Utilization of Wet Forest Biomass as both the Feedstock and Electricity Source for an Integrated Biochar Production System

A. J. Eggink, K. D. Palmer, M. A. Severy, D. J. Carter, A. E. Jacobson

Abstract. *A belt dryer and gasifier generator set were integrated into a biochar production plant to use process heat to dry biomass feedstock from forest residuals and to provide electric power to the plant using a side stream of dried biomass. Experiments were conducted to characterize the dryer throughput and drying capacity using process heat from a stack heat exchanger attached to the biochar machine flare. A matrix of tests was conducted at high and low flow rates for both the heat exchanger air flow rate (which varied the temperature and heat input to the dryer) and the residence time of feedstock in the belt dryer. Mean feedstock input moisture during dryer characterization was 45% and the mean moisture after exiting the dryer was 27%. The optimal test condition, providing the greatest water removal rate, was determined to have high air flow rate through the heat exchanger and short dryer residence time. This condition was used to demonstrate the integrated system for an 8-h production day. The integrated system dried incoming feedstock from 36% to 22% with a dryer throughput rate of 495 kg h^{-1} w.b. and an evaporation rate of 88.8 kg h^{-1}, providing the necessary dry feedstock for the 20-kW gasifier generator set and the biochar machine, which produced 75 kg h^{-1} of biochar. This system required the operational effort of 0.92 labor hours per production hour. Results from this demonstration indicate that the integrated system provides key benefits in a biochar production operation including greater control of feedstock drying and the ability to operate without an external (non-biomass) source of fuel for electricity generation.*

Keywords. *Biochar, Biomass, Biomass drying, Forest residuals, Gasification, Pyrolysis.*

Forest residuals resulting from resource extraction and forest management typically remain piled on the landscape where they are burned or left to decay because recovery cost exceeds their economic value (Springsteen et al., 2011; McElligott et al., 2011). This management method can result in undesirable emissions, uncontrolled forest fires, and long-term soil damage (Rhoades and Fornwalt, 2015). Research conducted into biomass conversion technologies has shown that applying processes such as pyrolysis, gasification, densification, and torrefaction to forest residuals can produce value-added products providing for an alternative management method from an unrealized resource. Pyrolysis and gasification of forest residuals can be used to produce biochar. Biochar, a carbonaceous material, is used primarily as a soil amendment to improve moisture retention capacity and reduce nutrient leaching (Lehmann and Joseph, 2012). In comparison to forest residual management practices such as open-pile burn or decomposition in-place, converting forest residuals into char for use as a soil amendment has the potential to improve forest health and sequester carbon, reducing greenhouse gas emissions such as carbon dioxide and methane (Springsteen et al., 2011). Soil under an open-pile burn showed significant changes compared to the properties of unburned soil including an increase of pH by 14%, decrease of organic matter by 36%, decrease in carbon by 29%, and a decrease in nitrogen by 26% (Page-Dumrose et al., 2017). Additionally, removing forest residuals from the forest floor has been shown to reduce the risk of catastrophic wildfire. In a 34-year United States Department of Agriculture (USDA) study, piles left to decay required at least 30 years to lower the fire hazard to a comparable condition prior to resource extraction (Wagener and Offord, 1972).

The economic feasibility of recovering and harvesting forest residuals is a major barrier for utilization of this biomass. In the United States, comminuted forest residuals are transported to an end-use location using a truck and trailer, which represents a major component of the cost of recovery (Zamora-Cristales and Sessions, 2015). In general, the biomass load size should be maximized (Anderson et al., 2012), and the recovery distance of chipped forest biomass to the processing location should be less than 161 km (Fadali and Harris, 2007). Biomass load size is limited by either weight or volume capacity of the truck and trailer as defined by state transportation regulations. Green biomass [~50% moisture content on a wet basis (w.b.)] limits the maximum load size by weight and contributes to cost and inefficiency by shipping moisture that must be removed from the biomass prior to utilization or conversion. Therefore, to maximize biomass

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load size by volume, the energy density per load can be increased by reducing the biomass moisture content prior to transportation to a processing location (Sessions et al., 2013). Additionally, the transportation distance can be reduced by implementing a mobile biomass processing facility that can be moved to a near-woods location close to the biomass recovery effort, for example at a forest landing. Page-Dumroese et al. (2009) reports that in-woods biomass conversion using a portable pyrolysis system can improve the economic and environmental feasibility of residual utilization in small-scale systems. However, a mobile biomass processing facility will process less raw biomass (e.g., 1-5 tonnes/h) compared to a centralized facility, which limits the economies of scale that can be achieved in the woods. The tradeoffs between scale and biomass transportation costs need to be investigated in different contexts to determine the optimal system for each circumstance. These investigations are outside the scope of this study, but the technical results presented below allow for future analysis and comparison.

For an in-woods or near-woods site such as forest landing or former lumber mill, grid power may not be available for a temporary biomass processing facility. To produce electricity at this site, an alternative to a diesel generator is a biomass gasifier generator set (Severy et al., 2016a). Powering a biomass processing facility via gasification with readily available, low-value biomass can be a competitive method of conversion if technical barriers are overcome (Asadullah, 2014). Compared to a diesel generator, a gasifier will increase the utilization of forest residuals and reduce the use of fossil fuels.

The efficiency and feasibility of biomass conversion processes such as pyrolysis, gasification, or combustion are directly influenced by the moisture content of the biomass feedstock. For pyrolysis and gasification processes, product yield and process efficiency require pre-drying of biomass (Cha et al., 2016). For example, combustion efficiency can be increased by as much as 15% by using dried instead of wet biomass, with an optimal wet basis moisture content of 15% to 25% (Pang and Mujumdar, 2010). Ideal moisture contents for biomass gasification and pyrolysis are in the range of 10% to 20%, which results in increased energy efficiency and reduction of volatilized tars (Pang and Mujumdar, 2010).

Reducing feedstock moisture content, however, comes at the cost of increased energy consumption for the drying process. Alamia et al. (2015) compared gasification of biomass at 50% moisture content and 10% moisture content and found that the wetter feedstock required 22% of the feedstock's heating value to dry and heat the biomass to gasification temperatures while the dryer feedstock required just 2.5% of the feedstock's heating value. The increased efficiency of gasification of dryer feedstocks comes at the expense of increased energy used for processing. Thus, the efficiency of the overall process is dependent on the source of energy for moisture removal. Biomass conversion facilities that produce biochar, for example, have an abundant amount of waste heat that can be used for these on-site loads such as drying (Severy et al., 2016b). Therefore, incorporating a dryer upstream of the gasifier can offer efficiency improvements to the gasification process without requiring additional sources of heat.

The primary purpose of this article is to report the results of a case study where a waste heat recovery dryer and biomass gasifier generator set were integrated with a biochar production machine. This project involved installation and analysis of a waste heat recovery system to dry biomass feedstock from forest residuals for a biochar production facility. This facility is owned and operated by Redwood Forest Foundation Incorporated (RFFI) as part of a small commercial operation located at a former mill site in Branscomb, California without access to electrical or natural gas utility service. The feedstock supply is green forest residues harvested from thinning operations in a local forest. The moisture content of the feedstock upon delivery is too wet to use directly in the biochar machine, which requires less than 25% moisture (w.b.). Without a drying system on site, RFFI has been forced to passively dry wet feedstock by spreading and rotating piles of feedstock in the sunlight. This drying method increases production costs due to additional labor and limits the productive machine hours when dry feedstock was not available. In order to continue using green forest residues as the feedstock, RFFI was interested to implement a drying system upstream of the biochar machine that would allow processing of green biomass feedstock directly.

Using equipment available to the authors, an integrated waste heat drying and electrical generation system was setup at the biochar production facility. Waste heat produced from the biochar machine was used to dry incoming, wet forest residuals to a target moisture content of less than 25% (w.b.). These forest residuals were used as the feedstock for the biochar machine and for a gasifier generator set which provided electricity for the biochar machine and dryer. In order to understand the system, mass flow, moisture content, electric power, and temperature were measured at selected points throughout the system. As part of this work, throughput and drying capacity of the belt dryer using process heat were characterized prior to system integration. The primary objectives of the case study were to:

- Add waste heat drying to an existing biochar production facility to decrease labor effort and increase productive machine hours. In order to eliminate the need for solar drying, feedstock needs to be dried from 35% to less than 25% (w.b.).
- Demonstrate the functionality of an integrated biochar production system with a waste heat dryer and gasifier generator set.
- Characterize the dryer used in this study with waste heat as the fuel source.

The economics of this biomass conversion facility are not analyzed as part of this article. The economic results are presented by Berry and Sessions (2018).

Materials and Methods

This section describes the methods used for field testing, data collection, and data analysis. Field tests were performed during May and June 2016 in Branscomb, California, with an existing biochar machine. A dryer was configured to recover waste heat from the flare of the biochar machine. Biomass dried in the dryer would be directly fed into the biochar machine. A small stream of this biomass could be diverted for use in a gasifier generator set to provide electric power to the remote operation site. Testing occurred in two phases: 1) characterization of the dryer using waste heat to determine the optimal operating conditions; and 2) steady state operation throughout an eight-hour production day to assess the technical feasibility and labor requirements of the integrated system including the biochar machine, dryer, and gasifier generator. This section provides an overview of the major system components, the data analysis instrumentation, and the testing and analysis methods.

System Description

Equipment available to the Schatz Energy Research Center was combined with the existing biochar machine to demonstrate technical feasibility. The integrated system consisted of a biochar machine with stack heat exchanger (Biochar Solutions, Inc.), a 20-kW electricity-producing gasifier generator set (PP20GT Power Pallet, All Power Labs, Berkeley, Calif.), a belt dryer (Beltomatic 123B, Norris Thermal Technologies, Tippecanoe, Ind.), and a 20-kW backup diesel generator (Multiquip, Carson, Calif.). Automated conveyors and hoppers were installed to meter material flow and to minimize operator effort. All the system components were tested previously in a stand-alone capacity or as a part of another system to determine the characteristics necessary to design this system. A simplified diagram of the system is shown in figure 1, and a picture of the system is presented in figure 2.

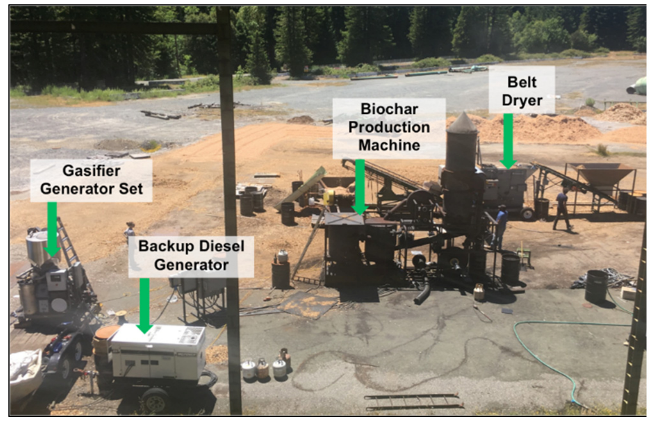

Figure 2. Picture of integrated biochar production system during steady state testing.

Biochar Production Machine

A biochar production machine (Biochar Solutions, Inc., Carbondale, Colo.) owned by Redwood Forest Foundation, Inc. (Fort Bragg, Calif.) was used for this experiment. The operating principles and a detailed system description are provided by Severy et al. (2016b). This biochar machine, which requires a single operator, has an average feedstock throughput rate of 385 kg h^{-1} (w.b.) and produces 43 kg h^{-1} of biochar with an average electrical demand of 12 kW (Severy et al., 2016b). The machine requires feedstock with less than 25% moisture content (w.b.) and less than 15% ash content (d.b.). The machine provides a significant quantity of waste heat that could be used for feedstock drying. Previous tests by Severy et al. (2016b) indicate that an average of 15% of the total waste heat, or 68 kW, can be recovered from the exhaust flare heat exchanger. The flare, which combusts syngas evolved from the biochar production process before emission to the atmosphere, includes a cross-flow, air-to-air heat exchanger, which transfers heat from the stack to a stream of air. Air flow on the cold side of the heat exchanger

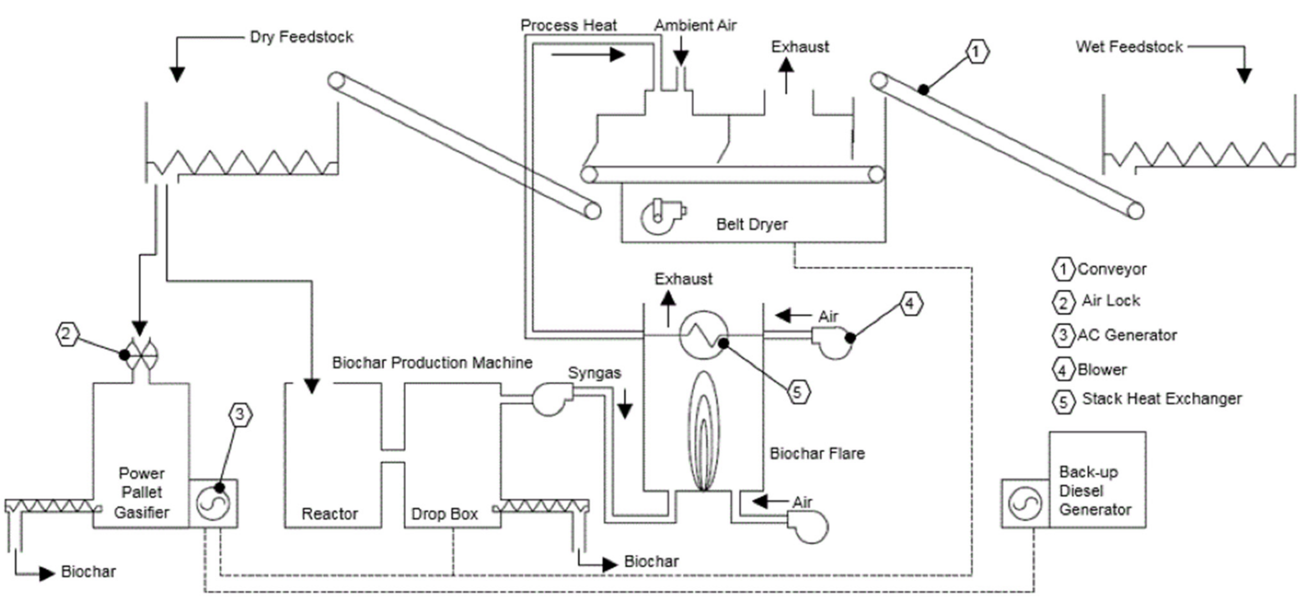

Figure 1. Simplified schematic of integrated biochar production system as tested.

(HEX) is controlled by a blower with a variable frequency drive (VFD). The VFD controls the speed of the blower and air flow through the HEX, which allows control of the outlet air temperature between 150°C and 260°C.

POWER PRODUCING GASIFIER GENERATOR

Using a gasification process to produce combustible gas from biomass chips, a PP20GT gasifier generator (All Power Labs, Inc., Berkeley, Calif.) produces electricity using an internal combustion engine and generator fueled by producer gas (syngas). The Power Pallet has a rated output of 20 kW and is powered by a General Motors 3.0 L 4-cylinder engine (Detroit, Mich.) in combination with a Mecc Alte NPE32 E/4 12-wire 4-pole generator (Vicenza, Italy). Previous test results of this machine indicated that the unit had robust load following capabilities and was capable of powering the integrated operation with an average fuel consumption of 1 kg of biomass (d.b.) per 0.55 kWh of electricity produced (Palmer et al., 2018). Based on the expected 10 kW load of the operation, the dry basis feedstock demand rate is 18 kg h^{-1}. The feedstock for the gasifier is required to have a moisture content between 10% and 30% (w.b.) and particle sizes screened to a dimensional range of 13 to 38 mm (0.5 to 1.5 in.) (All Power Labs, 2017).

BIOMASS DRYER

A packed moving bed dryer, or belt dryer, was used in this system. The Beltomatic 123B belt dryer utilizes an 85 m^3 min^{-1} (3,000 ft^3 min^{-1}), 2.2 kW (3 hp) fan to move air through a woven stainless steel belt that is 69 cm (27 in.) wide and 3.66 m (12 ft) long. The feedstock inlet bed depth is adjustable for a range of depths from 5 cm to 25 cm. The unit is rated by the manufacturer to have a maximum water evaporation of 54.4 kg h^{-1} (120 lb-h^{-1}) using the internal 1.055 GJ (1 million BTU h^{-1}) propane burner (Norris, 2017). The internal burner was not used during this project; instead, waste heat from the biochar machine was used as the heat source for the dryer. The basic process of the dryer, as shown in figure 3, is to force a mixture of hot and cool air through a mesh belt, which is transporting biomass through the length of the unit. Hot air passes over the surface area of the biomass twice, from the top input of the dryer through the belt where it is circulated by the fan, then back up through the belt to the exhaust port. These modifications, which were

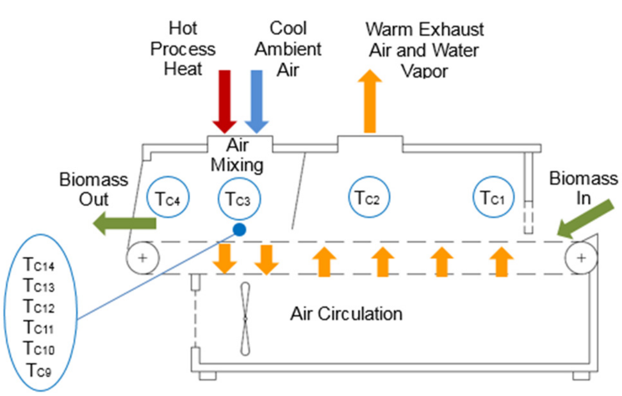

Figure 3. Schematic showing basic belt dryer operation and thermocouple measurement points.

approved by the dryer manufacturer, increased the dryer's water removal capacity and allowed it to exceed its rated specifications. Thermocouples were installed approximately as shown in figure 3 and with detailed positions noted in table 1. A six-point thermocouple (T_{C9}-T_{C14}) is mounted vertically, directly beneath the air inlet, beginning 1.3 cm above the belt within the feedstock bed, with measurement points every 4.5 cm up the vertical length of the thermocouple.

INSTRUMENTATION

Instrumentation was installed on the biochar production machine, the gasifier generator, and the belt dryer 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 input mass and inlet and outlet moisture content data were collected using digital scales.

FEEDSTOCK DESCRIPTION

The feedstock used for the tests included cedar and redwood for the dryer characterization and redwood for the integrated system testing. Both the cedar and redwood feedstocks were locally harvested and chipped to a nominal particle size of <51 mm in the week prior to testing then delivered to the test facility.

The operation of the gasifier generator requires dry feedstock prior to its production by the integrated system. It would be expected that in a production environment, dry feedstock would be available from previous production days to initiate electricity production from the power pallet. For this project, dry tanoak feedstock within manufacturer specifications for moisture content and particle size was used as feedstock for the gasifier generator.

TEST METHODS

The approach to this demonstration study was to first install the dryer system, gasifier, and instrumentation. Then, the dryer was tested at four different operating conditions to identify the parameters that achieve the highest biomass throughput rate with an outlet moisture content below 25%.

Dryer Characterization Testing Methods

Prior to steady state data collection on the integrated system, the dryer was operated at several different set-points to acquire an understanding of operating conditions and settings. To characterize the moisture reduction potential of the dryer during operation with the biochar machine using process heat, a set of experimental test runs, as described in table 2, consisting of high and low process heat input and high and low dryer residence time were conducted.

Dryer residence time was controlled by a variable frequency drive (VFD) located on the operator's control panel. To achieve a high and low residence time, the VFD was set according to a conversion table to either 100% belt speed (60 Hz), which is equivalent to 62.8 cm m^{-1} and a residence time of 5.5 min, or 50% belt speed (30 Hz), which is equivalent to 31.4 cm m^{-1} and 12.25-min residence time. The dryer's bed depth adjustment was set to have a constant depth of approximately 15 cm. Process heat was controlled by varying the motor speed of the hot air input blower to the

Table 1. Abbreviated list of instrumentation.

Name	Description	Type and Location
T_{C1}	Temperature of air at the dryer feedstock inlet	Type-K thermocouple mounted at the feedstock inlet, 10 cm above feedstock
T_{C2}	Temperature of air inside the dryer	Type-K thermocouple inside dryer, 1.2 m from inlet, 10 cm above feedstock
T_{C3}	Temperature of air inside the dryer	Type-K thermocouple inside dryer, 2.1 m from inlet, 10 cm above feedstock
T_{C4}	Temperature of air inside the dryer	Type-K thermocouple inside dryer, 3.0 m from inlet, 10 cm above feedstock
T_{C9}-T_{C14}	Temperature of the feedstock bed	Type-K 6-point thermocouple inside dryer, 2.1 m from inlet, measurement point at tip, then vertically every 4.5 cm, from 0 to 18 cm.
T_{H1}	Temperature of air from HEX at the dryer air inlet	Type-K thermocouple inside hot air inlet at dryer air inlet in the center of flow
T_{A1}	Temperature of the ambient air	Type-K thermocouple in ambient air
RH_A	Relative humidity of ambient air	Relative humidity of ambient air
RH_E	Relative humidity of dryer exhaust air	Relative humidity sensor directly over dryer exhaust
DP_A	Flow of ambient air into the dryer air inlet	Averaging pitot tube at ambient air inlet to dryer
DP_H	Flow of hot air into the dryer	Averaging pitot tube at ambient blower inlet to biochar HEX
P_G	Electric power from gasifier generator	Current transformers and power meter on main electrical supply
P_D	Electric power in to dryer and conveyor	Current transformers and power meter on dryer input electrical supply

Table 2. Matrix of test runs used for data collection.

	Process Heat	
Dryer Belt Speed	Low	High
Low	Test 1	Test 3
High	Test 2	Test 4

dryer from the biochar heat exchanger. High and low settings were evaluated experimentally through operation prior to testing and determined the high setting to be 80% of the blower's maximum, which is approximately 19.2 m^3 m^{-1} and the low setting to be 40% of the blower's maximum, which is approximately 11.7 m^3 m^{-1}. The internal dryer blower was set to operate at 100% (60 Hz), circulating air within the dryer through the chip bed, and drawing cool ambient air in through a partially open cool air inlet at an average rate of 3.5 m^3 m^{-1} for all tests. Typical air flow and temperatures of air input to the dryer are shown in figure 4. Higher flow rates through the biochar machine heat exchanger (light blue lines) result in lower temperatures than the low air flow rate (dark red lines).

Data were collected when the biochar machine was operating at steady state conditions. Feedstock entered the dryer in a continuous stream via a conveyor with flow metered by a level sensor placed at the dryer feedstock inlet. In addition to measuring initial mass, the feedstock moisture content before and after the dryer were measured in triplicate using a moisture balance (BEL Engineering, i-Thermo 163L, Monza, Italy).

System Integration Testing Procedures

After data were collected for test runs and a qualitative analysis of system operation was completed, a steady-state production run was carried out over the course of an eight-hour workday. To begin a test, the feedstock hopper on the gasifier generator was filled with biomass according to the manufacturer's particle size and moisture content specifications (All Power Labs, 2017). Feedstock for the gasifier had been dried and prepared using the belt dryer system on the previous day. The gasifier reactor was started, and producer gas was flared for a warm-up period of approximately 15 min. After the warm-up period, the syngas was directed to the engine via a ball valve. Then the engine was started and the generator was switched on. With electricity now being produced at the site, the biochar machine and dryer were started. The biochar machine was started first to enable production of process heat for drying. To start the biochar

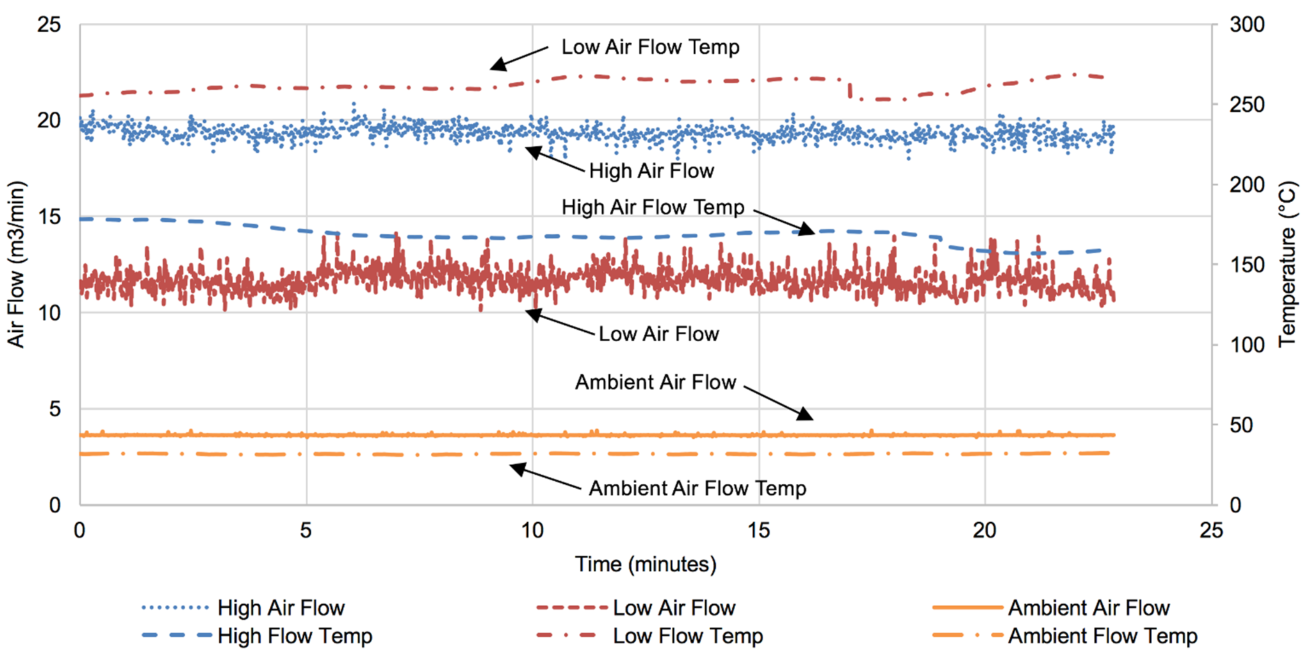

Figure 4. Air flow and temperature to the dryer.

machine, the reactor was filled with dry feedstock and ignited with a propane torch. The reactor was allowed to warm up, during which time the flare was ignited. During the warm-up period for the biochar machine, the dryer hopper was loaded with a weighed plug of wet feedstock. The moisture content of the feedstock was measured using the moisture balance. After a warm-up period of approximately 15 min, biochar production began. With the biochar flare at stable operating temperature, the flare heat exchanger blower was turned on to send hot air to the drying system. Ambient air was introduced to the drying system using the dryer's internal blower. This blower was operated at maximum velocity (60 Hz) and served two functions: 1) to draw in ambient air and 2) to circulate the mixed air through the chip bed. The ambient air inlet was partially restricted so that the fraction of ambient air entering the system was approximately 20% for all tests, holding this variable constant. Next, the dryer conveyor belt was started, and feedstock began to dry as it is moved through the dryer. After drying, the feedstock moisture content was measured as it was conveyed to the biochar machine hopper where it was then metered into the biochar machine reactor at the discretion of the operator. The biochar machine hopper, acting as an intermediate storage, allowed the operator a measure of flow control for both the dryer and the biochar machine to maintain steady state operation. Throughput matching of the equipment was dependent on the belt speed setting of the dryer. During steady state operation, biochar was collected and weighed at the outlet of the biochar production machine.

Data Collection Methods

Wet feedstock samples were collected and immediately tested for moisture content using the moisture balance analyzer. Dried feedstock samples were collected intermittently during test runs and steady state operation. The samples were mixed to make a composite sample that was then tested for moisture content using the moisture balance analyzer. Flow rates for hot air from the biochar stack heat exchanger and ambient input air were determined using averaging Pitot tubes (Nailor, 36 FMS, Houston, Tex.) and pressure sensors. The Pitot tube for the hot air was placed at the blower input so that data would be collected at ambient conditions. Electrical power production and consumption data were collected at the output of the gasifier and the electrical inlet of the dryer using current transformers and a power meter (WattNode ModBus, Continental Control Systems, Longmont, Colo.). Electrical consumption by the biochar machine was calculated by difference.

Time and Motion Study

A time and motion study was conducted during integrated system operation to determine labor requirements associated with steady state operation for an 8-h production day for each machine. Data were collected in 5-min increments. Data collection involved recording information about the operational effort required for a typical production day divided by task. For the task of electricity production, the labor required to operate the gasifier generator from start-up to shut-down was included, as well as labor to fill the feedstock hopper as needed. For the task of drying biomass, the labor required to operate the dryer from start-up to shut-down was included. The remaining tasks were associated with the production of biochar. This includes labor associated with operating the biochar machine from start-up to shut-down and the labor required for feedstock handling, including moving feedstock with a tractor and bucket to load feedstock into the dryer hopper at the beginning of the production line and end-product handling required for the finished biochar at the machine outlet.

RESULTS AND DISCUSSION

Results presented in table 3 show the matrix of test runs where high and low set-points were adjusted for both biochar process heat and dryer residence time. The biomass throughput rate ranged from 216 to 521 kg h^{-1} (d.b.) depending on the dryer belt speed. The water removal rate averaged 97 kg h^{-1} for the low belt speed and 245 kg h^{-1} for the high belt speed tests. Electric power demand for the dryer was similar for all tests, ranging from 3.1 to 3.5 kW, but using a higher blower speed on the HEX blower increased the biochar machine's power demand from 4.1 to 7.5 kW. Average dryer exhaust temperatures ranged from 36°C at 1.2 m from the inlet, 10 cm above the feedstock, and directly beneath the dryer exhaust, to 174°C at 2.2 m from the inlet, 10 cm above the feedstock, and directly beneath the thermal input.

Dryer Temperature Profile

A typical temperature profile of the dryer during steady state operation is shown in figure 5. As shown in figure 3, T_{C4} and T_{C3} were located in the mixed air inlet chamber of the dryer, and T_{C1} and T_{C2} were located in the exhaust chamber of the dryer. The mixed air inlet temperature is the highest profile temperature, ranging from 144°C to 184°C. The biochar machine HEX blower motor speed was set to 80% (48 Hz) during this steady state period, controlling the average air flow rate. The range of mixed air temperatures, and thus variations in process heat from the HEX, were the result of fluctuating burn rates in the biochar flare. This range can be seen throughout the temperature profile in figure 5 as the mixed air temperature entering the dryer.

Recalling that the feedstock bed depth is approximately 15 cm, thermocouples T_{C14}, T_{C4}, T_{C3}, and T_{C13} are above the

Table 3. Dryer characterization experimental tests.

Test ID	HEX Blower Setting	Feedstock Input Rate, kg h^{-1} (d.b.)	MC In, % (w.b.)	Water Removal Rate, kg h^{-1}	MC Out, % (w.b.)	Exhaust Relative Humidity, %	Avg. Electric Power, kW	Avg. Biochar Electric Power, kW	Mixed Air, °C	Avg. T_{C2}, °C	Avg. T_{C3}, °C
Test 1	40%	285	37%	91	21%	87%	3.2	4.1	206	36	163
Test 2	40%	521	53%	281	37%	82%	3.5	4.1	211	36	174
Test 3	80%	216	43%	103	24%	82%	3.1	7.3	149	36	138
Test 4	80%	464	45%	210	26%	82%	3.3	7.5	133	35	124

feedstock bed and exposed to the hot inlet air. T_{C2} and T_{C1}, also above the feedstock, are exposed to exhaust air, and thus have lower temperatures closer to ambient air. Thermocouples T_{C9}-T_{C12}, located vertically within the feedstock bed, have a temperature profile that is less smooth than the other measurement points. This was likely due to the variable contact with wood chips and interstitial pockets of air layered within the feedstock bed. Thermocouple T_{C12} was within the feedstock bed near the boundary where the inlet air meets the biomass feedstock. Variations in T_{C12} may have been due to existing slight variations in the feedstock bed depth, where T_{C12} may have been exposed to inlet air. These variations were the result of a mechanical rake at the feedstock inlet that spreads the feedstock according to the depth setting. Since the biomass has variations in chip sizes and dimensions, areas of slightly higher and lower depth occur in the feedstock bed as the biomass is metered into the dryer. These variations in depth are estimated to range from 1 to 3 cm. Thermocouples T_{C11} and T_{C10} were well within the vertical feedstock bed with reducing temperatures as the process heat moves through the wet feedstock. Thermocouple T_{C9}, showing the lowest temperature for the biomass feedstock profile, was in the feedstock bed 1.3 cm away from the stainless-steel mesh belt and was the closest to the boundary layer where the feedstock meets the belt.

Dryer Performance and Throughput

Under all test conditions, the dryer was able to remove between 20% and 25% of the original mass fraction of the biomass, as shown in figure 6. Regardless of the belt speed, the fraction of water removed was approximately equal for

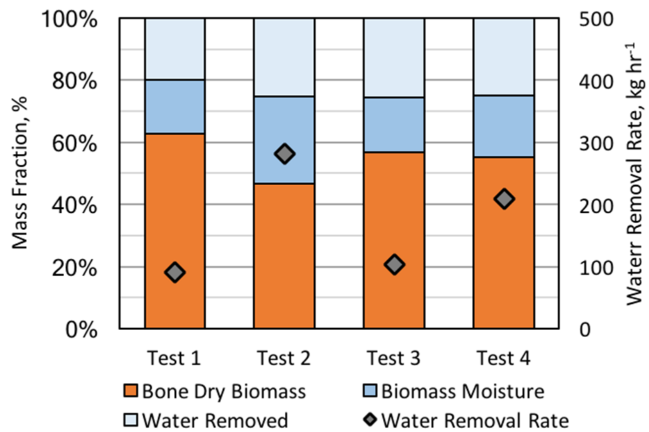

Figure 6. Mass fraction of biomass for each test showing fractions of bone dry biomass, moisture within biomass, and water removed during testing. The water removal rate, shown as diamond markers, is read from the right axis.

all tests. For example, Tests 3 and 4, which had the same heat input rate from the biochar machine, removed the same fraction of water despite the belt speed being twice as fast in Test 4. This shows that within the range of conditions tested, the residence time does not influence the extent of drying. Residence time becomes more important when drying biomass below the fiber saturation point, when moisture needs to diffuse through the cell wall before evaporation. Since all the drying in these experiments was removing free moisture above the fiber saturation point, shorter residence times with high belt speeds were able to remove more moisture because more chips were being exposed to the available waste heat.

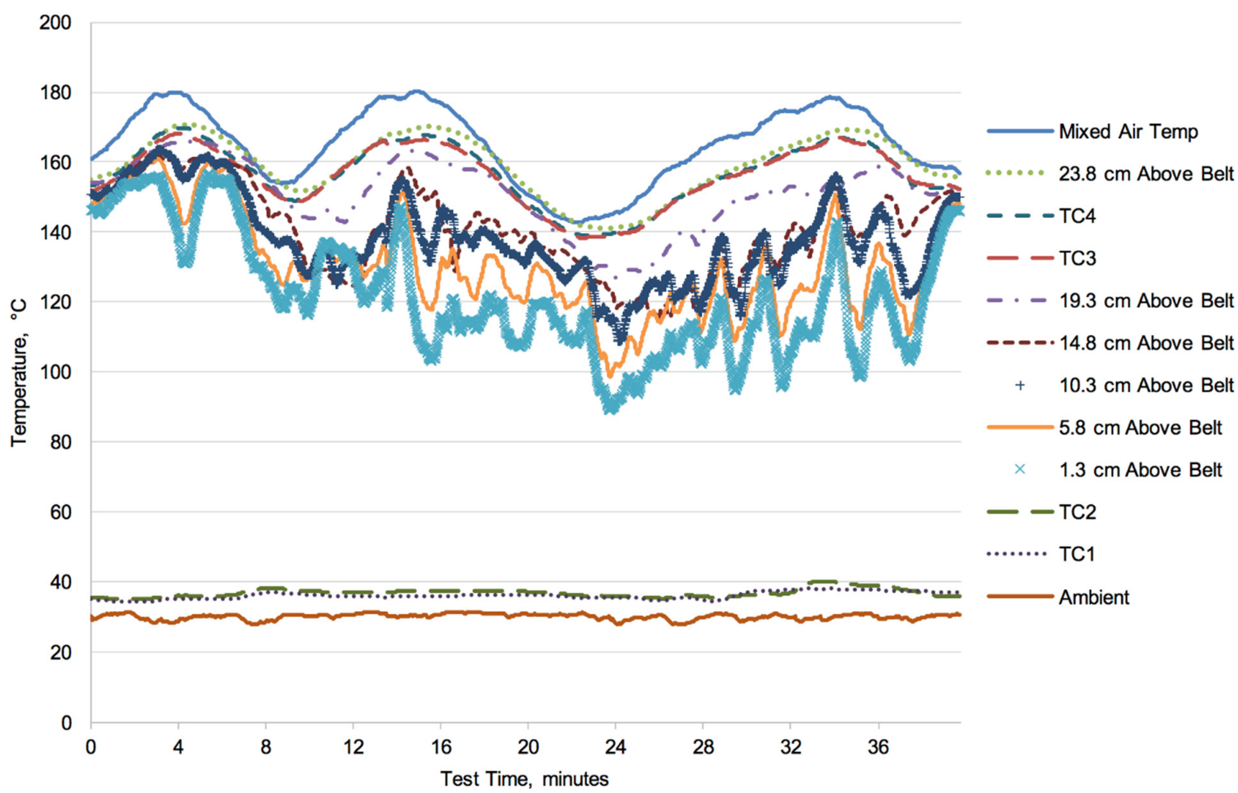

Figure 5. Dryer temperature profile during a dryer characterization test. Beginning at the top, legend entries are arranged from highest to lowest temperature, with the mixed air inlet temperature being highest and the ambient temperature, lowest.

By doubling the belt speed from Tests 3 to 4, we see that the higher belt speed directly influences the water evaporation rate by increasing the input rate of biomass into the dryer and applying the heat to more material. Residence time would become more important if the target outlet moisture content was lower and required removal of bound water from the biomass.

Dryer throughput was measured at two belt speed setpoints during the dryer characterization test runs. The higher belt speed of Tests 2 and 4 was determined to be the optimal operating condition for the dryer because it produced the highest water removal rates while also removing a similar fraction of moisture from the feedstock as discussed above. The higher belt speed decreases the residence time and allows more feedstock to be heated by the waste heat. Since all the drying occurs above the fiber saturation point, increasing the belt speed allowed more feedstock to be dried because residence time did not influence the drying capacity of free water in the feedstock within the range of conditions tested.

Integrated System

In a separate set of tests during an 8-h production day, mass and energy flow data collected from the integrated biochar production system are shown in table 4. For this test, the dryer was operated with the same parameters as Test 3, using a high belt speed and the HEX blower set to 80%. The system processed 500 kg h^{-1} of biomass at 36% moisture content (w.b.) to produce 75 kg h^{-1} of biochar without any external electricity power source or heat source for the dryer.

Steady state operation of the integrated biochar system produced the mass and energy flows that are detailed in table 4 and shown in the flow diagram in figure 7. The system input rate was 320 kg h^{-1} d.b. of biomass (500 kg h^{-1} w.b.) to the dryer. From the dryer output, 303 kg h^{-1} d.b. was directed to the biochar machine while 17 kg h^{-1} d.b. went to the gasifier generator set. The dryer was operated at a maximum belt speed of 62.8 cm min^{-1}, and the heat exchanger blower was operated with the VFD set at 80%.

Testing the integrated system provided the opportunity to demonstrate the results of several associated questions critical to operation. First, the throughput rate of the dryer during production must be equal to or greater than feedstock input required by the biochar machine and gasifier generator set. As shown in table 4 above, the high belt speed setting provided the necessary throughput by processing biomass on a dry basis at rates of 464 to 521 kg h^{-1}. Second, at the required belt speed, the dryer must process biomass feedstock to a

Table 4. Mass and energy flow through integrated biochar system.

	Dryer	Biochar Machine	Gasifier Generator[a]	Integrated System
Biomass input, kg h^{-1} w.b.	500	389	21	495
Input moisture content, w.b.	36%	22%	22%	36%
Biomass output, kg h^{-1}, w.b.	410			
Biochar output, kg h^{-1}, w.b.		75	0.45	75
Output moisture content, w.b.	22%			
Average electric demand, kW	2.8	6.6	-9.3	0.0
Peak electric demand, kW	9.0	13	-17	
Labor h required per machine h	0.16	0.49	0.28	0.92

[a] Negative values for electrical power indicate energy flow output to other parts of the system.

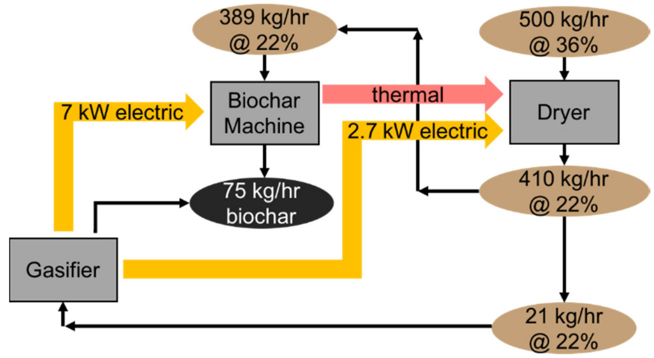

Figure 7. Process flow diagram and measured results for integrated biochar production operation. This diagram includes average values for characteristic operation, but instantaneous conditions will vary depending on specific conditions and flow rates.

moisture content suitable for use in the biochar machine and gasifier generator set. The mean feedstock input moisture content during the integrated system testing was 36%, and the mean delta MC was 14%, providing a finished product with a mean moisture content of 22% (w.b.). This is within the required specification for both machines, but is at the high end of the rated moisture content specification of 25% for the biochar machine and 30% for the power pallet. An input moisture content of 36% (w.b.) should be considered close to the maximum for this integrated system. Third, the gasifier generator set must be able to power the entire operation as a stand-alone system. The gasifier provided power for the system during the integrated system demonstration, but it did require significant operator effort. Lastly, as this project aims to demonstrate a commercial operation, operational effort must be characterized. Biochar production, as operated by Redwood Forest Foundation Inc., required one full-time operator prior to the installation of the integrated system. A time and motion study indicated that the labor hours per machine hour to support the biochar machine were 0.49 h h^{-1}, the gasifier generator set was 0.28 h h^{-1}, the dryer was 0.16 h h^{-1}, and the entire system was 0.92 h h^{-1}. This fits with RFFI's current labor effort, while adding the key benefits of advanced drying capabilities and power generated from a side-stream of biomass feedstock.

CONCLUSIONS

Testing this integrated system showed that this system can provide key benefits in a production operation.

- The demonstration system allowed the biochar operation to successfully operate with wet biomass feedstock. The inlet moisture content specification was increased from 25% to 35% with the addition of a waste heat dryer and allowed the system operator to eliminate the need for passively drying feedstock before utilization.
- Process heat from the biochar machine can be used to reduce the moisture content of incoming feedstock and should be utilized to the greatest extent possible. Ex-

perimental results indicate that the waste heat recovered from the biochar machine provided sufficient heat to the dryer, and operating the biochar machine blower at a high HEX speed and operating the dryer at a high belt speed provided the best result.

- Within the range of belt speeds tested in this study, residence time does not influence the fraction of water removed when drying biomass above the fiber saturation point. Thus, the dryer belt speed can be increased to maximize the water evaporation rate while maintaining the same outlet moisture content
- The operation can be powered in rural areas or where grid power is not available with a gasifier generator set that is fueled by a side stream of dried biomass feedstock.
- The operational effort to place this system in production requires less than one operator hour per machine hour, which is necessary for RFFI's current commercial operation.

Additional work is needed to identify and implement further improvements to the recovery of process heat from the biochar machine. Specifically, the HEX blower should be tested over a larger range of settings, and thermal efficiency should be calculated to determine if a redesigned heat exchanger would be more efficient. Implementing improved controls for hot and cool thermal inputs to the dryer would provide a more consistent drying regime. Additional heat recovery points should be identified with the possibility of a second heat exchanger and blower to increase the drying capacity of the system, thereby processing dried biomass for future production days or increasing the acceptable range of biomass MC.

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