of a torrefaction system optimized for a higher throughput rate at these conditions.*

Keywords. *Biomass, Biomass conversion technology, Bioenergy, Briquetting, Densification, Forest residuals, Pyrolysis, Torrefaction.*

Non-renewable energy resources such as coal, natural gas, and petroleum are the major fuel sources used for power and heat production (EIA, 2016). Woody biomass is a renewable resource that can be used in place of fossil fuels for these applications. Some of biomass' fuel properties and handling characteristics, however, make it a less attractive energy source, including its high moisture content, low bulk density, low calorific value, high grinding energy requirements, hydrophilicity, and non-uniformity of fuel properties and particle size. Torrefaction – a form of mild pyrolysis conducted at product temperatures between 250°C and 300°C – has been shown to improve fuel properties of biomass and make it more suitable as a combustion fuel (Tumuluru et al., 2011). Densification of torrefied biomass further improves the volumetric energy density facilitating more economical transportation and storage of biomass fuel (Bergman, 2005a). The resulting, densified product can be used as a supplemental or replacement fuel for coal in existing power plants (Bergman et al., 2005b; Li et al., 2012), thereby reducing use of non-renewable energy resources.

The torrefaction process decomposes a fraction of the biomass and removes moisture content to produce a higher quality, more energy dense fuel. The dry, resulting product typically yields 50% to 90% of its original mass while increasing its energy density by 5% to 40% (Chen et al., 2015). Dehydration and thermal degradation alters the biomass structure by softening the lignin, degrading the cell walls and decreasing the plastic and viscoelastic behaviors, making the biomass more friable and decreasing the energy required for grinding (Repellin et al., 2010). Torrefaction also reduces the water uptake capacity of biomass by destroying OH groups, which reduces the ability to form hydrogen bonds and increases the hydrophobicity of biomass (Bergman, 2005a).

The extent of these physical and chemical changes depends on the conditions of torrefaction. Temperature and residence time (RT) in the reactor are the main parameters controlling the degree of torrefaction. Higher temperatures and longer RTs increase the degree, or severity, of torrefaction, but temperature has the strongest effect on the severity of torrefaction and the characteristics of the final product (Strandberg et al., 2015). There are various tradeoffs to consider when selecting the reaction conditions. More severely torrefied biomass exhibits greater energy density (Phanphanich and Mani, 2011) and lower grinding energy requirements (Repellin et al., 2010). On the other hand, increasing

Submitted for review in March 2017 as manuscript number ES 12376; approved for publication as part of the Waste to Wisdom Collection by the Energy Systems Community of ASABE in October 2017.

The authors are **Mark A. Severy,** Research Engineer, **Charles E. Chamberlin,** Professor, **Anthony J. Eggink,** Research Engineer, and **Arne E. Jacobson,** Professor, Schatz Energy Research Center, Humboldt State University, Arcata, California. **Corresponding author:** Arne E. Jacobson, 1 Harpst St., Arcata, CA 95521; phone: 707-826-4345; e-mail: arne.jacobson@humboldt.edu.

Vol. 34(1): 85-98 ISSN 0883-8542 https://doi.org/10.13031/aea.12376

the degree of torrefaction breaks down more of the original components of the biomass and reduces the total energy yield from the process despite an increase in energy density (Chen et al., 2015). Further, it is suggested that severely torrefied material cannot be densified as easily because lignin – the main natural binding agent in biomass – begins to break down more readily at higher temperatures (Tumuluru et al., 2011).

Several pilot scale torrefiers have been reported in the literature ranging in throughput from 3 kg h^{-1} (Mei et al., 2015) to 274 kg h^{-1} (Karlsson, 2013). The pilot studies used different reactor designs including a continuous screw auger (Chang et al., 2012; Zheng et al., 2012; Shang et al., 2014; Strandberg et al., 2015; Rudolfsson et al., 2017), a rotary drum (Karlsson, 2013; Mei et al., 2015), a moving bed reactor (Nanou et al., 2016), and a vibrating electrical escalator (Doassans-Carrère et al., 2014). Only two of these studies densified the torrefied biomass, which is an important step in the commercialization of this process. Karlsson (2013), who observed production at a pilot plant in Klintehamn, Sweden, found that good quality pellets were produced when mixing water with lightly torrefied biomass (reaction temperature of 245°C), but higher degrees of torrefaction produced pellets with poor durability. Rudolfsson et al. (2017) produced torrefied biomass in a 200 kg h^{-1} continuous reactor then milled and added moisture to the biomass before pelletizing in batches. Their results show that low torrefaction temperatures and high biomass moisture content into the pellet mill produces pellets with high durability and low fines content at the expense of lower bulk density and higher grinding energy. The authors state that pellet quality is very sensitive to both the torrefaction and pelletization process conditions and that precise and consistent control of the torrefaction process is necessary to operate within the narrow window for successful pelletization.

Densifying torrefied biomass into briquettes offers an alternative to pellet production. Briquettes have been produced from torrefied biomass (see Felfeti et al., 2005; Benavente and Fullana, 2015; Araújo et al., 2016), though not with the scale and type of equipment proposed in the present study. Benavente and Fullana (2015) produced 5 cm diameter briquettes from torrefied olive mill waste, and Araújo et al. (2016) produced small, cylindrical briquettes (1.7 cm length × 3.3 cm diameter) from mildly torrefied (220°C) eucalyptus. Both studies showed promising results at a laboratory scale by producing briquettes with over 1,000 kg m^{-3} bulk density, increased energy density, and decreased water absorption. These studies, however, required milling the biomass to less than 0.5 mm before densification – similar to the requirements for pelletization – which significantly increases the preprocessing energy consumption. Densifying torrefied biomass into larger briquettes with dimensions between 10 and 30 cm, such as the briquettes produced in this study, allow for a broader range of feedstocks with less processing requirements.

A recent review by Chen et al. (2015) on torrefaction emphasized the need for future work with pilot- and demonstration-scale equipment to examine the scale up effects and integration into a larger commercial system. In this article, we present the results and analyses of a pilot scale, semi-mobile torrefaction and briquetting plant using forest residuals as the input feedstock. This system provides three distinct improvements to the pilot-scale systems described in the literature cited above. First, the capacity of this system (575 kg h^{-1}) is significantly higher than the other pilot-scale studies. Secondly, this system uses a briquetter that has limited feedstock processing requirements compared the requirements for use of the torrefied material in a pellet mill. Lastly, this system integrates the torrefier and briquetter to operate continuously and simultaneously rather than densifying in batches.

The plant was operated in a production setting to evaluate its capacity, energy consumption, specifications, and the quality of torrefied biomass over a range of reaction temperatures, residence times, and feedstock moisture contents. The objectives of this work are to 1) evaluate a commercially available torrefier to determine the throughput rates, electricity demands, feedstock specifications, and preprocessing requirements for this system, 2) understand the process conditions that create torrefied biomass with greater energy density, better grindability, and ability to be densified into a durable briquette, and 3) demonstrate torrefaction and briquetting technologies at a pilot-scale with the improvements outlined in the previous paragraph.

Methods and Materials

This section provides a description of the equipment used in the pilot plant and the methods for testing and analysis.

System Description

The semi-mobile pilot plant produced torrefied biomass briquettes during July and August 2016 in Samoa, California. The plant consisted of a belt dryer (Norris Thermal Technologies, 123B Beltomatic, Tippecanoe, Ind.), a continuous screw auger torrefier (Norris Thermal Technologies, CM600, Tippecanoe, Ind.), a hydraulic ram briquetting press (RUF Briquetting Systems, Lignum, Elryia, Ohio), and an appropriate set of hoppers and conveyors. A simplified diagram of the system is shown in figure 1 and pictured in figure 2. The plant is considered semi-mobile because it can be setup and disassembled in 6 h each with two people and two forklifts. The torrefier is permanently mounted on a trailer, while auxiliary components, such as the cooling auger, chiller, and flare, are loaded onto and off of a second trailer for transportation. The generator is permanently mounted to a trailer, while the briquetter, dryer, and additional components can all be loaded onto and transported with a separate flatbed trailer.

The torrefier comprises four major subsystems: 1) feeding system, 2) reactor, 3) product cooling system, and 4) gas handling. The feeding system is operated by loading feedstock onto a conveyor that moves material into the reactor hopper. An auger in the trough of the reactor hopper transfers feedstock through a rotary air lock into the reactor. Air locks are used to reduce oxygen infiltration into the reactor. The reactor is an electrically-heated, shaftless screw conveyor insulated with refractory lining. The dimensions of the reactor auger are: 6,000 mm long, 600 mm outside diameter,

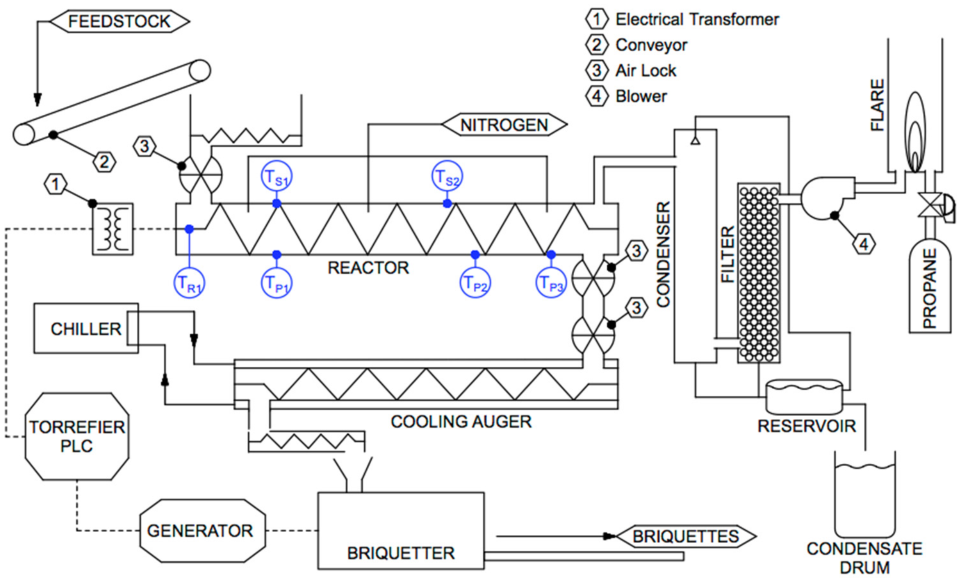


Figure 1. Simplified piping and instrumentation diagram of the densification and torrefaction system.

110 mm pitch, 210 mm ribbon height, and 10 mm ribbon thickness. A transformer converts AC electricity to the low-voltage, high-current DC supply required to heat the reactor auger. The hot surface of the reactor auger transfers heat to the biomass product to stimulate the torrefaction process. The temperature of the reactor is controlled based on a thermocouple mounted inside the auger. The residence time of the biomass feedstock is adjusted by the rotational speed of the auger. A rotary air lock ejects material from the outlet of the auger into a vertical duct, and another rotary airlock passes material into the cooling auger. The cooling auger is a shaftless screw conveyor with an external water jacket. Chilled water is supplied to the water jacket using a closed loop chiller system. After exiting the cooling auger, torrefied biomass is fed into the briquetter hopper with an auger.

Gas produced during the torrefaction process is pulled through the gas handling system with a blower. The blower speed is controlled with a variable frequency drive in order to maintain neutral pressure in the reactor using feedback from a pressure transducer mounted inside the reactor. Volatiles from the headspace of the reactor are drawn into a condensing tube, which is cooled with water from the chiller. A nozzle at the top of the condenser sprays recycled condensed liquid into the gas stream to help remove any suspended liquid or biomass particles. A filter with plastic media is installed downstream of the condenser. Liquid from the condenser and filter are collected in a reservoir, which empties into a collection drum. Gas exiting the filter is forced through a blower then into a flare. The flare is enriched with propane to maintain combustion.

Densified briquettes are produced with an automated hydraulic ram briquetting press, as shown in figure 3. The briquetting press has two stages of compression: First, an auger transfers material from the hopper into the precharging chamber, where a vertical piston performs the first stage of

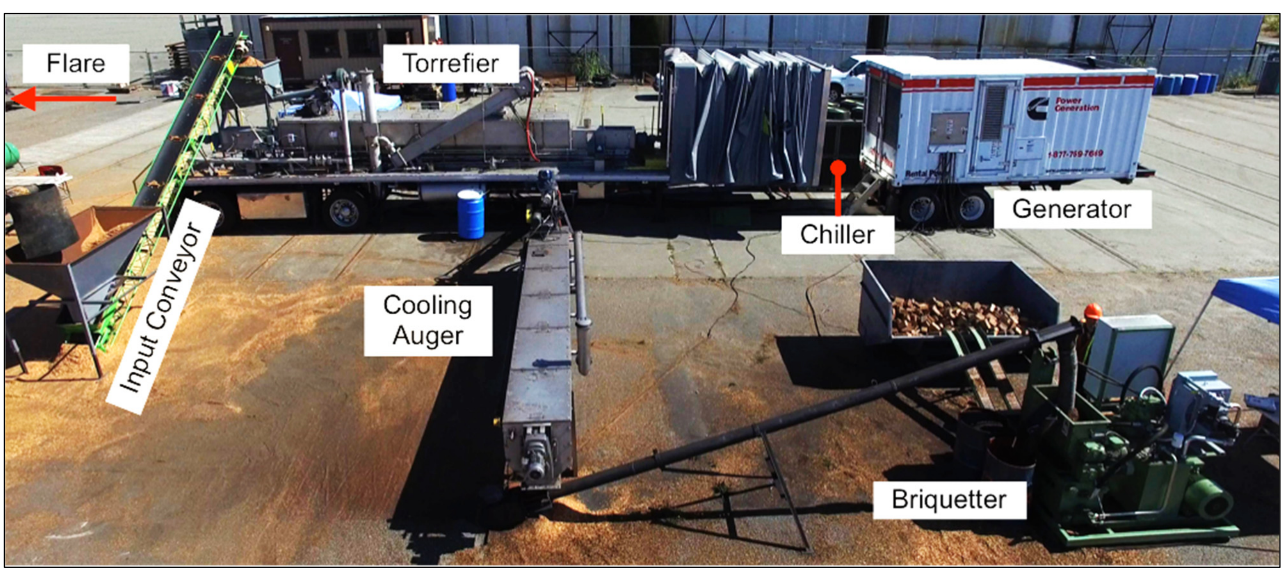


Figure 2. Picture of torrefier and briquetter system. The flare is located 6 m to the left and not shown in this image.

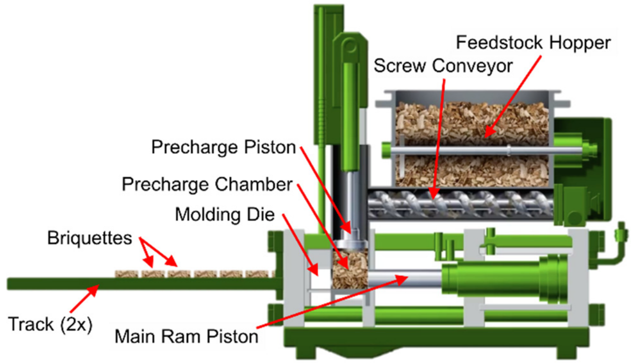


Figure 3. RUF briquetter annotated schematic (RUF, 2016; annotation added). The briquetter is shown performing the first stage of compression in the precharge chamber.

compression. Second, the horizontal main ram piston compacts material into an unheated molding die to form a briquette. As the main ram piston retracts, the molding die pushes the briquette to one side. When the piston engages again, a new briquette is made and the briquette from the previous stroke is ejected onto one of two tracks. The hydraulic pressure setpoint for the precharger and main ram piston were set at 180 and 250 bar, respectively, for all experiments. The molding die produced briquettes nominally 150 mm × 100 mm × 63 mm (6 in. × 4 in. × 2.5 in.), weighing approximately 0.72 kg.

Instrumentation was installed on the torrefier and briquetter to measure mass and energy flows in addition to key operational parameters for control and analysis. The main instruments used in this analysis are described in table 1.

Feedstock Description

The feedstock specification provided by the torrefier manufacturer required that inlet material be less than 25% moisture content (wet basis) and less than 25-mm (1-in.) particle size. Biomass feedstock was obtained from a local logging contractor who was chipping decked tanoak logs (*Notholithocarpus densiflorus*) for pulp and paper production through a debarker, chipper, then two star screens in series. Feedstock for the torrefier was collected from the fine fraction rejected from the star screens. The feedstock was further screened between a 25.4-mm (1-in.) and 3.175-mm (1/8-in.) vibrating screener to remove oversized or undersized particles. Feedstock particle size distribution after screening is shown as the solid line in figure 11. Prior to testing, feedstock was dried in a belt dryer depending on the target moisture content. A picture of the feedstock is shown in figure 4.

Figure 4. Picture of tanoak feedstock. Scale at the bottom of the image indicates 1 cm.

Methods

The following subsection details the methods for conducting a torrefaction and densification test and analyzing the material samples.

Production Test Methods

To start a test, the reactor was turned on, set to the target temperature, and allowed to preheat for approximately 40 min while empty. After preheating was complete and the reactor heating element had reached the temperature setpoint, feedstock was loaded into the system. The reactor was purged with nitrogen as feedstock filled the system to evacuate any oxygen within the headspace and avoid combustion. The nitrogen supply was shut off after the temperatures of biomass in the reactor (i.e., T_{P1}, T_{P2}, and T_{P3}) became stable, which typically took around 30 min. Lastly, the steady state testing period could begin after the output product appeared a consistent color indicating uniform torrefaction, which generally took 40 min after loading feedstock into the reactor or 10 to 20 min after closing the nitrogen purge gas.

A batch of feedstock was loaded into a self-dumping hopper and weighed to the nearest ±1 lb on a pallet scale (Global Industrial WB242434, Port Washington, N.Y.). The input mass flow rate was calculated as the mass of steady state feedstock divided by the test duration. This batch of preweighed biomass feedstock was loaded into the inlet hopper. The testing period began when the leading edge of the weighed feedstock passed into the reactor through the airlock. The weighed plug of biomass was tracked throughout the length of the entire system through briquette production by following a timetable, which indicated the duration of time required for material to pass through each portion of the

Table 1. Abbreviated list of instrumentation.

Name	Physical Property to be Measured	Type and Location
T_R	Temperature of screw conveyor heating element	Type-K thermocouple mounted inside reactor screw ribbon
T_{P1}	Temperature of torrefied product in reactor	Type-K thermocouple inside bottom of reactor, 1.2 m from inlet
T_{P2}	Temperature of torrefied product in reactor	Type-K thermocouple inside bottom of reactor, 4.4 m from inlet
T_{P3}	Temperature of torrefied product in reactor	Type-K thermocouple inside bottom of reactor, 5.3 m from inlet
T_{S1}	Temperature of headspace in reactor	Type-K thermocouple inside headspace of reactor, 1.2 m from inlet
T_{S2}	Temperature of the headspace in reactor	Type-K thermocouple inside headspace of reactor, 3.7 m from the inlet
P_T	Electric power to torrefier	Current transformers and power meter on main electrical supply to the torrefier
P_R	Electric power to torrefier reactor heater	Current transformers and power meter on high voltage side of transformer

system based on the reactor auger speed. Steady state tests lasted between 20 and 60 min depending on the residence time and mass of the test feedstock. When the inlet hopper became empty, additional feedstock was loaded directly behind the test plug to maintain the thermal mass inside the reactor, and the reactor steady state period was declared complete.

Data collection continued until the pre-weighed plug exited the briquetter as densified, torrefied biomass. The torrefied biomass output flow rate was calculated as the average briquette mass multiplied by the number of briquettes produced during steady state divided by the duration of the test. The condensate production flow rate was calculated as the change of mass in the condensate collection drum divided by the duration of the test.

Multiple tests were performed each day by changing the operating parameters following the end of each test, waiting for the reactor temperatures to stabilize, then loading another plug of pre-weighed feedstock into the system. After completing all of the planned tests for one day, the temperature setpoint was reduced to ambient temperature and the system was operated until empty.

Different tests were conducted by varying the reactor temperature setpoint, the nominal residence time, and the feedstock moisture content (MC). The test conditions are listed in table 2. Residence times were selected to be either fast or slow (10 or 20 min, respectively) with target moisture content of low (<11%), moderate (11% < MC < 18%), or high (>18%). Each steady state testing period consumed between 140 and 340 kg of feedstock (bone-dry) over a period of 20 to 60 min. A single test was conducted at each torrefaction condition described in table 2. This sums to eleven torrefaction and densification tests in addition to a densification test with non-torrefied, raw biomass feedstock. The feedstock for all tests were taken from the same bulk supply of biomass described above while only varying the moisture content. Each test is labeled with a unique test ID using the format 'X###Y', where 'X' represents the residence time as either 'F' or 'S', designating a fast or slow residence time; the three digit number references the reactor temperature setpoint in degrees Celsius; and 'Y' represents the moisture content as 'L', 'M', or 'H', designating low, medium, or high moisture content, respectively. The test labeled 'NTB' is an acronym for non-torrefied briquettes. Results labeled 'FS' refer to raw biomass feedstock.

Table 2. Torrefaction test conditions.

Test ID	RT, min	Reactor Temp. Setpoint, °C	Feedstock Moisture Content, % w.b.[a]	Test Date, month/day[b]
NTB	No Torrefaction; Briquetting Raw Biomass			8/9
F375H	10	375	24 (2)	7/29
F400L	10	400	4 (1)	8/2
F400H	10	400	25 (5)	8/2
F425L	10	425	9 (<1)	8/5
F425M	10	425	12 (2)	8/5
S300M	20	300	16 (2)	8/8
S325H	20	325	21 (1)	8/8
S350M	20	350	12 (<1)	8/4
S350H	20	350	22 (<1)	8/4
S400M	20	400	13 (1)	8/4
S400H	20	400	19 (<1)	8/4

[a] Standard deviation of are shown in parentheses for a sample size of three.

[b] All tests conducted in the year 2017.

The experimental conditions were selected to achieve a range of torrefied biomass from no torrefaction to heavy torrefaction within a limited two-week time frame for operating the equipment. Test conditions were altered based on previous results to fill in the range of torrefaction levels.

Material Analysis Methods

Three separate material samples were collected for each test: a sample of feedstock was collected just prior to loading the reactor; a sample of torrefied biomass was collected by compositing at least five small amounts of product throughout the entirety of the test before it entered the briquetter; and 20 torrefied briquettes were collected from the output tracks periodically throughout the test. All samples were stored in airtight plastic bags before analysis. After determining the moisture content of each individual feedstock sample, all of the feedstock samples were mixed together and dried in a 105°C oven before analyzing the rest of their characteristics on a bone-dry basis. The samples were analyzed to determine selected physical, mechanical, and chemical properties. The procedure for each test is summarized below.

- Bulk density – Measured for each feedstock and torrefied biomass by modifying CEN/TS 15103 (CEN, 2005) to use a 1 cubic ft box (12 in. × 12 in. × 12 in.). One replicate was performed.
- Briquette durability – Tested in a tumbler with modifications to ISO/DIS 17831-2 (ISO, 2013). Nine briquettes were placed in a 572-mm (22.52-in.) diameter cylindrical tumbler rotating at 21 rpm for 5 min. The tumbler was fabricated by the authors. After tumbling, all the material not passing through a 50.8-mm (2-in.) mesh sieve was weighed to the nearest ±0.005 kg as the durable fraction of briquettes. One replicate was performed.
- Briquette mass – Average mass of 20 briquettes individually weighed approximately 2 min after densification to the nearest ±0.005 kg (Adam Equipment, CPWplus 15, Oxford, Conn.).
- Briquette packing density – Determined by neatly stacking six briquettes in two rows inside a three-sided box then measuring the outermost dimensions of the stack to the nearest ±6.3 mm (±0.25 in.) and measuring the cumulative mass of these six briquettes to the nearest ±0.005 kg. Packing density is calculated as the total volume of the stack using the measured linear dimensions divided by the mass of six briquettes. One replicate was performed.
- Grindability – Measured for briquettes, torrefied biomass chips, and dry feedstock by modifying the SECTOR Determination of Grinding Energy test method (SECTOR, 2014). Briquettes were cut into 25 mm × 25 mm × 13 mm (1 in. × 1 in. × 0.5 in.) rectangular prisms weighing approximately 8 g with a band saw. Torrefied biomass chips and feedstock were separated into 8 g samples before input to the grinder. Material was fed in a mill (Thomas Scientific, Model 4 Wiley Mill, Swedesboro, N.J.) with a 2-mm grate for 120 s at

a feed rate of one 8-g sample every 10 s and allowed to grind for 180 s. The SECTOR method calls for a 1-mm grate, but a 2-mm grate was used for this test as it was the smallest available grate. The mill's electrical power consumption was recorded in one-second intervals (Continental Control Systems, WNC-3Y-208-MB and ACT-0750-020, Longmont, Colo.). The grinding power is calculated as the difference between the average power during 180 s of material grinding and the average idle power measured during 3 min before and after the test (see fig. 5). The average grinding power is used to calculate the specific grinding energy, or grindability, in Wh/kg. Duplicate tests were performed for each material then averaged for the final value. The standard deviations of grinding power are calculated using the data from 1-s intervals of both duplicate tests combined. The sample size of power measurements ranges from 300 to 600. The variability of the electricity demand during grinding leads to large standard deviations, some of which have coefficients of variation up to 50%.

- The particle size distribution of ground material was measured by shaking a stack of 203-mm (8-in.) diameter sieves with mesh sizes 2 mm, 1 mm, 0.5 mm, 0.35 mm, 0.25 mm, 0.15 mm, 0.075 mm, and pan for 10 min. After shaking, the mass retained on each sieve was measured to the nearest ±0.1 g (Ohaus, BrainWeigh B 3000D, Florham Park, N.J.).
- Gross Calorific Value – Measured for feedstock and torrefied biomass in a bomb calorimeter (Parr Instruments, Model 1241, Moline, Ill.) using standard operating protocols described by Parr Instruments (2017). Two replicates were performed.
- Moisture content – Measured for feedstock, torrefied biomass, and briquettes using a moisture analyzer balance (BEL Engineering, i-Thermo 163L, Monza, Italy). Three replicates were performed.
- Particle size distribution – Measured for feedstock and torrefied biomass by mechanically shaking for 10 min a stack of 8-in. diameter sieves with the following mesh sizes: 25.4 mm, 12.7 mm, 3.175 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, and pan. After shaking, the mass retained on each sieve was measured to the nearest ±0.1 g (Ohaus, BrainWeigh B 3000D, Florham Park, N.J.). One replicate was performed.
- Proximate analysis – Measured for feedstock and torrefied biomass using a thermogravimetric analyzer (TA Instruments, Q50) with the following temperature program: under a nitrogen purge gas, heat to 95°C at a ramp rate of 80°C min^{-1} then to 105°C at a ramp rate of 10°C min^{-1} and hold for 10 min to dry the sample; heat to 685°C at a ramp rate of 80°C min^{-1} then to 700°C at a ramp rate of 10°C min^{-1} and hold for 25 min to measure volatile matter; then switch the purge gas to air and hold at 700°C for 10 min to measure ash content. One replicate was performed.
- Transportation simulation – Measured for feedstock, torrefied biomass, and briquettes in an environmental chamber (Espec, EPL-3H). Densified material was measured using two briquettes; torrefied biomass chips and feedstock were measured using approximately 5 g. The temperature and humidity in the environmental chamber were changed in 2-h increments to simulate an eight-day shipping route from the Pacific Northwestern United States to East Asia using environmental conditions adapted from Leinberger (2006). Temperatures ranged from 14°C to 26°C with relative humidity between 77% and 88%. After removal from the environmental chamber, briquettes were put through the durability test described above. Two replicates were performed.
- Water absorption – Measured for feedstock, torrefied biomass, and briquettes by placing one briquette or approximately 100 g of raw or torrefied biomass in an environmental chamber (Espec, EPL-3H, Hudsonville, Mich.) at 50°C, 95% relative humidity. Briquette mass was measured to the nearest ±0.1 g every 24 h. The test was complete after the change in mass was <0.1% in 24 h. Water absorption is reported as the mass gained as a percentage of dry weight. Two replicates were performed.

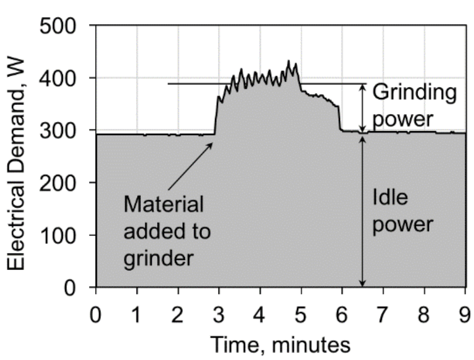


Figure 5. Electrical demand for the mill during a grindability test for F400L.

RESULTS

The average values for input rates, production rates, and a mass balance of the system during each test are reported in table 3. Mean values for electrical demand and reactor temperatures during steady state operation of the torrefier for each test are shown in table 4. The material properties and

Table 3. Mass balance of torrefier system.

	Mass Inputs		Mass Outputs		
Test ID	Biomass Input, kg h^{-1} (d.b.)	Moisture Input, kg h^{-1}	Torr. Output, kg h^{-1} (w.b.)	Condensate Production, kg h^{-1}	Torr Gas Output, kg h^{-1} [a]
F375H	648	209	576	137	144
F400L	649	28	552	100	26
F400H	417	141	404	122	32
F425L	466	46	325	95	93
F425M	439	61	349	86	66
S300M	203	39	184	40	19
S325H	194	50	183	76	6
S350M	204	28	141	54	38
S350H	216	60	183	85	7
S400M	205	30	84	109	41
S400H	197	46	129	100	13

[a] Calculated by difference.

Table 4. Torrefier operating characteristics including electrical demand and reactor temperature profile.[a]

Test ID	Avg. Total Elec Power, kW	Avg. Elec Power, Heater Only, kW	Avg. T_{P1}, °C	Avg. T_{P2}, °C	Avg. T_{P3}, °C	Avg. T_{S1}, °C	Avg. T_{S2}, °C	Sample Size
F375H	112 (71)	98 (63)	100 (1)	128 (3)	156 (8)	239 (7)	261 (6)	1,140
F400L	135 (46)	111 (45)	112 (2)	230 (11)	267 (14)	294 (2)	324 (2)	540
F400H	139 (60)	117 (52)	103 (3)	145 (16)	176 (25)	276 (16)	301 (18)	2,330
F425L	142 (47)	121 (41)	113 (1)	217 (9)	275 (11)	254 (3)	288 (4)	1,003
F425M	160 (46)	132 (34)	103 (<1)	169 (2)	226 (5)	240 (1)	270 (1)	1,065
S300M	93 (52)	83 (53)	100 (<1)	145 (5)	171 (6)	193 (2)	214 (2)	1,347
S325H	91 (48)	86 (49)	100 (<1)	143 (1)	188 (4)	200 (1)	219 (1)	1,470
S350M	72 (55)	66 (52)	108 (1)	224 (6)	265 (11)	220 (3)	254 (6)	2,509
S350H	102 (52)	92 (50)	102 (<1)	168 (9)	215 (16)	228 (2)	253 (2)	1,580
S400M	79 (56)	69 (54)	107 (1)	244 (14)	314 (19)	232 (6)	251 (7)	2,590
S400H	91 (54)	78 (51)	102 (<1)	206 (9)	287 (5)	222 (2)	252 (5)	2,101

[a] Standard deviations are shown in parentheses; calculated with the sample size listed in the table.

quality characteristics are shown in table 5 for feedstock and torrefied biomass chips and table 6 for briquettes. Torrefied biomass and briquettes from run F400L are pictured in figure 6.

Condensate production rates reported in table 3 are influenced by moisture content input rate and torrefaction conditions. The condensate is composed primarily of water with some condensable tars and gases. The amount of water condensed is influenced by the moisture content of the feedstock, and the production of condensable tars is influenced by the reaction conditions. Greater moisture content input rates, which are calculated as the product of feedstock input rate and moisture content (w.b.), tend to accumulate more condensable gases. The two tests with the highest moisture content input rates, F375H and F400H, also have the highest condensate production rates of 137 and 122 kg h^{-1}, respectively. Torrefaction conditions also influence the condensate production rate, where higher temperatures and longer RTs create more condensable gases. A weak correlation was discovered between the temperature of the headspace at the end of the reactor (T_{S2}) and the condensate production rate.

Unexpectedly, the ash content of the torrefied product was lower than the ash content of the feedstock biomass. The

Table 5. Quality characteristics of feedstock and torrefied biomass chips.[a]

Test ID	Torr. Chip Moisture Content, % w.b.[b]	Ash Content, %, d.b.[b]	Volatile Matter, %, d.b.[b]	Fixed Carbon, %, d.b.[b]	Bulk Density, kg m^{-3} (w.b.)	Gross Calorific Value, MJ kg^{-1} (d.b.)	Grindability, Wh kg^{-1} (w.b.)	Grindability Sample Size, No. of Power Readings	Geometric Mean Particle Size, mm
FS	Varies	3.4	81	16	200	19.6 (0.1)	115 (46)[c]	525	5.9
F375H	5.9 (<0.1)	0.8	83	17	221	20.0 (0.2)	168 (85)	403	4.9
F400L	0.6 (<0.1)	1.4	75	24	208	21.2 (<0.1)	30 (17)	367	5.5
F400H	2.2 (0.5)	1.8	81	17	234	19.9 (0.2)	143 (58)	359	3.7
F425L	0.9 (<0.1)	2.5	71	27	198	23.0 (<0.1)	26 (17)	359	4.2
F425M	0.3 (<0.1)	2.5	79	19	232	20.8 (0.1)	98 (59)	355	5.9
S300M	0.4 (<0.1)	2.7	80	17	221	19.7 (0.2)	107 (54)	360	5.0
S325H	0.5 (0.1)	1.7	81	17	235	19.7 (0.1)	117 (56)	358	2.7
S350M	0.6 (<0.1)	2.2	74	23	211	21.7 (0.2)	38 (24)	368	6.3
S350H	0.4 (<0.1)	1.3	81	17	237	19.7 (0.0)	104 (50)	371	5.6
S400M	0.9 (<0.1)	13.4	37	49	163	25.8 (0.1)	6 (8)	351	4.9
S400H	0.9 (<0.1)	4.1	72	24	214	20.7 (0.1)	41 (20)	358	5.0

[a] Standard deviations are shown in parentheses where available; calculated using a sample size of two for HHV, three for moisture content, and the listed sample size for grindability.
[b] Proximate analysis is measured on a percent mass basis.
[c] Feedstock grindability was tested bone-dry, while all the torrefied sampled were tested at their as-received moisture content.

Table 6. Briquette quality characteristics.[a]

Test ID	Avg. Mass, kg (w.b.)	Moisture Content, % mass, w.b	Packing Density, kg m^{-3} (w.b.)	Grindability, Wh kg^{-1} (d.b.)	Grindability Sample Size, No. of Power Readings	Durability, % DU	Durability after Transportation Simulation, % DU
NTB	0.78	8.3	920	323 (98)	347	85%	84%
F375H	0.75	4.1	974	234 (55)	333	95%	51%
F400L	0.70	0.6	977	117 (13)	319	96%	71%
F400H	0.73	3.3	885	200 (22)	364	69%	10%
F425L	0.71	0.6	1000	123 (17)	328	93%	77%
F425M	0.70	0.2	896	95 (41)	335	90%	33%
S300M	0.70	0.7	810	173 (32)	330	80%	12%
S325H	0.72	0.7	923	176 (30)	325	85%	41%
S350M	0.69	0.5	942	110 (13)	325	92%	79%
S350H	0.70	1.1	911	165 (36)	339	80%	14%
S400M[b]	n/a	n/a	n/a	n/a	n/a	n/a	n/a
S400H	0.70	0.9	921	113 (19)	324	68%	76%

[a] Standard deviations are shown in parentheses where available; calculated with the sample size listed in the table.
[b] Did not bind together to form a briquette.

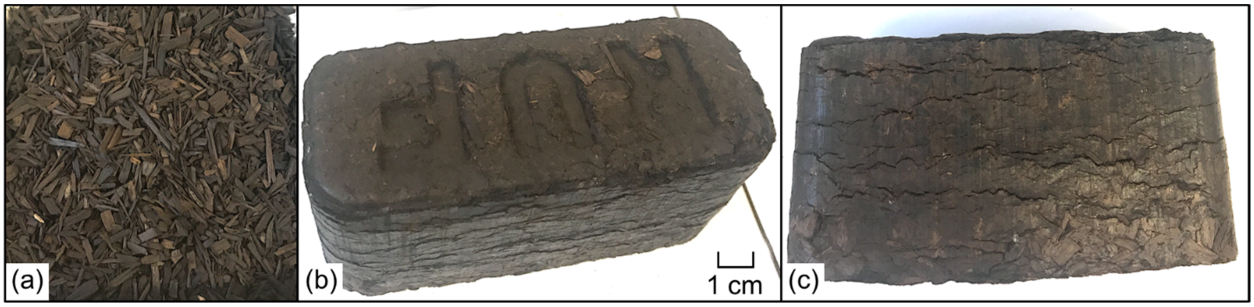


Figure 6. Pictures of (a) torrefied biomass, (b) isometric, and (c) side views of torrefied briquettes produced in run F400L. All pictures use the same 1-cm scale.

relative ash content was expected to increase after torrefaction, as seen by Felfli et al. (2005) and Li et al. (2012), because the torrefaction process releases some volatile matter while retaining all the non-volatile ash content. However, the ash content decreased in this study, which was also observed in some cases by Phanphanic and Mani (2011) and Strandberg et al. (2015). The ash content is hypothesized to decrease because small, dense mineral particles were retained in the bottom of the trough in the auger-based reactor and cooling systems. After completing the torrefaction tests, a sizeable amount of inorganic, noncombustible mineral content was observed resting between the flights of the auger and the trough both in the reactor and in the cooling system. Ash particulate could also be lost as suspended particles in the gas stream or on the inlet or outlet conveyors.

Water absorption characteristics were evaluated by measuring 1) the moisture content after a transportation simulation and 2) the mass gained after reaching saturation in a 50°C, 95% relative humidity environment. Results for water absorption of torrefied biomass are shown in table 7 for chips and briquettes.

To characterize the degree or severity of torrefaction, the mass yield, energy yield, and energy density enhancement factor (EDEF) are calculated in table 8. The EDEF is the ratio between the higher heating value of torrefied biomass and the feedstock, calculated as $EDEF = HHV_{torr} / HHV_{FS}$, where HHV_{torr} is the higher heating value of torrefied biomass on a dry basis and HHV_{FS} is the higher heating value of the feedstock on a dry basis. The EDEF represents the degree of torrefaction, where higher values indicate more severely torrefied biomass. Even though some of the feedstock's original mass and energy is lost during the torrefaction process, the resulting torrefied biomass has a greater energy density as indicated by EDEFs greater than 100%.

Table 8. Calculated metrics.

Test ID	Mass Yield, dry basis	Energy Yield	Energy Density Enhancement Factor
F375H	84%	85%	102%
F400L	84%	92%	108%
F400H	95%	96%	102%
F425L	69%	81%	117%
F425M	79%	84%	106%
S300M	90%	91%	101%
S325H	94%	94%	100%
S350M	69%	76%	111%
S350H	85%	85%	100%
S400M	41%	53%	132%
S400H	65%	69%	106%

DISCUSSION

This section provides a discussion and interpretation of the results presented above.

REACTOR TEMPERATURE PROFILE

A typical reactor temperature profile from startup to shutdown is shown in figure 7. Point (1) shows that, as the reactor is preheated without feedstock, all temperatures within the reactor increase toward the setpoint. Both temperature measurements in the headspace, TS1 and TS2, increase beyond the setpoint, indicating that heat is being released within the reactor from combustion of residual biomass from the previous day and air that filled the reactor when it was

Table 7. Moisture absorption characteristics.[a]

Test ID	Chips: Absorptivity, % mass gained, d.b.	Chips: Moisture Content after Transportation,% mass, w.b.,	Briquettes: Absorptivity, % mass gained, d.b.	Briquettes: Moisture Content after Transportation,% mass, w.b.
NTB	14%	8.6%	10%	10.9% (0.2%)
F375H	10%	9.3%	13%	8.6% (0.4%)
F400L	7%	4.1%	11%	5.7% (0.1%)
F400H	12%	8.9%	13%	10.2% (0.4%)
F425M	7%	8.6%	16%	8.1% (0.5%)
F425L	15%	5.7%	11%	5.7% (0.5%)
S300M	14%	9.6%	16%	9.1% (0.4%)
S325H	6%	10.3%	16%	8.3% (<0.1%)
S350M	8%	4.0%	10%	5.9% (0.2%)
S350H	13%	8.2%	13%	9.0% (0.1%)
S400M	15%	n/a	n/a	n/a
S400H	7%	6.2%	9%	5.7% (0.2%)

[a] Standard deviations are shown in parentheses where available for a sample size of three.

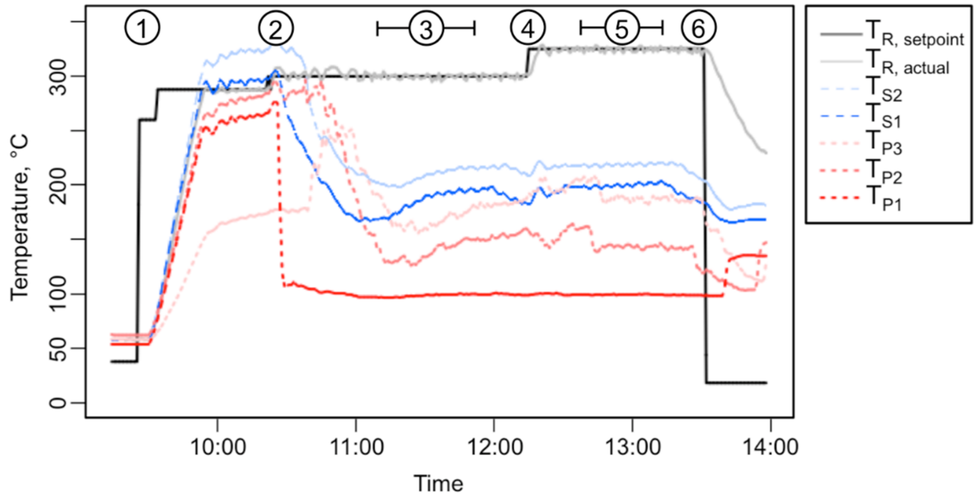


Figure 7. Reactor temperatures during tests S300M and S325H. Circled numbers highlight events that are described within the text.

shutdown. Also during preheating, TP3 approaches a much lower temperature than the other temperature measurements within the reactor. This may be due to the close proximity between the TP3 thermocouple and the reactor exit into the cooling auger. Air flowing backwards through the reactor exit air lock may be cooling the exposed thermocouple until it is covered with biomass.

Feedstock is introduced to the system at Point (2). The temperature at T_{P1} immediately drops to approximately 100°C. Conversely, T_{P3} sharply increases in temperature as combusting biomass on the leading edge of the plug flows through the end of the reactor. Biomass appears very dark in color and partially combusted as it begins to enter the cooling auger. Following Point (2), nitrogen purge gas is added to the reactor to evacuate any residual oxygen in the headspace. By 11:10, when combustion appears to have subsided because T_{P3} becomes relatively stable around 160°C, the nitrogen purge gas is shut off and the first steady state test can begin.

The first steady state period is centered around Point (3) during which no adjustments are made to the setpoints or controls. After that test is complete, the temperature setpoint is increased from 300°C to 325°C at Point (4). Once the reactor temperatures stabilize again around 12:25, the second steady state test is conducted centered around Point (5). After the second test is complete, the reactor heater setpoint is changed back to ambient temperature at Point (6). The addition of feedstock is terminated at approximately 13:45. At this point, T_{P1} increases sharply, followed subsequently by increases in T_{P2} and T_{P3} as the reactor becomes empty.

All tests displayed similar temperature profiles to those described above. The first biomass temperature measurement T_{P1} hovers around 100°C as shown in figure 7 and table 3, indicating that water is being evaporated. The two highest mean temperatures at T_{P1} of 111°C come during tests with the driest feedstock F400L (4%) and F425L (9%). During these tests, the moisture had already evaporated before reaching T_{P1} and the biomass began heating beyond water's boiling point. Biomass continued to be heated while moving through the reactor. Within the 0.9 m distance between the final two product temperature measurements – T_{P2} and T_{P3} – the biomass is being heated at a rate between 8°C min^{-1} and 35°C min^{-1}. The final temperature measurement of biomass in the reactor at T_{P3} is significantly lower than the reactor temperature setpoint, showing that the temperature setpoint cannot be used as the torrefaction target temperature in this reactor.

While conditions for torrefaction occur between 250°C and 300°C, the target reactor temperature must be set much higher for the biomass to reach these temperatures near the outlet. The temperature at T_{P3} rather than the temperature of the heating element is the best metric to gauge the degree of torrefaction, as indicated by the plot of EDEF versus T_{P3} in figure 8. Higher temperatures at T_{P3} generally indicate a greater EDEF. The two tests with the highest temperatures at T_{P3}, however, have a large spread between their EDEF. Test S400M reached an average of 314°C at T_{P3} and an EDEF of 132%, which exceeds the torrefaction regime and became more akin to a biomass char. The next highest T_{P3} temperature (S400H at 287°C) produced torrefied biomass with an EDEF of only 106%; besides this test, the EDEF followed a fairly predictable trend as a function of the TP3 temperature.

For a continuous reactor to operate at commercial scale, it is important to have good control over product quality and

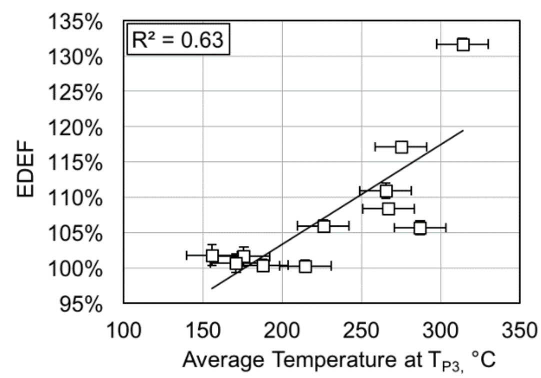


Figure 8. Energy density enhancement factor as a function of product temperature near the exit of the reactor. Error bars show one standard deviation from the mean.

characteristics even if there is variation on the feedstock inlet. Rather than controlling the torrefaction temperature by selecting the heating element temperature setpoint, it would be more effective to select a target temperature at the reactor outlet and have a maximum heating element temperature as a safety feature.

Electricity Consumption

Electricity consumption of the torrefier is primarily a function of the thermal load required in the reactor, which depends on the reactor temperature and residence time. Average electrical demand ranged from 112 to 160 kW for 10-min residence times and 72 to 102 kW for 20-min residence times (table 3). The reactor heating element consumes the majority of this energy, comprising approximately 90% of the total load (table 3). The specific electricity consumption, calculated as the average electricity demand divided by the production rate of torrefied biomass, is shown in figure 9 for 10-min (triangle symbols) and 20-min (circle symbols) RT tests. The data show that, despite a higher power demand in kW during 10-min RT tests, the increased throughput rate from shorter RTs consume less energy to produce an equivalent amount of torrefied biomass. This indicates short RTs may be desirable for high throughput and lower electrical energy consumption, as long as the torrefied biomass can reach the appropriate quality standards. Figure 9 also shows that for a consistent RT, higher reactor setpoint temperatures require more specific electrical energy due to increased load of the reactor.

Electricity consumption of the briquetting process did not vary based on the feedstock type or degree of torrefaction. Briquetting raw feedstock or torrefied biomass both required approximately 0.03 kWh per briquette. The average electricity demand was 27 kW when the briquetter was operating, but it could occasionally drop to zero if the briquetter's throughput was outpacing the production rate of the torrefier.

Grindability

Torrefaction reduces the specific grinding energy required to comminute biomass into a powder. Figure 10 shows the relationship between specific grinding energy and torrefaction temperature (mean temperature at T_{P3}). The two horizontal lines indicate baseline values for specific grinding energy of non-torrefied briquettes or bone dry feedstock. The grindability of torrefied chip exiting the reactor (grey circles in fig. 10) can be divided into two groups: greater than 100 Wh kg^{-1} and less than 40 Wh kg^{-1}. The first process that reduces the specific grinding energy requirements for torrefied biomass is through dehydration. The first group (greater than 100 Wh kg^{-1}) displays similar grindability to bone-dry feedstock (horizontal line), and the final product temperature of these six tests is less than 225°C, indicating that significant thermal decomposition did not occur. The two torrefied biomass samples that exited the reactor with moisture content above 2% (F375H and F400H) required more energy to grind than the bone-dry feedstock, which is expected because dehydration is the first mechanism to improve grindability and the feedstock was analyzed at 0% moisture content. The second mechanism to improve grindability is decomposition. The five torrefied chip samples with specific grinding energies less than 40 Wh kg^{-1} were the same five tests with EDEF greater than 105%. The severely torrefied chip from test S400M had a grinding energy of just 5.7 Wh kg^{-1}. Densifying the torrefied biomass increased the grinding energy requirements (shaded squares in fig. 10) compared to the non-densified chips, but the grindability was still significantly better than raw biomass briquettes produced in test NTB (upper dashed line). Torrefied briquettes with an EDEF greater than 105% had grinding energy requirements approximately 30% of the raw biomass briquettes.

Briquette Durability

Torrefied biomass was compressed into briquettes without difficulty using identical settings on the briquetter. All tests produced dense, durable briquettes except for test S400M, which would not bind together because it was so severely torrefied (EDEF = 132%). The other torrefied briquettes showed durability values ranging from 68% to 96%; raw biomass produced briquettes with 85% durability. The durability was tested a second time after cycling through an

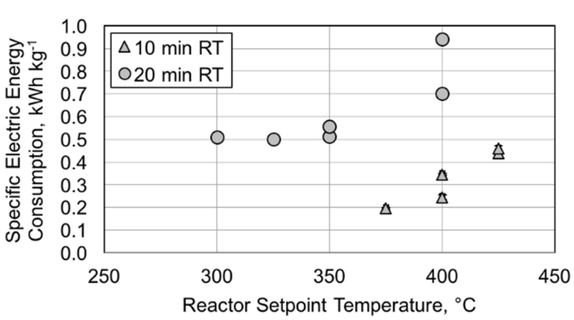


Figure 9. Specific electricity demand during steady state versus reactor temperature setpoint. Specific electrical load is calculated as the average power divided by the torrefied biomass output rate. Vertical error bars show the estimated standard deviation based on first-order propagation of error. Most of the error bars are so small they are hidden behind the data marker.

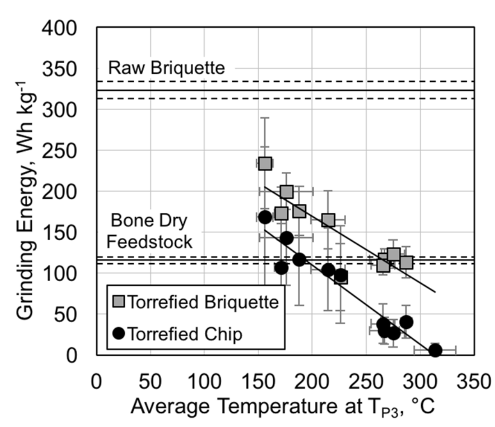


Figure 10. Specific grinding energy of torrefied briquettes (grey squares) and chips (black circles) versus temperature of biomass towards exit of reactor (T_{P3}). Error bars show one standard deviation. Horizontal lines show baseline grindability for raw briquettes (top) and bone dry feedstock bottom, where the dashed lines show a 95% confidence interval for the baseline value.

eight-day overseas transportation simulation with temperature and humidity fluctuations, as described in the methods section. The durability of raw briquettes was less affected by transportation, showing a reduction of just 1%, while the durability of the torrefied briquettes was reduced by values ranging from 13% to 68% except for S400H, which unexpectedly showed an increase in durability. The environmental variation experienced during the transportation simulation affect the durability of the torrefied briquettes to a greater extent than the raw briquettes. This could pose a potential drawback for long distance shipping of torrefied briquettes and should be investigated further.

Further research and testing is required to fully understand which physical parameters are influencing the briquette durability because a clear pattern does not arise from these test data. Five of the torrefaction conditions (F400L, F400H, F425M, F425L, and S350M) produced briquettes that were greater than 90% durable, three of which also displayed a greater than 75% durability after transportation (F400L, F425L, and S350M). This subset of three tests that displayed the best durability results is also the same three tests that had the highest EDEF (excluding test S400M, which was so heavily torrefied that it appeared to be a biochar). These results indicate that torrefied biomass with a relatively high EDEF (108%-117%) also produces briquettes with the best durability values of greater than 90% and 75% before and after transportation, respectively.

Particle Size Distribution

The particle sizes of biomass become smaller following torrefaction. The geometric mean particle size of all torrefied biomass samples combined was 4.9 mm compared to 5.9 mm for raw feedstock. Figure 11 shows the particle size distribution of torrefied biomass from each test (dashed lines) compared to bone-dry feedstock (solid line). In all cases except for one test, the torrefied biomass contains more small particles, especially in the 1 to 3 mm range. Due to the tighter packing structure of smaller particles sizes and reduced biomass swelling after moisture removal, the bulk density of the torrefied biomass is higher than the feedstock on a bone-dry basis.

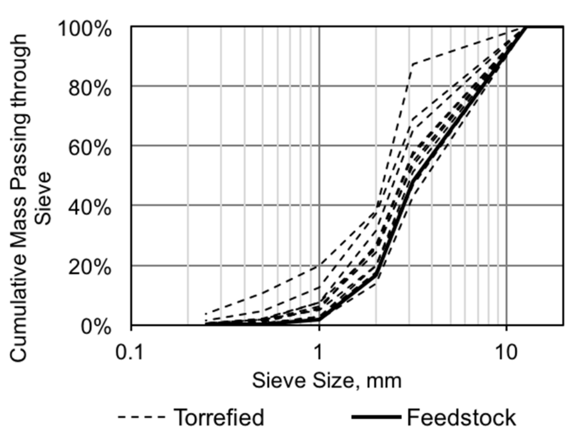


Figure 11. Particle size distribution of biomass before and after torrefaction.

Energy Density

Torrefaction increases the energy density on a mass basis by decomposing hemicellulose and giving off molecules with low energy values contained in the original biomass feedstock. Although up to 20% of the original bone-dry mass and total energy content may be lost, the volumetric energy density [GJ m^{-3}] increased because the torrefied biomass has higher bulk density and calorific value than the original feedstock. The volumetric energy density is further increased between 300% and 500% by briquetting the torrefied biomass. Figure 12 shows the volumetric energy density of the feedstock (~4 GJ m^{-3}), torrefied biomass (~5 GJ m^{-3}), and briquettes (16-23 GJ m^{-3}) for all tests.

Optimal Torrefaction Conditions

The optimal torrefaction conditions will create a torrefied biomass that 1) can be transported effectively with a high energy density, 2) can be used as an alternative to coal, and 3) is produced quickly with low energy demand. These three desirable production characteristics are evaluated and discussed below.

Efficient transportation of biomass requires high calorific value, density, and durability after transportation. This characteristic is evaluated as the volumetric energy density after the transportation simulation, which is calculated by multiplying the heating value, briquette packing density, and post-transportation durability. This quantifies the energy delivered per unit volume after being exposed to temperature, humidity, and mechanical disturbances during transportation. Figure 13 plots these results for all briquette types. Five briquettes perform notably better than the rest, delivering over 14 GJ m^{-3} after transportation, including non-torrefied briquettes (NTB) and four torrefied briquettes: F400L, F425L, S350M, and S400H. This group of five briquettes performed well in this category primarily because they had the highest post-transportation durabilities (>70%) relative to the other tests.

To gauge the torrefied briquettes as a suitable replacement or supplemental fuel for coal in power plants, they are evaluated based on specific grinding energy, moisture absorption, and heating value. These properties were determined to be the most important because low grinding energy is required to pulverize biomass before entering a coal power

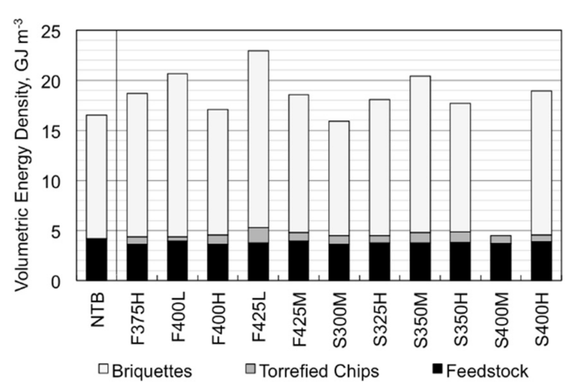


Figure 12. Volumetric energy density at different stages of the process. The maximum height of each shaded region of every bar represents the energy density of that product, i.e., torrefied chips are in the range of 4 to 6 GJ m^{-3} and briquettes range from 16 to 23 GJ m^{-3}.

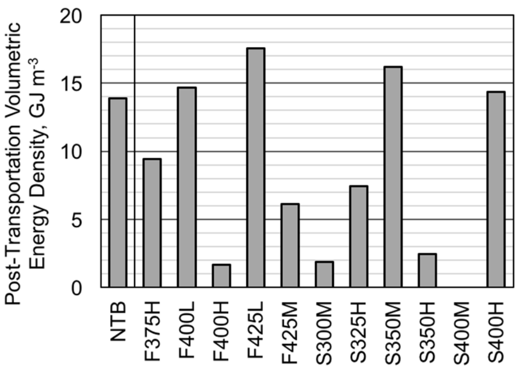
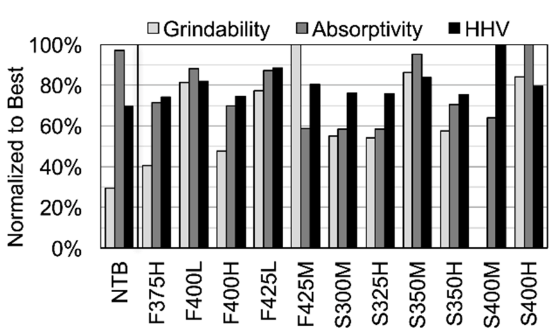


Figure 13. Volumetric energy density multiplied by transportation durability for all tests after the transportation simulation.

plant, low absorption is desirable to maintain low moisture content during storage in wet or humid environments, and high calorific value is necessary to deliver an energy density similar to coal. The results for each of these properties, normalized against the best result across all tests, are displayed in figure 14 (The values are normalized against the best performing sample for each property. For tests where lower values are desirable, i.e. grindability and absorption, the normalized value of property x for sample i is calculated as $N_{x,i} = min(x_{all\ tests}) \div x_i$. For test where higher values are desirable, i.e., the HHV, the normalized value of property x for sample i is calculated as $N_{x,i} = x_i \div max(x_{all\ tests})$. To determine the most suitable replacement for coal across all three measures, the normalized result is averaged with each property having equal weight. The average value and relative rankings are shown at the bottom of figure 14. The four highest ranking briquettes are F400L, F425L, S350M, and S400H, which are the same four torrefied briquettes identified above that provide the highest volumetric energy density after transportation.

Lastly, a high production rate with low electrical demand is preferable for the producer to generate revenue at the greatest rate. Of the four torrefaction conditions identified above that are effective for transportation and a good replacement for coal, two of the torrefied briquettes were produced with a 10-min RT and two were produced with a 20-min RT. As shown in Table 3 in the results section, the bone-dry input rates for the two selected 10-min RT tests are at least 100% higher than the two 20-min tests: 466 and 649 kg h^{-1} compared to 197 to 204 kg h^{-1}, respectively. Additionally, the specific electrical energy consumption in kWh/kg for all 10-min RT tests was lower than all 20-min RT tests (see fig. 9). Thus, the shorter residence times of F400L and F425L provide both higher throughput rates and lower energy consumption, making the 10-min RT superior to the 20-min RT.



	NTB	F375H	F400L	F400H	F425L	F425M	S300M	S325H	S350M	S350H	S400M	S400H
Average	65%	62%	84%	64%	84%	80%	63%	63%	88%	68%	82%	88%
Ranking	8	12	4	9	3	6	10	11	1	7	5	2

Figure 14. Grindability, absorptivity, and higher heating value (w.b.) of briquettes normalized to the best result in each category. The values below the chart indicate the average of the three normalized values and the respective ranking of each torrefied briquette.

Taking into account the three desirable characteristics discussed above – transportability, replacement for coal, and high production – two test conditions, F400L and F425L, appear the most favorable. Both of these test conditions processed low moisture content feedstock at a short residence time. These results indicate that:

- A shorter residence time is best as long as the process can sufficiently torrefy biomass to over 106% EDEF.
- It may be advantageous to use a separate biomass drying system upstream of the torrefier reactor so that the feedstock enters at a low moisture content, rather than using the beginning of the torrefier to evaporate moisture.

Briquettes produced in this study are compared against typical properties of coal in table 9. The moisture and ash contents of torrefied briquettes are lower than coal, but the fixed carbon content is comparable to low-grade, lignite coal. The bulk density of both torrefied and non-torrefied briquettes compares to the higher range of coal bulk densities. The heating value of torrefied briquettes is slightly lower than bituminous coal, while the heating value of raw briquettes falls in the upper limit of lignite coals.

Comparison between Raw and Torrefied Briquettes

The torrefied briquettes identified in the previous section outperform raw biomass briquettes in terms of higher heating value, volumetric energy density, grindability, and durability. The raw briquettes, however, appear to be slightly more resistant to moisture by displaying lower absorptivity and better durability after transportation simulation. Furthermore, production of raw briquettes will be significantly cheaper and less energy intensive by removing the torrefaction processing step. Raw biomass briquettes may be a better fuel if there are not strict guidelines for heating value, volumetric energy density, and grindability for the end user. In the case of utilizing existing coal boilers and fuel handling systems that require fuel within a specific range of grinding energy, moisture content, and calorific value, torrefied briquettes can be an effective alternative or supplemental fuel.

Conclusions

A pilot-scale plant to produce torrefied and densified biomass from forest residuals has been demonstrated. High quality torrefied briquettes were produced at a rate of up to 550 kg h^{-1} while displaying EDEFs over 108% with sharp reductions in grinding energy, high durability before transportation, and better volumetric energy density than raw biomass briquettes. Experimental results indicate that low

Table 9. Fuel properties of coals and biomass briquettes.

	Fuel	Moisture Content (w.b.)	Fixed Carbon (d.b.)	Ash Content (d.b.)	Bulk or Packing Density[a], kg m^{-3}	HHV, MJ kg^{-1}
Coal	Anthracite[b]	< 15%	85%-98%	10%-20%	800-930	30-35
	Bituminous[b]	2%-15%	45%-85%	3%-12%	670-910	26-35
	Lignite[b]	30%-60%	25%-35%	10%-50%	640-860	9-19
Biomass	Torrefied Briquettes[c]	0%-1%	24%-27%	1.4%-2.5%	900-1,000	21-23
	Raw Biomass Briquettes[d]	8%	16.0%	3.40%	920	19.6

[a] Bulk density listed for coal; packing density listed for briquettes.
[b] Data from Bowen and Irwin (2008) and Yaşar (2012).
[c] Range of values for tests F400L and F425L.
[d] Data from test NTB.

moisture content and short residence time of torrefaction are favorable for production of biomass with high throughput rate and low electricity demand.

Future work should investigate scaling up the equipment and improving key aspects of the process, which are identified below.

- The output rate of the system should be further increased and optimized for the conditions identified above.
- Alternative heating sources, such as utilizing energy from the syngas produced during the reaction, should be investigated to reduce the electrical demand of the reactor heating element.
- Long term tests should be conducted on the gas handling and tar removal system to determine operations and maintenance requirements over a longer time period.
- Additional research should be conducted to understand how torrefaction conditions affect the durability of torrefied briquettes after moisture and humidity fluctuations (transportation simulation).
- The economic feasibility of installing a biomass dryer upstream of the torrefier should be examined so that a broader range of feedstock moisture contents can be input to the reactor at ideal conditions. Additional benefits of a separate dryer may also be realized, including a reduction in time spent evaporating water within the torrefier reactor and a decrease in the amount of condensate collected in the gas handling system.

Acknowledgments

This material is based upon work supported by a grant from the U.S. Department of Energy under the Biomass Research and Development Initiative program: Award Number DE-EE0006297. Funding for the work using the dryer was provided by the California State University, Agricultural Research Institute: Award Number S3062.

The authors appreciate the support of Norris Thermal Technologies for technical assistance and operation and maintenance of the torrefier and dryer; RUF Briquetting Systems for providing a briquetting press; Green Diamond Resource Company and California Redwood Company for access to a testing site in Samoa, California; Steve Morris Logging Company for providing feedstock for testing; and Dr. Han-Sup Han, Professor of Forest Operations and Engineering at Humboldt State University, for his guidance and insight directing this project. The authors also acknowledge support from personnel at Schatz Energy Research Center for field work, data analysis, project management, and laboratory analysis from David Carter, Emily Klee, Kyle Palmer, Yaad Rana, and Richard Williams, which was integral to the success of these experiments. The authors appreciate constructive comments from five anonymous reviewers.

References

Araujo, S., Boas, M. A. V., Neiva, D. M., Carneiro, A. C., Vital, B., Breguez, M., & Pereira, H. (2016). Effect of a mild torrefaction for production of eucalypt wood briquettes under different compression pressures. *Biomass Bioenergy, 90*, 181-186. https://doi.org/10.1016/j.biombioe.2016.04.007

Benavente, V., & Fullana, A. (2015). Torrefaction of olive mill waste. *Biomass Bioenergy, 73*, 186-194. https://doi.org/10.1016/j.biombioe.2014.12.020

Bergman, P. C. A. (2005a). Combined torrefaction and pelletisation: The TOP process. ECN Report, ECN-C-05-073. Utrecth, Netherlands: ECN.

Bergman, P. C. A., Boersma, A. R., Zwart, R. W. R., & Kiel, J. H. A. (2005b). Torrefaction for biomass co-firing in existing coal-fired power stations. ECN Report, ECN-C-05-013. Utrecth, Netherlands: ECN.

Bowen, B. H., & Irwin, M. W. (2008). Coal characteristics: CCTR basic facts file #8. West Lafayette, IN: The Energy Center at Discovery Park, Purdue University. Retrieved from http://www.purdue.edu/discoverypark/energy/assets/pdfs/cctr/outreach/Basics8-CoalCharacteristics-Oct08.pdf

CEN Stnadards. (2005). CEN/TS 15103:2005 Solid biofuels: Methods for determination of bulk density. Brussels, Belgium: CEN.

Chang, S., Zhao, Z., Zheng, A., He, F., Huang, Z., & Li, H. (2012). Characterization of products from torrefaction of sprucewood and bagasse in an auger reactor. *Energy Fuels, 26*(11), 7009-7017. https://doi.org/10.1021/ef301048a

Chen, W.-H., Peng, J., & Bi, X. T. (2015). A state-of-the-art review of biomass torrefaction, densification and applications. *Renewable Sustainable Energy Rev., 44*, 847-866. https://doi.org/10.1016/j.rser.2014.12.039

Doassans-Carrere, N., Muller, S., & Mitzkat, M. (2014). REVE: A new industrial technology for biomass torrefaction: Pilot studies. *Fuel Process. Technol., 126*, 155-162. https://doi.org/10.1016/j.fuproc.2014.04.026

EIA. (2016). International Energy Outlook 2016. Washington, DC: U.S. Department of Energy, Office of Energy Analysis. Retrieved from www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf

Felfli, F. F., Luengo, C. A., Suarez, J. A., & Beaton, P. A. (2005). Wood briquette torrefaction. *Energy for Sustainable Development, 9*(3), 19-22. https://doi.org/10.1016/S0973-0826(08)60519-0

ISO Standards. (2013). ISO/DIS 17831-2 Solid biofuels: Determination of mechanical durabilitliy of pellets and briquettes. Part 2: Briquettes. Geneva, Switzerland: ISO.

Karlsson, J. (2013). Evaluation of torrefaction pilot plant in Klintehamn, Gotland. MS thesis. Lund, Sweden: Lund University, Department of Chemical Engineering.

Leinberger, D. (2006). Ocean container temperature and humidity study. Technical Report. Xerox Corp.

Li, J., Brzdekiewicz, A., Yang, W., & Blasiak, W. (2012). Co-firing based on biomass torrefaction in a pulverized coal boiler with aim of 100% fuel switching. *Appl. Energy, 99*, 344-354. https://doi.org/10.1016/j.apenergy.2012.05.046

Mei, Y., Liu, R., Yang, Q., Yang, H., Shao, J., Draper, C.,... Chen, H. (2015). Torrefaction of cedarwood in a pilot scale rotary kiln and the influence of industrial flue gas. *Bioresour. Technol., 177*, 355-360. https://doi.org/10.1016/j.biortech.2014.10.113

Nanou, P., Carbo, M. C., & Kiel, J. H. (2016). Detailed mapping of the mass and energy balance of a continuous biomass torrefaction plant. *Biomass Bioenergy, 89*, 67-77. https://doi.org/10.1016/j.biombioe.2016.02.012

Parr Instruments. (2017). Operating instructions for the 1241 oxygen bomb calorimeter. No. 203M. Chicago, IL: Parr Instruments. Retrieved from https://www.parrinst.com/wp-content/uploads/downloads/2012/06/203M_Parr_1241-Oxygen-Bomb-Calorimeter-Inst_Rev-0888.pdf

Phanphanich, M., & Mani, S. (2011). Impact of torrefaction on the grindability and fuel characteristics of forest biomass. *Bioresour. Technol., 102*(2), 1246-1253. https://doi.org/10.1016/j.biortech.2010.08.028

Repellin, V., Govin, A., Rolland, M., & Guyonnet, R. (2010). Energy requirement for fine grinding of torrefied wood. *Biomass Bioenergy, 34*(7), 923-930. https://doi.org/10.1016/j.biombioe.2010.01.039

Rudolfsson, M., Boren, E., Pommer, L., Nordin, A., & Lestander, T. A. (2017). Combined effects of torrefaction and pelletization parameters on the quality of pellets produced from torrefied biomass. *Appl. Energy, 191*, 414-424. https://doi.org/10.1016/j.apenergy.2017.01.035

RUF. (2016). Briquetting process. Retrieved from www.ruf-briquetter.com/our-process

SECTOR Standards. (2014). Determination of grinding energy. Leipzig, Germany: SECTOR.

Shang, L., Ahrenfeldt, J., Holm, J. K., Bach, L. S., Stelte, W., & Henriksen, U. B. (2014). Kinetic model for torrefaction of wood chips in a pilot-scale continuous reactor. *J. Analytical Appl. Pyrolysis, 108*, 109-116. https://doi.org/10.1016/j.jaap.2014.05.010

Strandberg, M., Olofsson, I., Pommer, L., Wiklund-Lindstrom, S., Aberg, K., & Nordin, A. (2015). Effects of temperature and residence time on continuous torrefaction of spruce wood. *Fuel Process. Technol., 134*, 387-398. https://doi.org/10.1016/j.fuproc.2015.02.021

Tumuluru, J. S., Sokhansanj, S., Hess, J. R., Wright, C. T., & Boardman, R. D. (2011). A review on biomass torrefaction process and product properties for energy applications. *Ind. Biotechnol., 7*(5), 384-401. https://doi.org/10.1089/ind.2011.7.384

Yasar, D. (2012). *Energy production, conversion, storage, conservation, and coupling.* London, U.K.: Springer.

Zheng, A., Zhao, Z., Chang, S., Huang, Z., He, F., & Li, H. (2012). Effect of torrefaction temperature on product distribution from two-staged pyrolysis of biomass. *Energy Fuels, 26*(5), 2968-2974. https://doi.org/10.1021/ef201872y